August 30, 2001

Mr. Howard J. Faulkner
Director, Office of International Programs
U. S. Nuclear Regulatory Commission
Rockville Pike
Rockville, Maryland

Dear Howard,

Enclosed is a suggestion for the Agency's consideration as it develops its regulatory review plans for a possible construction application for the Pebble Bed Modular Reactor (PBMR) While recognizing the numerous attractive attributes of the PBMR, several unique licensing issues appear to be presented by this unique high temperature gas-cooled reactor nuclear power plant. Among these are the overall reactor and power plant compactness, reactor fuel design, reactor and coolant operating temperatures, reactor fuel handling processes and depleted fuel storage concepts, and lack of a conventional containment vessel

Moreover, the PBMR differs in other respects from its nearest design predecessor, the Atom Versuchs Reaktor (AVR) near Juelich in the Federal Republic of Germany. I am familiar with the AVR and its commercial successor, the Thorium High Temperature Reactor (THTR), from previous AVR fuel consulting experience at Nuclear Utility Services (NUS Corporation). The PBMR design, based admittedly on my limited knowledge, appears to offer important advances in the design of gas-cooled reactor power plants, and I am a supporter of the PBMR concept.

The PBMR appears to present several possibly unique regulatory issues to the NRC under existing U. S. licensing practices and regulations. The enclosed "suggestions" focus on the unique characteristics of the PBMR fuel design which is intended to form the principal barrier to migration of some fission products. I am confident that the NRC's previous licensing experience with U. S. HTGRs (the Peach Bottom Unit 1 and Fort St Vrain stations as well as proposed successor commercial HTGRs by General Atomics) will support the agency's prospective reviews of the prototype PBMR design and later operation in South Africa.

I wish the NRC well in its important task of ensuring the reliable and safe operation of prospective PBMRs in the U. S.

Sincerely,

Jack C. Scarborough

9/20

SUGGESTIONS FOR U. S. NRC REVIEW OF
PEBBLE BED MODULAR REACTOR (PBMR) FUEL

A recent email to me from Dr. Chrysanth Marnet of Stadwerke Dusseldorf (SWD) included the business cards of a visiting NRC delegation The NRC team consisted of Howard J. Faulkner (OIP), Stuart D. Rubin (Nuclear Reactor Regulation), Vanice A Perrin (Fuel Cycle Safety & Safeguards), Donald E. Carlson (NRR), Amy E. Cubbage (NRR's Future Licensing Organization), Alexander P. Murray (NRR Process Engineering), & Undine Shoop (NRC office not readable). I applaud NRC's on-site investigation of the AVR design and operational experience as helpful background for possible future U. S. PBMR licensing applications.

Recognizing that substantive differences exist between the AVR and PBMR plant designs, I am sure that the NRC team benefited by learning about the operational history of the decommissioned AVR demonstration plant from the 'AVR Geschaftsfueher', Dr. Marnet. AVR operation was distinguished by its excellent fuel and plant operational performance, as well as subsequent good decommissioning experience. The availability of former senior AVR technical staff could be of future value to the NRC in its evaluation of a possible U. S. application for construction permit for a U. S. PBMR power station.

Based upon Dr. Kelvin Kemm's "A New Era for Nuclear – The Development of the Pebble Bed Modular Reactor" published by The European Science and Environment Forum, many similarities exist between the AVR and PBMR reactor concepts Among the similarities are those of fuel element design, fuel circulation method, on-line fuel element burnup determination, normal reactor control and emergency shutdown method, and spent fuel storage concept. Continued technical exchanges between the U. S. NRC, the F. R. G., and South Africa's electric utility, Eskom, may aid possible U. S. licensing of the PBMR.

The safety of the PBMR without conventional reactor plant containment depends significantly upon retention of fission products from coated fuel particles in each fuel sphere under various plant operational, upset, and accident conditions. According to Dr. Kremm, PBMR fuel elements consist of a 60 millimeter (mm) molded sphere containing 75% natural graphite and 25% synthetic graphite. Each fuel element contains pyrolytic carbon (PyC) and silicon carbide (SiC) coated fuel particles imbedded in an inner 50 mm diameter centralized spherical matrix of coated fuel particles and powdered graphite. Fission product retention of this fuel design requires maintenance of the integrity of the pyrolytic-carbon (PyC) and silicon carbide (SiC) coatings layers surrounding the individual uranium-dicarbide fuel particles through life.

Presumably the NRC would review production processes of the PBMR fuel vendor at an appropriate time to assess the applicability of U. S. licensing regulations to this particular fuel form. Fuel fabrication processes of particular importance would appear to be operational regimes of the fluidized bed fuel particle coating equipment ("coaters") employed including gas flow rates, coater temperatures, and coater pressures, all as a function of fuel particle size and heavy metal throughput (mass of heavy metal per unit time) The fuel coaters apply the inner PyC, intermediate SiC, and outer PyC coatings to successive batches of fuel particles; these coatings are intended to contain all fission products to design fuel burnups

Thus, the operational regimes of fluidized bed coaters employed for production of fuel for U. S. licensed PBMRs would appear to be of safety significance since they establish "cladding effectiveness"; i. e., the coating thicknesses and mechanical and chemical qualities of each fuel particle. PBMR fuel production regimes would thus appear to be subject to NRC regulation, with appropriate quality determinations or specifications for all coated particle fuel as well as the inner and outer non-fueled graphitic components of each fuel sphere.

Typically, the process variables of pyrolytic-carbon coaters used for production nuclear fuel lots are experimentally determined or 'mapped' by the fuel supply vendor in advance of normal fuel production campaigns to establish operational limits for each PyC coater. These limits in turn are usually based upon examination of small production lots of coated particles from a given coater, each lot having been produced under carefully specified process conditions to yield specified attributes for the uranium dioxide spherical particle; the inner porous-carbon sacrificial or "buffer" layer; the inner PyC coating layer; the intermediate SiC coating layer; and the outer PyC coating layer. An initial "buffer" carbon layer surrounds each spherical uranium dioxide fuel particle, followed by the successive layers enumerated.

Determination of the required <u>thicknesses</u> and <u>material properties</u> of the various layers to achieve essentially 100% retention of all fission products at peak design burnups is an important design requirement of PBMR fuel; presumably these requirements would require extensive test confirmation. Operational conditions of fluidized beds establish the thicknesses for each coating layer; these operating conditions typically include specified temperatures, pressures, and gas flow rates as a function of uranium or heavy metal (HM) throughput (kilograms of fuel heavy metal (HM) per unit time).

In previously licensed U. S. coated fuel production campaigns for the Fort St. Vrain and Peach Bottom Unit 1 stations, these conditions were established to a considerable extent from experimental fluidized-bed coater operations; performance capabilities were determined by detailed measurements of trial production batches of 'test' coated particles (trial coating times, coater operating temperatures, gas flow rates, heavy metal batch sizes, etc.). For specified fuel particle diameters in these U. S. HTGRs, the necessary coating properties and thicknesses were subsequently established from successful test irradiations (negligible coating failures) at design fuel burnup and fast neutron fluence. Irradiation of test fuel batches to design conditions was followed by post-irradiation examination of statistical samples of these coated particle batches, and often by comparison to calculations of fuel particle performance under identical test conditions (e g., coated fuel particle analytical models such as STRESS-1 or successor models).

Thus, required fuel particle coating densities and thicknesses of these U. S. fuels have been based upon both sample fuel irradiation results and analytical simulations of design coated particle performance which served to verify the design particle parameters such as particle fuel diameter and coating dimensions, uranium-235 content, and demonstrate retention of integrity of buffer, PyC, and SiC coating shells to design burnups. The coating property data used in such calculations were based either on experimentally-determined values; previous experience; or literature values for similar production coater operational regimes (temperatures, pressures, and fuel throughputs in kgs HM/unit time).

The intent of this fuel design and development effort was to ensure compatibility of specified PyC and SiC coating properties and thicknesses with specified fuel design fission rate, fast neutron fluence, cumulative fuel burnup, and operational temperature. Coated fuel particle operational limits in turn were usually based upon analyses of fuel element temperatures and end-of-life burnup for specified plant 'design', 'upset', and 'accident' conditions.

Validation of these coated fuel particle analytical simulations required a sufficiency of in-pile coated fuel particle irradiation samples under limiting environmental conditions, followed by subsequent post-irradiation examination of appreciable numbers of fuel particle batches to verify the model(s) used. Verified or 'qualified' models (together with fuel particle irradiation data) could then be used to assess the overall acceptability of the fuel design under various plant transients, usually specified for end of life burnups.

NRC may wish to consider employing current state-of-art coated fuel particle models (computer programs) in evaluating proposed U. S. PBMR fuel design under plant normal and 'upset' modalities; the agency may also wish to require appropriate fuel irradiation tests to confirm the design under plant normal and 'upset' conditions at end of fuel life. Such evaluations would help establish design limits for fuel particle uranium and burnable poison loadings for specified U-235 enrichments; they would also identify the required coating mechanical properties and thicknesses for all particle coatings to ensure PBMR fuel integrity throughout life. A possible vendor 'fuel production certification' protocol would assure that these properties are achieved as well as applicable limits on fuel coating dimensions.

Good coated fuel particle performance is important for safe operation and maintenance of owner's financial investment of the 'non-contained' PBMR under normal, upset, and accident conditions NRC's prior licensing experience with Peach Bottom -1 and Fort St Vrain HTGR fuel designs included use of coated particle fuel performance codes as well as analyses of core reactivity, shutdown margins, and plant operational transients. This experience will support the agency's analysis and evaluation of PBMR plant and fuel performance, including specification of appropriate safety margins. New NRC analyses would serve to ensure maintenance of shutdown reactivity margins, establish limits for allowable reactivity insertions, and permit evaluation of possible fuel damage regimes from unanticipated reactivity insertions as a result of plant operational incidents and/or major component failures.

I wish my former NRC colleagues well in these and other important PBMR safety evaluations to ensure prospective reliable and safe operation of PBMRs in the U. S.