Attachment 8

HTGR NUCLEAR ANALYSIS:
AREAS FOR POTENTIAL COOPERATION
BETWEEN NRC AND THE EUROPEAN COMMISSION

Revised April 18, 2002

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On reviewing the HTR-N project description presented in Georges Van Goethem's letter to Tom King, dated October 3, 2001, we find that all of the ongoing and planned HTR-N activities either clearly or potentially include safety-related topics of interest to the NRC. The relationship of the HTR-N activities to the safety-related nuclear analysis issues listed and described herein should be clarified through technical discussions with the leaders of the HTR-N activities. Such discussions will provide a basis for developing detailed recommendations on potential cooperative efforts.

Listing of NRC Nuclear Analysis Issues for HTGRs

1. Temperature coefficients of reactivity (pebble, prismatic)
2. Reactivity control and shutdown absorbers (pebble, prismatic)
3. Moisture ingress reactivity (pebble, prismatic)
4. Reactivity transients (pebble, prismatic)
5. Pebble burnup measurements and discharge criteria (pebble)
6. Pebble-bed hot spots (pebble)
7. Pebble fission power densities and temperatures (pebble)
8. Pebble decay heat power densities (pebble)
9. Graphite annealing heat sources (pebble, prismatic)
10. Fuel and burnable poison zoning effects (prismatic)
11. Validation and modeling for criticality safety (pebble, prismatic)
12. Nuclear analysis of HTGR spent fuel (pebble, prismatic)
13. Safeguards and security for reactors and fuel materials (pebble, prismatic)

Description of NRC Nuclear Analysis Issues for HTGRs

1. *Temperature coefficients of reactivity*: The NRC staff's safety evaluations should be able to confirm that the reactivity feedback effects from temperature changes in the fuel, moderator graphite, central graphite region, and outer reflector graphite are adequately treated in the applicant's safety analyses. Based on sensitivity analyses and validation against representative experiments and tests, the evaluations should assess and account for computational uncertainties in the competing physical phenomena, including for example the positive contributions to the fuel and moderator temperature coefficients associated with ^{135}Xe and bred fissile plutonium.

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2. *Reactivity control and shutdown absorbers*: The reactivity worths of in-reflector control and shutdown absorbers can vary significantly with small changes in the radial positioning of the absorbers. The tests and analytical evaluations for reactivity control and hot and cold shutdown should also account for absorber worth variations through burnup cycles and the transition from initial core to equilibrium core loadings as well as absorber worth validation and modeling uncertainties and absorber worth variations caused by temperature changes in the core and reflector regions, xenon effects, variations or aberrations of pebble flow, and accidental moisture ingress.

3. *Moisture ingress reactivity*: Although the absence of high-pressure, high-inventory water circuits in closed Brayton cycle systems makes this issue less of a problem than in earlier steam cycle HTGRs, the effects of limited moisture ingress will nevertheless have to be evaluated for depressurized or underpressurized accident conditions. Effects to be evaluated include the moisture reactivity itself (i.e., from adding hydrogenous moderator to the undermoderated core) as well as the effects of moisture on temperature coefficients (e.g., from spectral softening), shortened prompt-neutron lifetimes (i.e., faster thermalization), and reduced worths of in-reflector absorbers (i.e., fewer neutrons migrating to the reflector).

4. *Reactivity transients*: T/H-coupled spatial reactor kinetics analyses will be needed for assessing axial neutronic stability as well as reactivity transients caused by credible events such as overcooling, control rod ejection, rod bank withdrawal, shutdown system withdrawal or ejection, seismic pebble-bed compaction, and moisture ingress. Of particular importance in the reactor safety evaluations is the need to identify, through safety analysis and risk assessment efforts, credible events that could produce rapid power transients. Particular attention should go to any credible events that could cause a prompt supercritical reactivity pulse. The intensities and estimated probabilities of the worst-case credible power transients should be considered in establishing any related plans or requirements for rapid transient testing and analysis of HTGR fuels. For loss-of-cooling passive-shutdown events with postulated failure of the active shutdown systems (i.e., ATWS), the delayed recriticality that occurs after many hours of xenon decay may also require spatial kinetics analysis models to account for the unique spatial power profiles and feedback effects caused by the higher local reactivity near the axial ends and periphery of the core where temperatures and xenon concentrations are lower.

5. *Pebble burnup measurements and discharge criteria*: Certain pebble-bed reactor designs specify that selected fission-product gamma rays will be measured to determine the burnup of each fuel pebble and that this measured burnup will serve as the criterion for discharging the pebble or passing it back through the reactor. The particular burnup value used as the discharge/recycle burnup criterion will be chosen to limit the maximum pebble burnup to a given target value (e.g., 80 GWd/t). Therefore, determining a suitable value for the discharge/recycle burnup criterion will require consideration of in-core pebble residence time spectra, together with supporting neutronics calculations, in order to statistically characterize the maximum burnup increment that might accrue during a pebble's final pass through the core. Burnup measurement uncertainties will also have to be considered. Furthermore, since pebble burnup measurements (unlike the pebble reactivity measurements used in THTR-300) cannot distinguish pebbles with different initial fuel enrichments, the same discharge burnup criterion must be applied to the initial charge of lower-enrichment fuel pebbles (e.g., 4%) as to the higher-enrichment pebbles (e.g., 8%) that are added in transitioning to an equilibrium core. Neutronics calculations will be needed to bound the higher neutron fluence experienced

by the lower-enrichment pebbles in reaching the maximum burnup levels allowed in the transitional cores.

6. *Pebble-bed hot spots*: The results of melt-wire experiments conducted in the German AVR test reactor demonstrated the existence of unpredicted local hot spots under normal operating conditions in pebble bed cores and that such hot spots determine the maximum normal operating temperatures of the fuel. These hot spots may arise from a combination of higher local power density (e.g., due to moderation effects near the reflector wall or from chance clustering of lower burnup pebbles), lower local bed porosity due to locally tight pebble packing, and reduced local helium flow due to the increase of helium viscosity with temperature. Whereas the slow evolution of loss-of-cooling heatup transients will tend to wash out any effects of pre-accident local flow starvation on subsequent peak fuel temperatures, the effects of higher local fission power densities will be retained throughout the heatup transient in the form of higher local decay heat powers. Therefore, the effect of decay-power hot spots, in particular, may need to be considered in evaluating the maximum fuel temperatures arising in pressurized or depressurized loss-of-forced-cooling accidents.

7. *Pebble fission power densities and temperatures*: While the normal overall flux and power profiles in a pebble bed reactor with multiple pass fueling may be well approximated by skewed axial cosine and radial Bessel functions, each computational node in the core model (e.g., an R-Theta-Z mesh) will generally contain fuel pebbles with a wide range of burnups (i.e., a statistical combination of 1^{st}-pass, 2^{nd}-pass,..., N^{th}-pass pebbles) and, hence, a wide range of pebble power densities. The computational models may therefore need to account for pebble-to-pebble burnup and power variations within nodes. Note that in calculating operating temperatures inside a pebble, the reduction of pebble power with pebble burnup may tend to be offset by the reduction of graphite thermal conductivity with neutron fluence.

8. *Pebble decay heat power densities*: Much as with fission power densities (see previous item), each node in the core calculational model will contain pebbles with a broad range of decay heat power densities. Computational studies may therefore be needed to establish technical guidance (and possibly a technical standard analogous to ANS 5.1 for LWRs) on accepted modeling approximations (e.g., nodal averaging methods) and assumptions (e.g., local hot spots, power histories) for calculating decay heat sources in pebble bed reactors while accounting for validation uncertainties associated with the shortage of applicable experimental data.

9. *Graphite annealing heat sources*: Although continuous annealing effectively prevents any significant buildup of Wigner energy at the high operating temperatures of HTGR graphite, there is nevertheless a significant accumulation of higher-energy graphite lattice distortions that anneal out only at the elevated graphite temperatures encountered in loss-of-forced-cooling accidents (e.g., conduction cooldown events). This high-temperature annealing heat source should be evaluated and, where significant, added to the nuclear decay heat sources used in the analysis of loss-of-forced-cooling heatup events. (Note that the recovered thermal conductivity caused by high-energy lattice annealing during slow graphite heatup accidents can substantially reduce the peak fuel temperatures reached during the accident, an effect that has traditionally been credited in the heat removal models used for MHTGR accident analyses.) While nuclear analysis will be used in evaluating the neutron fluences that

cause the higher-energy graphite lattice distortions, the evaluation of graphite annealing phenomena will be predominantly a materials analysis effort.

10. *Fuel and burnable poison zoning effects*: Physics analysis issues unique to prismatic HTGRs such as the GT-MHR relate mainly to the effects of burnable poisons, the presence of both "fissile" and "fertile" coated fuel particles (with 19.9% enriched and natural uranium, respectively) in the fuel compacts, reactivity control for cycle burnup effects, and the power shaping effects of zoned fuel and poison loadings.

11. *Validation and modeling for criticality safety*: In the analyses for criticality safety at the front end of the fuel cycle (i.e., enrichment plants, fuel fabrication facilities, material transport packages), criticality validation issues are expected to arise for HTGR fuel and fuel materials due to the shortage of evaluated critical benchmark experiments involving neutron moderation by graphite, materials with 5 to 20% enrichment, and particle fuel geometries. In addition, technical guidance may be needed on the criticality modeling of particle fuel forms, which are generally much more reactive than would be predicted by simplified computational models that smear the fuel particles, coatings, and matrix materials into a homogeneous mixture.

12. *Nuclear analysis of spent fuel*: Nuclear analysis issues for storing, shipping, and disposing of high-burnup spent fuels from future HTGRs would ultimately involve the assessment of modeling assumptions and approximations, needs for specific validation data, and validation uncertainty treatments in the prediction of decay heat sources for cooling, radiation sources for shielding, and spent-fuel reactivities for criticality safety (i.e., burnup credit). Material safety issues for spent fuel will become important later than those for fabrication, storage, and transport of the fresh fuel materials.

13. *Safeguards and security for reactors and fuel materials*: Specific nuclear analysis activities will play a major role in assessing safeguards and security issues for advanced HTGRs and their fuel cycles. The reactor systems and fuel cycles of pebble-bed and prismatic HTGRs should be analyzed and compared against those of other existing and advanced reactor types, such as LWRs and CANDUs, in order to establish a consistent technical basis for assessing: (a) the potential consequences from internal and external hostile threats to reactor facilities, fuel enrichment facilities, fuel fabrication facilities, shipments of fresh fuel materials, shipments of spent fuel and waste, storage facilities for spent fuel and waste, and waste disposal facilities; (b) the adequacy of material control and accounting (MC&A) and security measures for detecting and preventing material diversion throughout the respective fuel cycles; (c) the potential for overt and covert misuse of reactors to produce materials for fission weapons; and (d) the technological barriers to extraction and processing of materials for use in fission weapons and radiological weapons (i.e., dirty bombs). Work in these areas should be coordinated with the safeguards and safety activities of the IAEA and with other government agencies, as appropriate.