Project No. 713

June 27, 2002

Mr. Kevin Borton, Licensing Manager
Exelon Generation
200 Exelon Way
Kennett Square, Pennsylvania 19348

SUBJECT: REQUEST FOR ADDITIONAL INFORMATION (RAI) ON PEBBLE BED MODULAR REACTOR (PBMR) NUCLEAR FUEL; FUEL FABRICATION QUALITY CONTROL MEASURES AND PERFORMANCE MONITORING PLANS AND; PBMR FUEL QUALIFICATION TEST PROGRAM

Dear Mr. Borton:

The U.S. Nuclear Regulatory Commission's (NRC's) objectives for the Pebble Bed Modular Reactor (PBMR) pre-application review are to obtain information from Exelon on the PBMR design and its technical bases in order to: (1) identify significant technical issues, safety issues and policy issues and, (2) identify a path for resolution of the issues. Achieving these objectives is expected to enhance the effectiveness and efficiency of the staff's review of an actual PBMR license application and to provide guidance to Exelon that is useful in the preparation of an application.

The staff recognizes Exelon's announced plans to end its participation in the PBMR project in South Africa when the current PBMR feasibility study is completed, and that Exelon is terminating its PBMR pre-application review activities with the staff. Therefore, the staff understands that in most cases Exelon does not plan to respond to the enclosed RAIs. Even so, we believe that there is a mutual desire to address and document the current PBMR pre-application review work in manner which would be of benefit to the staff, to others who might seek to resume PBMR pre-application review activities and to interested stakeholders. Therefore, the staff is transmitting the enclosed RAIs to formally document the results of the staff's review of these white paper topics to date and to place them on the public record.

Since June 2001, the NRC staff has conducted periodic public meetings with the Exelon Generation Company (Exelon) and the U.S. Department of Energy (DOE) to receive presentations and obtain information on a range of technical and programmatic topics supporting the PBMR pre-application review. These periodic meetings provided a starting point for obtaining information from Exelon on the PBMR design and its technical bases and for identifying significant issues for which staff resolution guidance would be pursued.

Early in the pre-application review, the staff requested Exelon to document the information that had been informally presented in these meetings and to formally submit it for staff review. Accordingly, between October 2001 and March 2002 Exelon formally submitted the requested documents as technical "white papers." As shown in Enclosure 1, Exelon submitted white papers for most of the technical and programmatic topics that were presented at the public meetings.

Exelon requested that the staff provide feedback on the technical, safety or policy issues, including staff questions related to each of the submitted technical white papers and associated presentations. The white papers, including any updates and formal responses to staff identified issues and questions, were to provide the primary basis for the staff's pre-application review findings, conclusions, positions and guidance.

The purpose of this letter is to provide the staff's feedback on technical, safety or policy issues in terms of requests for additional information (RAIs) on selected technical white papers and the associated meeting presentations. The selected white papers (and number designations) are: "PBMR Nuclear Fuel" (8); "Fuel Fabrication Quality Control Measures and Performance Monitoring Plans for PBMR Fuel" (9) and; "Pebble Bed Modular Reactor Fuel Qualification Test Program" (10).

Enclosure 2 contains the RAIs for each of the three white papers. The RAIs for each paper have been grouped into one of two categories. The RAIs in Category 1 are those that are considered relevant to either policy issues or significant safety or technical issues that are the focus of the PBMR pre-application review. Category 2 RAIs involve safety or technical issues for which responses would be required if a PBMR license application were to be submitted. Additionally, selected RAIs in Category 2 are considered significant to support the development of the NRC's infrastructure of tools, data and expertise that would be needed to conduct a PBMR license application review. These have been identified with an asterisk (*) and any responses would be of most benefit to the staff if provided in advance of a license application. All RAIs in Enclosure 2 have been identified by white paper number and RAI category.

It is requested that you review the enclosed RAIs and respond as to whether or when the requested information will be provided by Exelon to the NRC.

The reporting and/or record keeping requirements contained in this letter affect fewer than ten respondents; therefore, OMB clearance is not required under P.L. 96-511.

Please contact me (301-415-7499) or Stuart Rubin (301-415-7480) if you have any questions on this request.

Sincerely,

/RA/

Farouk Eltawila, Director
Division of Systems Analysis and Regulatory Effectiveness
Office of Nuclear Regulatory Research

Project No. 713

Enclosures: As stated

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Letter dated: June 27, 2002

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Letter dated: June 27, 2002

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JMoore, OGC
MVirgilio, NMSS

Table 1: PBMR Pre-Application Review Technical and Programmatic Topics Presented and Documented by Exelon

Meeting Date	Meeting Presentation Technical Topic	Exelon Technical White Paper		
		Title of Paper	Transmittal Date	No.
Jun 12-13, 2001	Fuel Overview -Design, Manufacturing, QC and Qualification	PBMR Nuclear Fuel	5/24/02	8
		Fuel Fabrication Quality Control Measures and Performance Monitoring Plans for PBMR Fuel	1/31/02	9
Jul 17-18, 2001	Design Codes and Standards	Summary of PBMR Design Codes and Standards	10/30/01	3
		RPV and Connecting Piping - White Paper	12/17/01	4
	Fuel Irradiation Program	(See Technical White Paper No.10)	3/18/02	-
Aug 15-16, 2001	Analytical Codes and Software Control	PBMR Analytical (Computer) Codes Data Table	10/30/01	5
	Fuel Design Logic	None	11/16/01	-
	Core Design	PBMR Design and Heat Removal Preliminary Description	3/04/02	6
	Heat Removal			
Oct 25, 2001	High Temperature Materials Graphite	Graphite Presentation to USNRC in Support of PBMR Pre-application Activities	10/23/01	1
	Control of Chemical Attack	Control of Chemical Attack in the PBMR	10/23/01	2
	Systems Design Approach and Status	None	N/A	-
	High Temperature Materials	None	N/A	-
Nov 29-30, 2001	Operational Modes and States	PBMR Operational Modes and States	11/27/01	7
	Testing Requirements for a Combined License	Testing Requirements for Issuance of a Combined License	11/27/01	11
Mar 28 2002	Fuel Qualification Test Program	Pebble Bed Modular Reactor Fuel Qualification Test Program	3/18/02	10

PBMR Nuclear Fuel
(White Paper No. 8)

8. PBMR Nuclear Fuel

8.1 Category 1 RAIs are considered relevant to either potential policy issues or significant safety issues or technical issues that are the focus of the PBMR pre-application review.

8.1.1 The in-reactor performance (e.g., failure rates) of coated particle fuel is closely related to the properties of the coatings. The coating properties are dependent on the CVD coating process variable specifications for each layer (e.g., temperature, pressure, flow rates of carrier gas to coating gas, coating rates). Provide a comparison of the specified values and ranges of the significant coating process variables of the PBMR fuel to those that were used to fabricate the German reference fuel particles. What are the material, physical, chemical and microstructural characteristics that will be used to determine whether the PBMR fuel particle coating process variable specifications are equivalent to those used for the German coated particles. Discuss the coating process specifications that will be combined with the particle product specifications to establish the complete fuel fabrication specifications.

8.1.2 Discuss how finished coated particle “batches” will be mixed to make finished coated particle “lots” for use in making fuel elements . Discuss the statistical analysis of coated particle batches and the statistical analysis of coated particle lots with respect to acceptance criteria. Will it be acceptable for some coated particle batches with unacceptable statistical sampling characteristics to be blended with other acceptable batches to make coated particle lots which can be accepted?

8.1.3 Discuss the method that will be used to determine the BAF for layers 2 and 4 for PBMR fuel coated particles. Compare the PBMR fuel fabrication plant method to the method that was used by the German NUKEM plant. If the method that will be used for the PBMR fuel plant is different than the NUKEM plant, discuss any planned or past comparison of results of the two methods on anisotropic pyrolytic carbon layer test specimens.

8.1.4 Discuss and explain any differences in the coated particle failure fractions that occurred during accident simulation heatup testing of AVR 21-2 fuel (irradiated in the AVR) and the accident simulation heatup testing of AVR 21-2 proof test fuel (irradiated in a materials test reactor).

8.1.5 Fuel burn-up, fast neutron dose and temperature are mentioned as important factors in determining the integrity of fuel pebbles. Discuss the importance of pebble multi-pass temperature cycling and power cycling on fuel integrity. Reference test data to support these conclusions.

8.1.6 Provide references and discuss the prototype materials used in Phase 1 tests. Compare these materials to the materials that will be used for the PBMR fuel. Include a discussion of the matrix graphite materials used in the Phase 1 tests and the PBMR fuel.

8.1.7 Phase 1 (as well as Phase 2) irradiation tests involve accelerated burn-up conditions in material test reactors. Accelerated burn-up results in test data being available in less time. Some aspects of accelerated burn-up testing, such as higher particle power and higher particle temperatures (compared with an actual power reactor), may be considered conservative with respect to particle failure due to high particle pressure (i.e., high tensile stress in the SiC layer). However, failure mechanisms involving adverse chemical interaction between fission products and the SiC layer (e.g., SiC corrosion) may not be conservative due to the shorter time for the chemical interactions to occur in an accelerated irradiation. Give references for data and discuss why accelerated irradiation test results are always conservative with respect to particle failures.

8.1.8 Explain and cite references that describe how each of the Phase 1 generic irradiation tests were used to derive the range of fission product transport equations covering all of the transport mechanisms applicable to German pebble fuel elements.

8.1.9 Discuss the quality assurance procedures (e.g., assuring accurate temperature measurements, fast fluence calculations and burn-up calculations) that were used for the Phase 1 irradiation and accident simulation heatup testing experiments and data analysis. Discuss the peer review, if any, that was conducted for the of Phase 1 experiments and data analysis.

8.1.10 Discuss Phase 1 irradiation tests which were conducted to assess fission product transport above 1300 °C. If tests were not conducted above 1300 °C, discuss how fission product transport equations for calculating source term will be established for potential fuel irradiation (core) temperature conditions above 1300 °C.

8.1.11 The Phase 1annealing tests were conducted at constant temperature. No particle failures were observed for the 1600 °C annealing tests. However, heat-up tests on AVR fuel that had been irradiated in the AVR and were annealed with a heat-up that simulated the predicted time- temperature heat up to 1620 °C from a depressurization accident. These annealing tests resulted in particle failures. Discuss whether additional time-temperature accident simulation heat-up testing will be conducted to supplement the constant temperature annealing tests to assess particle failure fractions during PBMR design basis accidents.

8.1.12 For the HTR-Module, design value for the irradiation-induced failed particle fraction was established by multiplying the expected value for the irradiation-induced failed particle fraction by a fixed factor. The application of the fixed factor was used, in part, to account for non-conservatism and uncertainty in the experimental data used to develop the expected value. These included: a single coating batch in the irradiation test data versus many coating batches in an actual core; some irradiated particles not attaining the target burn-up; and fast neutron fluence not meeting the target in some tests. The PBMR proof test program will (presumably) be designed and implemented so as not to have these non-conservativisms and uncertainties. If so, will the PBMR design value for the irradiation-induced failed particle fraction still be established by multiplying the expected value for the irradiation-induced failed particle fraction by a similar fixed factor? Explain.

8.1.13 Explain whether the design value for the irradiation-induced failed particle fraction for PBMR fuel will be applied in the same way as the HTR-modul with respect to burn-up effects.

8.1.14 For the HTR-Module, the design value for the heat-up-induced failed particle fraction was established by multiplying the expected value for the heat-up-induced failed particle fraction by a fixed factor. This was also done to account for non-conservatism and uncertainty in the experimental data used to develop the expected value. The PBMR proof test program will (presumably) be designed and implemented so as not to have these non-conservative and uncertainty factors. If so, will the PBMR design value for the heat-up-induced failed particle fraction still be established by multiplying the expected value for the heat-up-induced failed particle fraction by a similar fixed factor? Explain.

8.1.15 Explain whether the design value for the heat-up-induced failed particle fraction for PBMR fuel will be applied in the same way as the HTR-modul with respect to accident temperature distribution and time-dependent effects.

8.1.16 To calculate the radiological consequences of “beyond the design basis events,” will the design values or the expected values be used for manufacturing-induced, irradiation-induced and heat-up-induced failed particle fractions (i.e., for calculating the mechanistic source term)?

8.1.17 For postulated reactivity pulse events which deposit large amounts of energy in the fuel over very short time intervals, cite the reference(s) and a provide a discussion of any Phase 1 experimental data or planned Phase 2 experimental data that describes the fuel element and fuel particle behavior, failed particle fraction and fission product transport and release for PBMR fuel.

8.1.18 For postulated severe oxidation events, such as might occur due to a large break loss of coolant accident event followed by air entry and flow through the core, provide a reference and discuss any Phase 1 or planned Phase 2 experimental data applicable to fuel element and fuel particle behavior, failed particle fraction and fission product transport and release for PBMR fuel.

8.1.19 Provide the results for the annealing tests on fuel pebbles with LEU-TRISO which had been irradiated in the AVR. Discuss the results for the annealing test at the different annealing temperatures. Compare the results of these annealing tests, including particle failures, to the results of the annealing tests for fuel elements with LEU-TRISO that had been irradiated in the materials test reactors for fuel with similar burn-ups and accident (annealing) temperatures.

8.1.20 Figure 5 demonstrates data based on burn-up and fast neutron fluence. Please provide the correlation between the data, including the uncertainty analysis. Also, provide a justification for why the temperature and other parameters (including the difference in the number of fuel particles per pebble) can be excluded from consideration. Please also provide additional information on the HFR tests used in creating the correlation.

8.1.21 One of the SiC layer tests showed some degradation of the layer following 500 hours at 1600 °C. Please justify why the conclusions section mentioned that damage would only occur after long periods of time (>500 hours) based on the results of one test. Justify the statistical significance of the database used for this conclusion

8.1.22 In supporting conclusions from the experimental database, justify why other parameters were considered insignificant or unimportant in the uncertainty analysis.

8.1.23 Over the residence time of the fuel in the core, how much local cyclic fluctuation in the fuel temperature is there? What is the effect of the fluctuation on the prediction of the fuel failure probability?

8.2. Category 2 RAIs are considered relevant to safety issues or technical issues for which responses would be required at the time of or before a PBMR license application is submitted.

8.2.1 Discuss the sample size and analysis methods associated with the sampling of each layer (i.e., at each stage). What are the acceptance/rejection criteria for the batch?

8.2.2 What are the provisions to ensure that excessive levels of soot in the CVD furnace do not negatively impact the quality of the coatings and the binding strength between coating layers?

8.2.3 What is the expected maximum burn-up of PBMR fuel on its final pass through the PBMR core including the effects of the worst case fuel pebble burn-up measurement inaccuracy. Compare this maximum burn-up with the burn-up at which the tensile stress in the SiC layer would be predicted to exceed the SiC layer tensile strength.

8.2.4 What are the deformation limits of the porous carbon layer? What is the maximum stress that the porous carbon layer can withstand and still maintain integrity? What change in size of the particle does this correlate too? Provide the same information for the other three coating layers.

8.2.5 How does carbonization (of the fuel pebbles) differ from graphitization? Explain how the fuel pebbles are carbonized and provide the resulting pebble physical properties and characteristics. Quantify the differences in properties and characteristics of carbonized and graphitized material.

8.2.6 It was previously stated that the fuel kernel needs to be perfectly centered in the particle or else the kernel will migrate out of the particle. What stresses are introduced on the particle during the formation of the fuel pebble? What is the impact on fuel particle deformation and subsequent fuel kernel migration?

8.2.7 It is discussed that the graphite powder contains a mixture of two separate graphite powders. What properties do each of the powders contribute to the mixture and final product and why was this proportion of the two powders chosen?

8.2.8 Provide additional information of the how the over coating in the “sweetie barrel” takes place.

8.2.9 It was mentioned that the fuel particles maintain integrity up to 1600 °C. During the fuel pebble annealing process, the temperature approaches 2000 °C. Describe how the annealing process is performed while maintaining fuel particle integrity.

8.2.10 What is the final conclusion of the Phase I tests in relation to PBMR? It is not clearly stated nor directly supported in the paper. Please clarify.

8.2.11 In estimating of the failure probability of the SiC layer, what is the assumed distribution of the stress on the SiC layer as a function of temperature and fluence?

8.2.12 It is unavoidable that a certain number of pyrolitic carbon coatings will not be perfectly spherical. In addition fast fluence causes further anisotropic structural changes in the particles. What is the contribution to the failure probability of the production tolerance with regard to particle roundness?

Request for Additional Information
Fuel Fabrication Quality Control Measures and Performance Monitoring Plans for PBMR Fuel
(White Paper No. 9)

9. Fuel Fabrication Quality Control Measures and Performance Monitoring

9.1 Category 1 RAIs are considered relevant to either potential policy issues or significant safety issues or technical issues that are the focus of the PBMR pre-application review.

9.1.1 Studies have shown that the fuel fabrication process specifications for HTGR fuel are as important or even more important than the design or product specifications for the fuel. The importance of manufacturing process was recognized in Germany and was included, along with the product specifications, in the fuel manufacturing specification. The NUKEM process for this batch was the state-of-the-art in Germany at the time that the German HTGR fuel fabrication program ended. In what respects will the PBMR process specifications differ from the NUKEM process specifications for the AVR 21-2 fuel? Explain why these differences are not expected to result in significant differences in fuel quality and irradiation and accident performance?

9.1.2 Discuss if and how the PBMR fuel manufacturing process specifications will be included PBMR fuel manufacturing specification. Discuss the measures and QA methods that will be used to assure that the various process specifications are being met for each batch of kernels and coated particles.

9.1.3 What is the sensitivity of the performance of the fuel to variations in the AVR 21-2 fuel product specifications? In particular, quantify the variation with regard to those specifications that differ from the PBMR specifications.

9.1.4 What is the sensitivity of the performance of the AVR 21-2 (and PBMR) fuel to the key parameters in manufacturing process. Why are these deemed the key parameters in the manufacturing process?

9.1.5 Discuss the key fuel fabrication process parameters (e.g., temperature, flow rate, pressure, coating rate) that will be controlled for each coating layer of the coated particle. Discuss the range of permitted values for each parameter. Discuss the process controls that will be utilized to stay within the permitted ranges. Discuss the methods that will be utilized to ensure that the process is operating within the permitted ranges. Alternatively, discuss the resulting coating properties (e.g., SiC layer grain size, grain orientation, crystalline structure) that will be used to verify that the coating process is providing the required physical, material, crystalline, etc. layer properties. Discuss the QA methods that will be used to ensure that these characteristic are within the desired ranges. Provide similar fabrication process information for the fuel kernel.

9.1.6 Discuss the method that will be used to measure the BAF for the ILTI and OLTI and whether the method will be different than the method used in Germany. Identify any PBMR fuel design specification characteristics for which the type of equipment that will be used to measure the characteristic will be different than the equipment used in

Germany. Discuss the basis for acceptability of the PBMR equipment as giving accurate and reproducible results.

9.1.7 In the coating process steps what is the batch size and the sample size. What sampling strategy is employed? Discuss the sampling technique that will be used to show that the specified characteristics of the produced fuel element component meets the specification for the characteristic.

9.1.8 Discuss how it will be verified that the alternative coke source used in the manufacture of the graphite matrix material for the PBMR fuel results in equivalent performance as the German matrix graphite material, including the diffusion rate of fission products through the matrix material.

9.1.9 The neutron flux measurements will utilize ex-core detectors while the helium coolant temperature measurements will rely on measurements at the vessel inlet and outlet locations. These give integral or core averaged values. Since there are no thermocouples in the fueled core region it is assumed that the determination of local core temperatures and temperature distributions will based on thermal-fluid model predictions. Discuss the anticipated accuracy and required margins of conservatism that will be used for the analytical methods. Discuss whether melt-wire experiments, similar to those at AVR, will be conducted at the demonstration plant to benchmark these methods. How will the temperature conditions be verified during a postulated accident?

9.1.10 How will fission product plate-out, which is relevant to accident analysis, be predicted?

9.1.11 Discuss the capability of the PBMR coolant activity monitoring system to detect fuel particles that are intact but are either: (1) significantly and systematically degraded (i.e., latent failure) due to undetected irradiation conditions that are beyond the design conditions (e.g., temperature) or; (2) significantly and systematically weakened due to a key particle manufacturing process parameter(s) (e.g., coating rate, temperature, CVD furnace cleanliness) having been significantly outside the specified range. That is, discuss the technical basis for PBMR coolant activity monitoring system being capable and qualified to detect systematically degraded PBMR fuel before the degradation would be revealed as a failed particle fraction due to high fuel temperature (i.e., during a core heat up accident) being significantly higher than the design failure fraction.

9.1.12 Discuss the plans, if any, for monitoring fission product releases over the period from initial core power operation until equilibrium core conditions as a means to validate the best estimate particle failure fractions during normal operation.

9.2. Category 2 RAIs are considered relevant to safety issues or technical issues for which responses would be required at the time of or before a PBMR license application is submitted.

9.2.1 Is the fuel manufacturing process with respect to quality checks a batch or a continuous process? Discuss the statistical analysis methods, including sampling methods for kernels particles and fuel pebbles that will be used for assessing manufactured fuel against the specified limits. Discuss this for the various quality control points in Fig 1.

9.2.2 It is stated that "The first check is performed as needed on the incoming feed materials." What decision criteria is used for "as needed"?

9.2.3 How does the optical particle size analyzer reject particles? The traditional vibrating surface does it on a particle basis. What is the error in the optical particle size analyzer?

9.2.4 How much variation is expected in the number of particles per fuel sphere? How many fuel spheres are in a batch?

9.2.5 What is the calculated distribution of the fuel particles within the pebble and what is the uncertainty associated with this distribution? What steps are taken to ensure that the fuel particles are evenly distributed throughout the pebble?

9.2.6 It is stated that fuel integrity will be directly monitored by measurement of the noble gas fission product levels in the coolant. How will the failure mode (i.e. failure of a few particles or leakage from many particles resulting in the same release) be distinguished from the integrated value, such as the noble gas fission product level in the coolant?

9.2.7 What are the "remedial measures" when the fuel failure fraction shows signs of increasing beyond expected values?

9.2.8 Describe the pebble burn-up measurements and discharge criteria for the initial, transitional, and equilibrium cores. It is stated that selected fission-product gamma rays will be measured to determine the burn-up of each fuel pebble and that this measured burn-up will serve as the criterion for discharging the pebble or passing it back through the reactor. The particular burn-up value used as the discharge/recycle burn-up criterion should be chosen to limit the maximum pebble burn-up, which is stated as nominally 80 GWd/t. Therefore, determining a suitable value for discharge/recycle burn-up criterion (<80 GWd/t) will require consideration of in-core pebble residence time spectra, together with supporting neutronics calculations, in order to statistically characterize the maximum burn-up increment that might accrue during a pebble's final pass through the core. Burn-up measurement uncertainties will also have to be considered. Furthermore, since pebble burn-up measurements (unlike the pebble reactivity measurements used in THTR-300) cannot distinguish pebbles with different initial fuel enrichments, the same discharge burn-up criterion will need to be applied to the initial charge of 4%-enrichment fuel pebbles as to the 8%-enrichment pebbles that are added in transitioning to an equilibrium core. Neutronics calculations will be needed to bound the higher neutron fluence experienced by the 4%-enrichment pebbles in reaching the maximum burn-up levels allowed in the transitional cores.

9.2.9 Explain how the burn-up measurement system performs extensive self-diagnostics, including, the time intervals, the alarm level and detection limits.

9.2.10 Discuss the basis for concluding that the fuel pebbles flowing downward at the surface of the reflector will have sufficient velocity so as not to exceed the burnup limit on the final pass though the core. Discuss whether the PBMR burn-up measurement system can determine if fuel pebble flow anomalies (hangup, below expected flow rate) are causing excessive burnups. Is so, what would be the action level and what would be the remedial actions.

Request for Additional Information
Pebble Bed Modular Reactor Fuel Qualification Test Program
(White Paper No. 10)

10. Pebble Bed Modular Reactor Fuel Qualification Test Program

10.1 Category 1 RAIs are considered relevant to either potential policy issues or significant safety issues or technical issues that are the focus of the PBMR pre-application review.

10.1.1 With respect to establishing the fuel performance requirements, discuss the licensing basis events considered.

10.1.2 According to the preliminary internal at-power licensing basis events submitted by Exelon for the PBMR, a very large break opening is part of the PBMR licensing basis. Additionally, air ingress tests for a break in the PBMR hot gas cross connect vessel conducted at the Julich Reserch Center's NAKOC facility shows that, in time, air enters and flows naturally through the core. Accordingly, explain why it is stated that air ingress is not considered to be within the PBMR licensing basis and that PBMR-specific fuel testing is not planned to address air ingress.

10.1.3 The irradiation and accident performance of TRISO fuel is a strong function of the TRISO particle behavior under irradiation and accident conditions. The particle behavior is in turn a strong function of the design specifications, the fabrication product specifications and the fabrication process specifications that are used to make the TRISO particles. The fabrication process specifications for the PBMR fuel have not yet been established and validated although they will be based on the NUKEM process specification. As such, it remains to be determined whether or not the PBMR fuel fabrication will result in fuel particle characteristics which will result in fuel irradiation and accident performance that is equivalent to the German fuel. In the absence of established and validated PBMR fuel process specifications, discuss the basis for the statement that the "PBMR fuel qualification test program will be confirmatory in nature."

10.1.4 Discuss the experimental data that will be used to develop and validate the analytical codes that will be use in the PBMR safety analyses of fuel particle failures and fission product transport and release from the fuel during normal operation and postulated accidents.

10.1.5 Density and thickness are the only measured characteristics for the SiC layer. The strength, modulus of elasticity and fission product retention capability of the SiC layer are additional significant physical characteristics and mechanical properties. According to experimental work conducted in China in the mid-1990s, the deposition temperature of the SiC layer can have a major effect on SiC strength and a significant effect on the Young's modulus. Additionally, the deposition rate for SiC can have a significant effect on the SiC performance characteristics that are not determined by thickness and density alone. Densities below 3.2 g/cm^3 can result in a large variation in SiC strength. Additionally, a major study conducted in Germany in the early-1980s found that the fission product retention capability of the SiC layer could not be correlated with a specifiable and measurable SiC characteristic even when a wide range of physical, chemical, ceramographic methods were assessed. For the SiC layer, what process specifications, if any, will be included in the PBMR fuel manufacturing specification to assure irradiation and accident performance is consistent with the German fuel over the life of the PBMR fuel supply.

10.1.6 In general, discuss whether the PBMR licensing strategy will include manufacturing specifications on the fuel product characteristics and the fuel fabrication process so as to ensure continuing fuel quality and performance consistent with the qualification and proof test program results over the life of the plant.

10.1.7 The AVR 20/2 and AVR 20/20 reload fuel accident condition testing showed that fuel which is operated at high temperature for short time periods would not result in increased fuel failures or fission product release during normal operation. However, the adverse effects of high operating temperature resulted in higher than normal fuel particle failures during the subsequent accident condition testing. In view of these results, explain how fuel fission product gas release during normal operation can be used as an indicator of the state of the fuel and its ability to withstand accident conditions. What data set was used to develop the correlation between the state of the fuel under normal operating conditions and it’s ability to withstand accident conditions? What is the most sensitive parameter in this correlation? And which other parameters have been studied to determine that they are not a more important predictor of the ability of the fuel to withstand accident conditions.

10.1.8 How will the PBMR fuel irradiation program be used to validate the statement that “the release of fission product gases from the coated fuel particles under normal operation can be used as an indicator of the state of the fuel and its ability to withstand accident conditions (e.g., elevated temperature)” and qualify the coolant activity monitoring system.

10.1.9 The body of data on fission product release due to heat-up accidents is based on a ramp-up and hold (at constant) temperature to bound the expected accident temperature versus time history. However, accident condition tests which closely simulated the expected accident temperature versus time resulted in non-zero particle failures. Discuss the basis for Exelon’s view that the ramp and hold accident condition testing is adequate and conservative relative to expected accident temperature versus time simulation testing. Will the fuel qualification and proof tests for PBMR production fuel include actual temperature vs time heat up profiles to confirm or supplement the ramp-up and hold safety testing and to allow a side-by-side comparison of the two testing methods? Explain.

10.1.10 It is indicated that the accident response of PBMR fuel will be addressed by the testing irradiated fuel under conditions that conservatively approximate those that would be encountered by the fuel under accident conditions. Discuss whether PBMR fuel accident testing will include fuel behavior and performance (e.g., fuel failures, release of gaseous and metallic fission products) due to chemical attack (e.g., water, air) and prompt reactivity events.

10.1.11 For postulated PBMR reactivity addition events, what is the enthalpy limit for PBMR fuel and what is its experimental basis for the limit?

10.1.12 Discuss the statistic that will be used to conservatively assess PBMR fuel particle failure and fission product release performance against performance requirements during irradiation and accidents.

10.1.13 PBMR fuel that is subject to accident condition testing at lower burn-ups will not be available for later accident simulation testing at higher burn-ups. How, if at all, will the lower burn-up test results be included in the statistical analysis of “particles tested” at the higher and design burn-up. If the lower burn-up accident simulation test results are included in the higher and design burn-up statistic, how will the lower (non-conservative) burn-up be accounted for in the design burn-up test statistic. If the lower burn-up test results are to be used for justifying initial (low burn-up) power operation, how will the reduced number of particles involved in these tests be accounted for in the 95% confidence level particle failure rate statistic.

10.1.14 It is stated that the PBMR fuel manufacturing and quality control processes and methods will be comparable to the German fuel fabrication (i.e. NUKEM) plant. Discuss the quantitative measures and the sensitivity levels that determine “comparable” with regard to manufacturing specifications, input raw materials, important fuel manufacturing process and equipment parameters, working parts used for critical processes and QA procedures and tests. In what important way’s will these be different?

10.1.15 To the extent that larger capacity equipment (e.g., drying ovens, CVD coaters) will be used for the manufacture of PBMR fuel compared to the reference German fuel, how will the resulting increased variability of fuel characteristics be accounted for in the qualification program.

10.1.16 Discuss how the PBMR fuel qualification test data (Phase2) will be used to validate (qualify) the safety analysis models that were generically developed in Phase 1 that will be used to calculate PBMR fuel failure, fission product transport and release. What quantitative acceptance criteria will be used to determine whether the PBMR fuel qualification data falls within the envelope of the (Phase 1) German fuel performance test data. That is, how will the acceptability of applying the Phase 1 data to the PBMR fuel safety analysis models and methods be determined?

10.1.17 Discuss the quality assurance procedures that will be used for the PBMR fuel qualification irradiation tests and safety tests. Compare these quality assurance procedures to 10 CFR 50 Appendix B.

10.1.18 The German irradiation testing of UO_2 coated fuel particles generally was conducted for irradiation temperatures up to 1100 °C. Some limited testing at irradiation temperatures between 1100 °C and 1200 °C was also conducted. Additionally, the PBMR fuel qualification test program is designed to bound the burn-up, fluence, temperatures and temperature gradients expected in the PBMR and to limit the test conditions/parameters to values that will not result in inadvertent failure of the fuel. Such testing does not provide information on burn-up, fluence, temperature and temperature gradient thresholds where coated particle failure rates might begin to significantly increase (safety margins). What testing, if any, has been conducted on German fuel, and/or will be conducted on PMBR production fuel, to establish the burn-up, fluence, temperature and temperature gradient thresholds where the particle failure rate PBMR fuel begins to significantly increase?

10.1.19 Provide an assessment of the applicability of out-of-reactor, post-irradiation heatup tests and power transient tests for demonstrating TRISO fuel performance in reactor accidents. Assess the physical changes that occur during the time intervals between fuel irradiation and testing. Such physical changes would include the decay of short-lived fission products and actinides as well as any other differences involving time- or temperature-dependent processes (e.g., material cooling, creep, annealing, precipitation, condensation, diffusion, permeation, migration) that could affect the mechanical loading and effective strength of particle coatings under the respective simulated or actual accident conditions. If available, the results from similar out-of-reactor and in-reactor accident tests on TRISO fuels should be compared and discussed.

10.1.20 Identify and discuss the analytical code(s) and the materials properties data basis for determining PBMR fuel oxidation rates, particle failures and fission product releases for postulated events caused by air ingress at elevated temperature. Discuss any plans for conducting tests on PBMR fuel for establishing and validating the oxidation rates, particle failure, fission product diffusion and fission product release model predictions for such events. If “sufficient data are already available” with regard to UO_2 coated particle fuel performance under oxidizing conditions, provide a quantitative assessment, rather than a qualitative assessment of the residual risk associated with air ingress events.

10.1.21 In Germany, irradiated particles and spheres were subjected to an air environment. Loose particle tests showed failures increasing to 100% at 1500ºC. Sphere testing showed low failures at 1300ºC and increasing at 1400ºC. Discuss existing or proposed tests that establish the conditions wherein the probability of irradiated particle failure becomes significant for moisture or air ingress as a function of irradiation. How will the accident oxidation limit for PBMR production fuel be established?

10.1.22 Cite the reference(s) for the earlier testing that show that intact coated particles are not affected by water. Under what conditions does this cease to be true? Did these tests involve irradiated fuel?

10.1.23 How will the presence or the absence of: (1) irradiation-induced IPyC cracking, (2) PyC creep failure, (3) kernel migration, (4) palladium attack, (5) SiC thermal decomposition and (6) enhanced SiC permeability be verified for the irradiated PBMR fuel? Will PIEs be conducted on irradiated PBMR fuel to assess the presence or the absence of the potential failure mechanisms?

10.1.24 For modeling purposes and failure prediction with a significant statistical power at different operating and accident conditions requires knowledge of the contributions from the different modes of failure as discussed in the previous material. The estimate of ~200,000 particles to achieve the needed statistical power is associated with the integral value of total failure fraction. This does not distinguish between failure modes. Such a distinction in the failure modes to the power that is proposed would require far more data. Please respond to these points.

10.1.25 It is stated that PBMR production fuel will not be available in large quantities for the PBMR fuel qualification test program. Accordingly, the statistical mean (and variability) of the manufactured characteristics (e.g., SiC layer density) of the fuel (e.g., particles) used for the qualification tests will be quite different compared to the statistical mean (and variability) of the manufactured characteristics of the production fuel within an actual PBMR core. This difference is due to the fact that an actual PBMR core will be composed of many hundreds of batches of production fuel particles. Discuss how the potentially non-conservative statistical mean and variability of large-scale production fuel particle manufactured characteristics will be accounted for in the fuel qualification program. How will the fuel qualification program results be accounted for in the PBMR licensing analyses?

10.1.26 For the production fuel qualification test elements, discuss the procedures that will be used for combining and mixing fuel kernel batches to provide the feed for making each coated particle batch. Discuss the procedures that will be used for combining and mixing particle coating batches to make each batch of fuel pebbles. Compare these procedures with the procedures that will be used for large-scale fuel production. Compare the number of manufacturing ‘lines” (e.g., coaters, furnaces) that will be involved in the production fuel qualification tests with the number of manufacturing lines that will be use during large-scale production.

10.1.27 Will the process or the equipment that is used to make the fuel for the qualification tests of the production fuel be permitted to change after the fuel for the qualification tests of the production fuel is fabricated? If so, explain.

10.1.28 Is “HOT” the highest operating temperature anywhere in the PBMR Core? Does it refer to the fuel pebble surface temperature, the average fuel pebble temperature or the temperature of the hottest coated particle in the hottest fuel element? Explain. Define and explain “LOT.” Discuss the uncertainties that are accounted for in establishing these temperatures?

10.1.29 Explain how, if at all, will the production fuel tests be used to support the mechanistic source term (fuel fission product release) models. Will the safety test involving “HOT” and moderate BU be used to validate safety analysis models?

10.1.30 Discuss the purpose of the South African lower burn-up (i.e., 4% and 6% FIMA) tests. Will the test results be included in the statistical data base (even though the burn-up is less than the design burn-up)? If so, explain.

10.1.31 In general, fuel performance can be correlated with the rate of irradiation. All irradiations in the test matrix are 1.5 and 3 times real time. Please give the rational that accelerated testing does not affect conclusions, or how the effect will be taken into account.

10.1.32 Cite the data references having general applicability to the PBMR fuel as demonstrating very large margins for transient overpower events."

10.1.33 German fuel irradiation and post-irradiation heat-up testing data show that, depending on the matrix graphite used, the matrix graphite diffusion coefficients for cesium and silver for normal operation and accident temperature conditions can differ by an order of magnitude or more. The original petroleum coke source used to make German fuel is no longer available to make the matrix graphite for the PBMR production fuel. Since the PBMR production fuel matrix graphite will be different from the matrix graphite used in the German tests, discuss any plans for conducting tests to validate the PBMR fuel matrix graphite diffusion coefficients used for fission product release calculations.

10.1.34 What plans, if any, exist for confirmatory accident simulation testing of PBMR fuel which has achieved its cyclic burn-up conditions in an operating PBMR similar to the accident simulation tests that were done for fuel irradiated in the AVR?

10.2 Category 2 RAIs are considered relevant to safety issues or technical issues for which responses would be required at the time of or before a PBMR license application is submitted.

10.2.1 Describe the QA program used for the base German fuel test program from which the fuel response characteristics used in the COL application will be primarily based.

10.2.2 Discuss or reference the results of the most recent HTR-10 fuel irradiation and accident simulation heat-up testing in support of HTR-10 licensed power operations.

10.2.3 Discuss how the fuel qualification test program will provide the technical basis for the PBMR plant technical specification fuel operating limits (i.e., limiting conditions for operation) and fuel safety limits.

10.2.4 PBMR fuel elements will have ~15,000 particles per pebble. This compares with ~9,600 particles per pebble for the AVR21-2 fuel. What effect, if any, is the difference in number pf particles expected to have on the initial (manufacturing) failed particle fraction?

10.2.5 Discuss the fission products that will be measured and the PIEs conducted for each qualification program test (row).

10.2.6 How many PBMR cycles will be simulated in the production fuel demonstration tests? How does this compare to the maximum number of passes of fuel through a PBMR core? What is meant by an "average pebble?"

10.2.7 Is the "high operating temperature+100°C for a few hours" intended to simulated a PLOFC as an operating basis event (standby core cooling system available) or as a design basis event (core cooling via the RCCS)?

10.2.8 How are the following terms defined: "peak temperature," "goal burn-up," "goal fluence," "high operating temperature"?

10.2.9 Demonstration testing and confirmatory testing are not an equivalent statistical inference. Please formulate the statement in the form of a statistical hypothesis test.

10.2.10 It is stated that 12 pebbles constitute the statistical demonstration test for the fuel." What is being demonstrated?

10.2.11 What is meant by statistical database for these tests? What are the figures of merit? What are the independent variables? What are the fixed and random effects parameters? What are the statistical models? Has any effort been made to apply experimental design techniques?

10.2.12 Clarify why only a few pebbles are needed to explore margins beyond the operating limit. Is the number currently projected a statistically significant number to provide confidence at the 95/95 level?

10.2.13* A 1600 °C maximum fuel temperature limits the maximum design power level. What is the sensitivity of PBMR power level to this temperature? What is the estimate and its uncertainty of the coolant bypass flow, and what are the consequences on the chose 1600 °C fuel temperature for a fixed core power level?

10.2.14 Are the metallographic results included in the statistical database? If so, how? That is, what variables are included and how are they quantified? How are they related to fuel performance models and their predictions?

10.2.15 It is stated that fission product location tests will be performed with a limited number of particles. Will this number comprise a statistically significant number?

10.2.16 How is it known from an core integrated gaseous fission product release value whether there are a few failed particles that have released all their fission gases, or there are many failed particles that have released a small fraction of fission product gases? The consequences in an accident are likely to be very different. Over the life of the reactor does the relation between measurement of fission gas in the coolant and the state of the fuel remain constant? What are the key design parameters that affect fuel performance in the range 1600 -1700 °C? What is the sensitivity of fuel performance to these design parameters at these temperatures?

10.2.17 Will the elevated temperature testing include tests with pebbles that have been previously cycled to create an irradiation history similar to what the pebble will experience after multiple core cycles?

10.2.18 It is stated that the first PBMR core loading will be manufactured before completion of the entire fuel qualification test program. Is an operating license being sought for initial core loading and power ascension only? What burn-up limit is expect for the first core?

10.2.19 Are the measurements at the quality control check points in the manufacturing process made by batch or continuous sampling? Discuss batch size, where appropriate, and the number of measurements, together with instrument and sampling errors.

10.2.20 What are the detection probability and “false alarm” limits for the acceptance levels of the measured QC characteristics for the UO_2 kernels and the coated particles?

10.2.21 How long does the heat treatment of the spheres at 1950 °C last?

10.2.22 It is stated that “the irradiation program for PBMR fuel is directed toward qualification for service under PBMR design conditions, with the understanding that results of this limited test program are supported by a large body of data from similar fuels tested under PBMR relevant conditions.” What is meant by “supported” from a quantitative and statistical standpoint? How will the differences in manufacturing processes in the “large body of data” be treated?

10.2.23 Irradiation history (e.g., burn-up, fluence) prior to heatup is an important determinant to fuel performance. It is mentioned that samples used in heatup tests have spanned burn-ups exceeding discharge burn-up. What were the related fluences and how do the burn-up-to-fluence ratios compare to that of PBMR?

10.2.24* What is the estimated probability density function for the fission gas pressure at the peak discharge burn-up? What is the assumed fission gas release fraction?

10.2.25* What oxidation conditions result in silicon carbide coating failure as a function of fuel irradiation conditions?

10.2.26* In the identified reactivity pulse tests, what was the incremental increase in particle failure? What trends, if any, of failure rate as a function of energy deposition and energy deposition rate applicable to PBMR can be derived from these data?

10.2.27* For the over pressure failure mechanism: What are the tensile strengths of unirradiated and irradiated PyC and SiC as a function of temperature? From theoretical standpoint, at what burn-up and temperature combinations would the onset of fuel-coating mechanical interaction be expected? Is oxidation of the particle coating accounted for in estimating the time to failure of the particle coating? If so how is that taken into account? Is there any evidence of fuel cracking so that local fuel-coating mechanical interaction can develop?

10.2.28* For the irradiation-Induced IPyC cracking failure mechanism: What is the sensitivity of the density of shrinkage cracks to degree of anisotropy as a function of irradiation and temperature? What is the relation between shrinkage crack density and tensile strength of the IPyC layer? What is the maximum stress that the IPyC layer can withstand? What is the maximum stress reached in the layer during operations?

10.2.28 For the kernel migration failure mechanism: How much do the AVR and THTR thermal gradients differ from PBMR? Are some failures due to the ameba effect in PBMR fuel expected?

10.2.29 For the fission product failure mechanism: What is the experimental evidence that the level of Pd attack is benign in particle fuel at PBMR conditions? How were the measurements made and how many particles were examined? How will the temperature gradient across the pebble be affected by the increased number of fuel particle used for PBMR fuel pebbles? How will this change impact he Pd attack and kernel migration?

10.2.30* For the SiC thermal decomposition failure mechanism: is there a temperature threshold for the onset of thermal decomposition of SiC? What is the rate of decomposition as a function of irradiation and temperature? With an increased number of fuel particles within each pebble the fast neutron fluence seen by each particle could increase. How will this increase impact the SiC permeability?

10.2.31 With respect to enhanced SiC permeability, (a) Is this a threshold effect? (b) What fraction of the release is attributed to this effect in the range of PBMR operating conditions?

10.2.32 Discuss the approach that will be taken for determining the limitations on the type(s) and frequency(s) of operational and/or design-basis events that a PBMR fueled core could experience before the PBMR fuel qualification test data could not be referenced as providing the technical basis for assuring continued safe operation of the irradiated fuel in the core (i.e., requiring the replacement of a significant number of pebble fuel elements).