From: Alex Murray
To: Amy Cubbage; Donald Carlson; Howard Faulkner; Stuart Rubin; Undine Shoop
Date: Tue, Aug 21, 2001 11:52 AM
Subject: Suggestions for updated findings

FYI,

I have attached suggested updates and modifications to the findings for incorporation into the final trip report. I will have some suggestions for the trip report itself momentarily.

Alex.

CC: Bill Gleaves; Sharon Steele

I-12

The NRC delegation considers the technical information obtained during visit to be an important step in the development of NRC staff expertise and capabilities with the goal of conducting effective and efficient safety reviews of HTGRs such as the PBMR and GT-MHR. The delegation therefore strongly encourages the technical staff to read in full the technical documents that were obtained in their respective areas of technical or professional interest. At this time, the NRC delegation and staff have not conducted a detailed review of the documents and presentations from the visit and can neither agree nor disagree with the conclusions from the German HTR program. The following technical information is viewed by the delegation as important to the safety or operational assessment of modular HTGRs:

1. The ~~To~~ manufacture of high quality fuel that consistently achieves fuel performance within expectations during irradiation and accident testing requires meticulous adherence to ~~proven~~ manufacturing equipment, ~~manufacturing~~ processes, and ~~manufacturing~~ procedures developed and proven over 25 years of experience. Quality is measured by sampling and destructive analyses - NDE does not appear to be used. Values of 1E-4 to 1E-5 were consistently mentioned for the failure rate (i.e., lack of intactness) of the silicon carbide layers. ~~must be utilized with meticulous adherence to manufacturing quality controls for all aspects of fuel manufacture. Exact compliance essential.~~

2. German fuel manufacturing for the HTR-M design would use 7-9% assay uranium. Oxide production begins with an ADU-like precipitation from a nitrate solution. Coatings are supplied by fluidized bed, chemical vapor deposition (CVD) processes. Pebble manufacture utilizes binders and graphite. More chemicals and flammable materials (and gases) and more operating processes would be used than in conventional, pellet-type fuel plants. Increased MC&A/Safeguard requirements are likely due to the assay level and the small size of the fuel components (particles and pebbles). Fuel pebbles in the German HTR program did not have unique identifiers or labels for quality control and tracking purposes.

3. ~~2.~~ The Natural Convection in Core with Corrosion (NAKOK) experiments were conducted at the FZJ to assess air ingress into an HTR-Modul reactor. From the experiments it was found that after a depressurization accident caused by a postulated break in the helium cross duct near the bottom of an HTR-Modul pressure vessel, the "diving bell" geometry will initially limit diffusion mixing of outside air with hot helium in the system. The geometry was found to provide a "grace period" (i.e., time delay) before the onset of natural convection flow of air through the core. After the grace period natural circulation of air through the core begins, subjecting core graphite materials such as the fuel elements to oxidation-induced corrosion. The analysis assumed that the reactor vessel and system have sufficient reliability of integrity that no other failures occurred in the pressure boundary.

4. Testing at Julich has shown that significant graphite corrosion (i.e., burning) can occur in the presence of air and water. Significantly, based on test results, an isolated HTR-M helium circuit and air containment volume could result in the corrosion of some 1,600 kg of carbon (out of a total of 500,000 kg in the reactor internals). This implies essentially complete reaction of the available oxygen in the air without any equilibrium limitations. It was not clear how the heat release from such corrosion was evaluated. Such a heat

release would seem to imply some hot spots in the fuel pebbles that could adversely affect the silicon carbide layer and release fission products. Water evaluations were based upon vapor pressures and equilibrium, and not upon a defined scenario such as a steam generator tube leak or an intercooler filure. Researchers have successfully coated pebbles and larger graphite surfaces with silicon carbide to reduce this corrosion. Some concerns were expressed by the fuel researchers about the durability of these coatings at the macroscopic scale due to abrasion and thermal cycling. The coated graphite and fuel pebble approach does not appear to be part of the basic HTR-M concept at this time.

5.
~~5.~~ Specific grade designations were established and assigned to the reactor graphites that were formerly manufactured for the German reactors. These grades were derived for the specific feed sources of coke that existed at the time that the graphite R&D was conducted for the German HTGR applications. Extensive irradiation testing programs had been conducted in Germany for these grades to establish their material and physical properties for use in reactor design and analyses. However, today none of the formerly widely tested graphite grades is available. For future HTGR projects, development and irradiation testing of new graphites will be required.

6.
~~6.~~ At THTR pebble flow through the core was significantly different than was seen in the scale model tests which had been conducted in air at uniform temperature. The initial core loading pattern produced a temperature profile with much higher temperature in the center axis of the core then at the outer reflector. The pebbles at the reflector moved much more slowly. By the time the outer pebbles reached the bottom of the core the burnup was greater than predicted. This resulted in the coolant temperatures at the outer reflector being lower due to the lower pebble power output there. This in turn resulted in relatively higher sliding friction between pebbles, further slowing the pebble movement. The increased core exit temperature gradient increased thermal stresses and the failure of mechanical components. The actual behavior of the pebble flow was difficult to model. This experience required implies a start-up period to empirically determine the pebble flow phenomena and coolant flow characteristics. Once determined, this minimized the potential for poor pebble mixing ("short-circuiting") in the core and potential hot spots (i.e., a higher temperature coolant has a higher viscosity and may not cool as effectively). The THTR pebble flow experience is expected to provide important input to the review of a range of safety and design analyses which are based on pebble flow behavior.

7.
~~7.~~ A special test conducted at the AVR indicated unpredicted local hot spots. In the test, approximately 20% of the 200 "melt-wire" pebbles that had passed through the core experienced significantly higher-than-expected maximum coolant temperatures (note: the AVR did not have in-core instrumentation within the fuel). The melt-wires indicated maximum core coolant temperatures were over 1280° C at full power. This is well above what had been predicted. FZJ is now preparing a report on the AVR test results. It will be provided to the NRC staff when it is completed. The report is expected to provide insights with regard to: (a) validating or correcting the code-predicted maximum fuel operating temperatures in a pebble bed reactor design and (b) assessing the need for similar tests and measurements for future pebble bed reactors.

8.
~~8.~~ The German safety analyses and safety evaluations for HTR design basis events involves a traditional deterministic approach with conservative assumptions. These include such aspects as the assumed failure of the first RPS trip signal, consideration of the worst single failure and no credit for non-safety related equipment. Other equipment was assumed to function; for example, a steel reactor vessel was assigned a failure rate of 1E-8/yr based upon the German approach and, thus, its failure was considered incredible. In addition, many of the accident scenarios assumed an active system had functioned prior to the operation of the passive features. For example, a reactor preservation system activates; the control rods are inserted, and the core is isolated (by valves, collapsible penetrations, or nitrogen blanketing) to prevent air and water ingress into the core. In the NRC regulatory envelope, such a low failure rate would likely correspond to an item of safety significance with qualifying testing, management measures, and quality levels (QA/QC programs). Code calculations utilize conservative inputs for physical, material properties and initial conditions. Shutdown, decay heat removal, and fission product retention must be shown. Postulated events in each event category are developed based on the design-specific features and equipment.

9. The HTR efforts at FZJ and elsewhere in Germany have been very focused on key technical areas and addressing specific conditions. The efforts and programs are generally of high quality. Much of the effort has been from an R&D perspective on demonstrating the HTR approach. The effort associated with regulatory aspects is less and includes implicit, specific assumptions about off normal situations, such as an isolated reactor.

10. German industry applied for a license to build a prototype of the HTR-M. After approximately one year, the consortium subsequently withdrew the license application for economic reasons (primarily to focus on LWRs). The regulatory authorities decided to complete the review for archival purposes, and ultimately concluded that the design would have received a license to start construction. Several safety features were identified, including active components in the reactor preservation system. Severe "chemical attack" (essentially large-scale graphite reaction with air and water) was judged to be a low probability event based upon the performance of safety systems to isolate the graphite and minimize releases (e.g., intermittent, "puff" release through filters; initial depressurization/blowdown and larger intermittent releases would bypass filtering). In addition, a strong confinement or containment would be needed to address external events, such as seismic events, crashes, and explosions, and their potentially detrimental effects upon isolation of the reactor.

11.
~~9.~~ Extensive measurements have been performed in Germany on heated beds of graphite pebbles in flowing air. For example results with pebbles at 900^{O} C indicate graphite corrosion rates of approximately 200 milligrams of reacted O_2 per square Cm per hour with air flowing at 0.046 meters per second. The reported corrosion rates cover a range of air flow velocities and graphite temperatures from 600^{O} C to 1200^{O} C. Less-extensive, large-scale testing has been done in the 1,200-1,600 C range.

12.
~~10.~~ Significant operating experiences occurred at the THTR. These included: pebble

breakage (without measurable increases in reactor coolant activity) due to control rod insertion; core-bypass helium flows nearly three times the predicted design values; pebble flow patterns significantly different than what had been predicted; core exit temperature gradients significantly larger than had been predicted resulting in breakage of a number of insulation attachment bolts; graphite dust problems greater than had been expected and; shortcomings in the online refueling system instrumentation and controls used to monitor pebble flow in the refueling system. Despite these problems which occurred over the few years of plant operation, overall performance for the THTR demonstration plant was viewed to be a success within the German nuclear community. The parties supporting the operation of the THTR did not have the resources to overcome the political forces seeking to shutdown AVR and they were not willing to operate the plant in light of the higher estimates of potential financial risks that had been identified. As a result, the reactor was decommissioned in 1989 only 4 years after licensing.

13. The AVR had a helium purification system based upon molecular sieves. This was primarily intended to remove tramp hydrocarbons from bearings, seals, and lubricated components. It was not clear to what extent such a coolant purification system is included in the HTR-M. In addition, carbon dust was found to be a significant concern and contributor to occupational doses. The AVR staff mentioned the need for HEPA filtration for many areas servicing the coolant and pressure boundary. It is likely that the potential impacts of coolant purification and carbon dust will need to be considered in future HTR designs.

14. In the HTR-M design, there were no incore structures or guide tubes for measurement, control, or pebble/gas flow mixing.

15.
~~11.~~ Decommissioning of the AVR and THTR is based upon a SAFESTOR approach. Significant quantities of activated graphite (containing carbon-14 and tritium) will likely require disposal at some time. The AVR had 500 tonnes of non-fuel graphite in the core areas. The larger HTR-M design would have more - an exact value was not specified. Thus, for perspective, an HTR-M design might have a graphite quantity comparable to a DOE reactor at the Hanford site (originally 2,000 Mwth or more); many of the Hanford reactors are being placed into SAFESTOR for a planned period of 50 years. For comparison, the NRC's preference is prompt decontamination of a nuclear facility within a short period after the cessation of operations. In addition, the experience indicates that the design and layout of these plants did not effectively provide for ease and radiological protection of workers during the decommissioning activities. Features that would ease decommissioning, such as more room, inspection ports, and means to facilitate robotic activities, such as the retrieval of fuel pebbles "trapped" in the coolant system, would likely be desirable in future HTR designs..

16. SNF from the AVR and THTR are being handled via metallic casks, similar in concept to those used in the United States. Specific power density and weight of uranium (MTHM) is lower but the volume is significantly higher (perhaps by an order of magnitude or more) than with LWR fuels. The casks used in Germany do not use helium backfilling and some oxidation of the graphite pebbles has been observed due to the small amount of oxygen in the cask/can system. The fuel pebbles are not held by fasteners or springs in the casks and are free to move.

17.
~~12.~~ Several key German organizations with extensive and expert technical knowledge and large archives of technical documents on German HTGR design and technology, have entered into agreements with ESKOM to support ESKOM's design and development of the PBMR and its licensing in the RSA. Most of these agreements are with ESKOM and provide access to extensive research, development, design, testing and operation and safety analyses and safety evaluations of German high temperature pebble bed reactors. Since these agreements involve direct assistance to ESKOM in support of PBMR licensing, NRC cooperation with the involved organizations in support of PBMR pre-application review in these technical areas would likely raise a conflict of interest for these organizations. Additionally, since these agreements prohibit ESKOM or the other involved recieving organizations from providing the information to third parties, NRC may not be able to obtain the reference technical information through Exelon. However, some of the German organizations have indicated that the technical information provided to ESKOM and PBMR could also provided to NRC under a separate agreement.

18. The main HTR designs considered in Germany, such as the HTR-M, used steam generators. Turbine power units, materials, and other component variations (e.g., a methane reformer) were tested in electrically heated test loops.

19. The principal metallic materials are mild carbon steels and cast iron. Very few higher alloys would be used in the HTR-M, perhaps for the steam generator tubes. Such carbon steels are ferritic and are more prone to helium diffusion effects. Extensive testing was performed at Julich to understand the impact of helium upon the steels, bearings, and other components due to the lack of formation of any surface oxide films. Without the proper design, some steel joints were found to fuse due to the helium. It was not clear why higher grades of steel and/or austenitic alloys were not used for potentially better temperature performance and improved properties in a helium environment.

This could be a finding, in the text, or both:

The design objective is a "catastrophe-free" approach to nuclear safety. The HTR-M plant would be designed with a "diving bell" approach for addressing accidents. In the design, the steam generators are located at an elevation below the core (the rationale being water cannot flow uphill into the core and react during an event). During an accident situation, a reactor preservation system activates; the control rods are inserted, and the core is isolated (by valves, collapsible penetrations, or nitrogen blanketing) to prevent air and water ingress into the core. A "chimney effect" from a failure in the pressure vessel needs to be avoided as it would lead to excessive graphite corrosion. Due to the elevation, higher coolant temperatures, and an intact vessel, the helium would be trapped and cover the graphite core and fuel pebbles, like a diving bell. Subsequent core cooling would be passive, with a peak fuel temperature of about 1,600 C for about 2% of the fuel pebbles, at around 20 or so hours into the event. Excess pressure would be periodically relieved by relief valves, occasional parting of the steel plates around the pressure vessel, or a combination of the two. It was not clear how temperature affected the concrete pressure vessel. Recriticality could occur after several days but at a low power level (0.5-1%), and, thus, some external measures (e.g., adding boron carbide or other neutron poisons) would need to be taken before that time to avoid the criticality. Note that in the NRC regulatory context, several of these features (the reactor preservation system, the control rods/shutdown system, the vessel, the isolation features, the relief valves etc.) would likely be considered active and be assigned a safety significance, requiring management measures and QA/QC programs to ensure their operability.

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Creation Date:	Tue, Aug 21, 2001 11:51 AM
From:	Alex Murray , NMSS
Created By:	AXM2@nrc.gov

Recipients

nrc.gov
owf1_po.OWFN_DO
HJF (Howard Faulkner)

nrc.gov
owf2_po.OWFN_DO
AEC (Amy Cubbage)

nrc.gov
owf4_po.OWFN_DO
USS (Undine Shoop)

nrc.gov
twf4_po.TWFN_DO
BCG CC (Bill Gleaves)
SAS CC (Sharon Steele)

nrc.gov
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DEC1 (Donald Carlson)
SDR1 (Stuart Rubin)

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