Request for Additional Information No. 5895 Revision 0

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Next Generation Nuclear Plant Pre-Application Activities
Department of Energy - Idaho National Laboratory
Docket No. PROJ 0748
SRP Section: ARP FQ/MST - Fuel Design Qualification/Mechanistic Source Terms
Application Section: Fuel Qualification and Mechanistic Source Terms

QUESTIONS for Advanced Reactor Branch 1 (ARB1)

ARP FQ/MST -1

RAI FQ-B1 / MST-B1: In stating that the fuel performance is "equivalent to or better than" the German fuel, what are the full set of parameters or figures of merit that are considered (i.e., fuel failure vs. burnup, temperature, varying reaction rates, etc.)? Does the statement mean that all considered figures of merit equal or exceed those of the German fuel? (FQ Section 1.3) {JV/F1}[1(a)]

Comment: The white paper statement noted above is expected to be revised in a future update to the white papers that will reflect the evolving position recently stated by INL [Ref] that the German data will not be used for determining statistical failure rates, but only to provide useful information in determining material properties such as diffusion rates and aid in fuel design (including the calibration of models used in the PARFUME fuel performance code).

Ref: Letter from INL to NRC, CCN 223977, Supplemental Information to the NGNP Fuel Qualification and Mechanistic Source Terms White Papers, May 3, 2011.

ARP FQ/MST -2

RAI FQ-B2 / MST-B2: A list of failure mechanisms is given in FQ section 3.1.2, page 19, but no data or images are presented to support these. Are they theoretical or have examples of each failure mechanism been observed in representative fuel particles? (FQ Section 3.1.2) {LE/F10}

Comment: Given the large number of particles, it does not seem possible to identify most in-pile failure mechanisms. In fuel compacts or pebbles, particle failures are identified by the detection of fission products; however, in most cases, the particle responsible for the release is not identified.

ARP FQ/MST -3

RAI FQ-B3 / MST-B3: The HM contamination is given as $\sim 10^{-5}$. What are the units on this number? Is it fraction of exposed kernels or particle defects or particle failures? Does it distinguish between enriched UCO/UO2 fuel, natural uranium, thorium, etc., and their respective sources and chemical forms? (FQ Section 3.1.2, page 20) {LE/F2}

ARP FQ/MST -4

RAI FQ-B4 / MST-B4: The FQ white paper states "…fuel particle failures in these irradiation experiments were caused by irradiation induced failure (cracking) of anisotropic IPyC leading to tensile stress intensification in the adjacent well-bonded SiC layer causing subsequent cracking in the SiC layer." Is the failure caused by mode I or mode II crack growth through the SiC? How is this included in the analytical models? (FQ Section 3.1.2.1) {LE/F3}

Comment: Materials can have significantly different fracture toughness, crack propagation, and fatigue crack growth for mode I and mode II cracks. From the description of the geometry, whether the crack is mode I or mode II may depend on if the particle layers have debonded. In general, mode II crack growth is not common and cracks will turn to become mode I. However, in some highly constrained geometries, mode II growth can occur. This may have implications for the material test program should accurate measurements of mode II toughness be needed.

ARP FQ/MST -5

RAI FQ-B5 / MST-B5: Some of the properties listed in FQ white paper Table 1 are path-dependent. This could have implications for testing and modeling. How is this path-dependence accounted for in the models? What is done to ensure that modeling and testing are covering the most severe service conditions for the material? For example, if the pyrocarbon shrinks from exposure to fast fluence and this shrinkage reduces stress in the SiC layer, higher burnup with lower fast fluence may be more limiting than high burnup, high fast fluence conditions. Table 6 shows a higher failure rate at lower burnup and lower fast fluence for heating tests at 1800°C. NGNP operating conditions are even lower burnup. What is done to guarantee that this data is conservative for NGNP? (FQ Section 3.1.2.2, Table 1; Section 3.2.3.1, Table 6) {LE/F4}

Comment: Path-dependence could greatly increase the complexity of the modeling to cover all possible conditions of the particles.

ARP FQ/MST -6

RAI FQ-B6 / MST-B6: Describe quantitatively hypothetical particle power pulses that, based on currently available information and insights on transient fuel performance, would reasonably be expected to cause TRISO SiC failure fractions in the pulsed particles to increase significantly (e.g. by a factor of 10 or more). (FQ Section 3.1.1.2) {JV(DC)/F2}

Comment: The requested description of hypothetical particle power pulses should address the transient particle power history and resulting temperature histories of the particle kernels and coatings. While the hypothetical power pulses considered should distinguish between those that are possible and those that are not physically possible in reactors moderated by graphite, or by graphite and moisture, this question does not concern the likelihood or plausibility of power transient events in any NGNP design, but rather seeks to understand the expected behaviors and failure thresholds of fuel particles in postulated severe transients (e.g., single or multiple rod ejection during or after massive moisture ingress) regardless of their likelihood or plausibility. The identification of power transients to be considered in NGNP licensing or risk analyses is a separate topic that will help determine any needs for transient fuel testing.

ARP FQ/MST -7

RAI FQ-B7 / MST-B7: With respect to thermal-mechanical fuel performance, describe how the testing that has been or will be performed will show that lifetime power variations in NGNP will not result in TRISO layer separation and fuel failure? (Section 3.1.2.1) {JV/F4}

Comment: Thermal-mechanical loadings in NGNP will include those due to load follow, power cycling, fuel sphere cycling, shutdown/restart, prismatic fuel block shuffling, and potential local power oscillations (e.g., as experienced in Fort Saint Vrain). The response should thus address how such loadings are represented in the MTR irradiation cycles for fuel qualification testing.

ARP FQ/MST -8

RAI FQ-B8 / MST-B8: Describe how the design analysis of coating layer stresses addresses non-spherical particles. (FQ Sections 3.1.2.1, 3.2.1.2) {JV/F5*}

Comment: Although fabrication techniques discuss the removal of non-spherical particles, there is no discussion of tolerances and the effects of non-sphericity on predicted stress and strain in the coating layers.

ARP FQ/MST -9

RAI FQ-B9 / MST-B9: Quantify the degree of SiC decomposition that occurs during the 1950 ºC fabrication annealing of fuel compacts and fuel spheres. (FQ Sections 3.1.2.2 and 3.2.1.2) {HL/F1}

Comment: Based on the temperatures quoted in these two sections it would seem that the SiC in the TRISO particles would start to decompose during the fabrication annealing step.

ARP FQ/MST -10

RAI FQ-B10 / MST-B10: What is the basis for using Kr 85 to determine that the fission product gaseous source term will be effectively retained in the fuel kernel? (FQ Section 3.2 footnote “h”) {JV/F6}

Comment: While the note is true for Kr 85 with a short half life, other fission products may decay to gaseous or high volatile materials that have sufficient half lives to migrate from the kernel; Xe to Cs for example. A more rigorous fission product release treatment should include the production and decay chains of the fission products and their mobility to justify such a white paper conclusion.

ARP FQ/MST -11

RAI FQ-B11 / MST-B11: The FQ white paper states that “In HTGR fuel, coated particles provide the main barrier against release of fission products; thus, attention is primarily focused on performance of the coated particles. Although the fuel sphere in the pebble design provides additional fission-product retention through diffusion and trapping and adsorption effects, the principal function of the sphere is to protect the embedded coated particles against external environmental and mechanical effects and to facilitate fuel handling. This means that all irradiation test results obtained on fuel samples containing coated particles of a design similar to that for the pebble-bed design can be included in the experience database when considering particle performance.” A similar logic seems to be applied in determining the applicability of fuel tests to TRISO particles in prismatic block fuel compacts and fuel elements. It is not obvious from this explanation why all the fuel samples can be included in the fuel experience data base. Please clarify this statement. (FQ Section 3.2.1) {LE/F5*}

Comment: The third sentence of the statement does not seem to be a logical conclusion from the first two sentences. To support such a conclusion, information would also be needed on the effectiveness of the respective fuel forms at protecting the fuel particles over specified ranges of conditions (loadings, temperatures, fluences, chemical attack by water, air, fission products, impurities, etc.).

ARP FQ/MST -12

RAI FQ-B12 / MST-B12: The FQ white paper states “coated particles are evenly distributed in this inner, fuel containing region to prevent the development of hot spots in the fuel sphere.” Hot spots may develop from clusters of particles in fuel pebbles or fuel compacts and this may be a statistical phenomenon. It is necessary to either ensure that hot spots cannot develop or analyze the hot spots to ensure that they do not impact performance. The same comment applies to other statistical anomalies such as a cluster of defective particles or of spheres with low burnup. How are these statistical anomalies analyzed? (FQ Section 3.2.1.2) {LE/F6*}

ARP FQ/MST -13

RAI FQ-B13 / MST-B13: The FQ white paper states “The release of silver from intact particles was observed at all heating-test temperatures, with the rate of release increasing substantially between 1600 and 1800 ^{o}C. Cesium was seen to be effectively retained in the intact particles at 1600 ^{o}C and for the first 100 h at 1700 ^{o}C, but intact particles dominated the cesium release at 1800 ^{o}C. Strontium was retained within the sphere at 1600 and 1700 ^{o}C but was released at 1800 ^{o}C.” Are such releases of Ag, Cs, and Sr considered “particle failures” when the particles are intact? (FQ Section 3.2.3.2) {LE/F7*}

Comment: Any release of fission products is a challenge for the fuel system. Intact particles are not providing a barrier if through wall diffusion of any of the fission products is occurring. More clarity may be needed in describing fuel performance in terms that distinguish between the mechanical integrity of kernels and coating layers (e.g., intact versus failed) and the functional retentiveness of intact kernels and coating layers.

ARP FQ/MST -14

RAI FQ-B14 / MST-B14: What justification can be given for the statement that “ …all irradiation test results obtained on fuel samples containing coated particles of a design similar to that for the pebble-bed design can be included in the experience database when considering particle performance” ? (FQ Section 3.2.1) {JV/F7}

Comment: Although the FQ white paper makes an argument that examination of the German fuel has resulted in identifying needed changes to the US fabrication process, a possible way to approach proof positive that all important dissimilarities have been corrected would be to show that for all testing the US fuel gives the same results as the German tests. If that is so, it should be addressed, possibly by reference to another section of the FQ white paper, to substantiate the claim of “similarity.”

Certainly even the German fuel has evolved, and fabrication techniques employed are very important in demonstrated performance. Fuel performance has so many synergistic effects that implying fuel performance equivalence by claiming “similarity” may be a questionable use of the term.

ARP FQ/MST -15

RAI FQ-B15 / MST-B15: With regard to checking for monodispersity in spherical shape, is testing performed at each stage of particle coating? (FQ Section 3.2.1.2) {JV/F8}

Comment: It is not clear from the FQ white paper whether the monodispersity test is done for each CVD step.

ARP FQ/MST -16

RAI FQ-B16 / MST-B16: How is the desired degree of uniformity in the random distribution of particles in a fuel compact or fuel pebble determined, specified, and verified? (FQ Section 3.2.1.2) {JV/F9*}

ARP FQ/MST -17

RAI FQ-B17 / MST-B17: Explain why some of data entries in Table 7 are blank. (FQ Section 3.2.3.2) {JV/F10*}

ARP FQ/MST -18

RAI FQ-B18 / MST-B18: It is stated that “Fuel-performance models would predict that the isothermal testing should be more challenging for the fuel…” Please elaborate on how this statement is justified and applied, as much of the experimental data is said to be isothermal. (FQ Section 3.2.3.2) {JV/F11*}

Comment: It is not clear that all failure modes are bounded by isothermal testing. Relevant failure modes and the corresponding bounding isothermal temperatures should be given and justified. Furthermore, it is not clear that test conditions are truly isothermal, given that MTRs may have frequent shutdown cycles for refueling, etc.

ARP FQ/MST -19

RAI FQ-B19 / MST-B19: Are the results presented in FQ Figures 7 and 8 characteristic of one or more particle failures in a sphere? How do Figures 7 and 8 support the conclusion that there were defective coated particles? (FQ Section 3.2.4) {JV/F12}

Comment: The release to birth (R/B) values for Kr and Xe do not identify which isotopes of these nobles are being considered, and therefore it is difficult to give a meaning to the half-life.

ARP FQ/MST -20

RAI FQ-B20 / MST-B20: With once through coating how are QC/QA assured at each coating step? (FQ Section 3.3.1.2) {JV/F13*}

ARP FQ/MST -21

RAI FQ-B21 / MST-B21: In the thermosetting-matrix-based compacting process, why is it important to assure monodispersity? Are the TRISO particles still checked for monodispersity before overcoating? Does the overcoating material have significant property differences from the “additional” matrix material that could result in discontinuities during the fuel’s lifetime? How thick is the overcoating, and how does this affect homogenization of the active fuel region in the compact and the volume fraction of the “additional” matrix material? (FQ Section 3.3.1.3) {JV/F14}

Comment: The prismatic fuel is going to switch to a thermosetting process using resin and overcoating of the TRISO particles versus the thermoplastic process used for FSV. The question is asked because it is not obvious why the coated particles need to attain monodispersity. This would be more important than checking this parameter after overcoating. Or, is it a concern that the thermosetting process will upset the previously assured (QC’d) particle monodispersity?

Also, the overcoating comprises another particle layer that could result in compatibility concerns with the matrix material, especially in terms of separation from the particle or matrix material.

ARP FQ/MST -22

RAI FQ-B22 / MST-B22: There appears to be little true transient testing of the TRISO particle. Have the temperature ramps of up to 190 ºC/hour mentioned been qualified against the accident envelope? (FQ Section 3.3.3 and 5.3.4.2) {JV/F15}

Comment: Although it is discussed that non-isothermal testing has been performed, and that further testing will be required, the past testing may not be indicative of the rapid heatups associated with reactivity excursions, and there is a concern that the FQ white paper seems to have unduly discounted such excursions.

ARP FQ/MST -23

RAI FQ-B23 / MST-B23: What are the justifications for assuming that the two concluding statements (numbered) at the end of Section 3.3.3 are applicable to the technical bases for the NGNP fuel design? (FQ Section 3.3.3) {JV/F16}

Comment: A stronger argument should be made about the acceptability of the German or other non-UCO transient tests to validate the proposed NGNP TRISO fuel design. In particular, the fuel design has been evolving with respect to not only the kernel material but the coating process and compact or sphere formation. It is difficult to keep track of the variations with respect to the different tests offered as representative. Maybe a detailed table would help, where known differences amongst the fuels undergoing tests are clearly laid out. There may be too many variable parameters that affect fuel performance and their synergistic effect to give full credit to any fuel test which does not fully replicate the material content and fabrication process, even to the extent of requiring that the samples come from the same fabrication facility.

ARP FQ/MST -24

RAI FQ-B24 / MST-B24: How well have the analytical methods (fuel performance codes) been able to predict blind test data, and what data has been used to verify or tune the codes? (FQ Section 3.3.4) {JV/F17}

Comment: Experience has shown that unless the fabrication tolerances are very tight, there can be a large uncertainty in a fuel code’s prediction. This is especially true here as the commercial fabrication facility for the NFNR has yet to come to fruition.

ARP FQ/MST -25

RAI FQ-B25 / MST-B25: How does the “sphere center temperature” or the compact center temperature relate to the kernel temperature and failure data? (FQ Section 4.2.2.3) {LE/F13}

Comment: The kernel temperatures may be different from the sphere or compact center temperatures.

ARP FQ/MST -26

RAI FQ-B26 / MST-B26: The FQ white paper states that “the specified value of 6×10^{-5} for a single fuel lot will be used as the design value for the free-uranium fraction in the core for establishing the relationship between failure fraction and temperature described in Section 4.2.3.4” However, if more manufacturing defects are assumed, fewer particle failures are estimated. Can it be shown that this is a conservative assumption? (FQ Section 4.2.3.1) {LE/F14}

ARP FQ/MST -27

RAI FQ-B27 / MST-B27: What is the fuel time constant for heat transfer? (FQ Section 4.2.2.2) {JV/F18)

Comment: To better understand the discussion on transient response, it would be beneficial to know what fuel time constant is assumed for transients and accidents.

ARP FQ/MST -28

RAI FQ-B28 / MST-B28: What consideration has been given to possible discontinuities or physical separation between the TRISO particles and the matrix material with irradiation? (FQ Section 4.2.2.2) {JV/F19}

Comment: Load following, shutdowns, fuel shuffling, and sphere cycling can cause temperatures and reaction rates to vary greatly over time. Differences in physical properties between the matrix material and particles may result in the development of a void, gap, or other discontinuities. It is not clear whether the temperatures are enough to result in recrystallization, but radiation enhanced creep or radiation induced growth or shrinkage may also contribute to the concern.

ARP FQ/MST -29

RAI FQ-B29 / MST-B29: What stresses on the spheres results from thermal expansion? Is there sufficient free volume in the core to accommodate expansion and no risk of pinning to cause stress on the spheres? (FQ Section 4.2.2.2) {JV/F21}

Comment: There appears to be no discussion on any effect that might prevent the free motion of the spheres. Nor is there a discussion of any mechanism that might contribute to stress on the spheres except for a mention that the authors are satisfied with the free drop test conducted on the spheres by the Germans.

ARP FQ/MST -30

RAI FQ-B30 / MST-B30: What is the justification for claiming a depressurization accident is more limiting than a reactivity excursion accident? What is the justification for using point kinetics to model reactivity excursion accidents? (FQ Section 4.2.2.2, 5.1) {JV/F22}

Comment: The FQ white paper continues to take the position that a depressurization accident is the limiting condition. While this may be further explained in another document, it is not covered in the FQ white paper to be sufficiently convincing. This accident would appear to establish the limiting temperatures that the fuel would need to be tested against. It is understood that in the pebble bed design, a large thermal capacity and limited excess reactivity are safety features. Still, the discussions on reactivity excursions for pebble bed and prismatic designs are unconvincing, especially when point kinetics are discussed as the modeling technique.

ARP FQ/MST -31

RAI FQ-B31 / MST-B31: No rod ejection accident is considered for these reactors. However, an inspection of the illustration showing the prismatic version of the core (Fig. 25) shows, the control rod drive elements are enclosed in housings, which operate at system pressure but are still vulnerable to failure (similar to a control rod drive flange failure in a PWR). How is the fuel expected to react to a sudden increase in power brought about by the addition of over one dollar of reactivity? Bear in mind that the initial power pulse is terminated by the Doppler effect alone. Are any pulsed power experiments planned for the fuel? (FQ Section 4.3.1) {HL/F10}

Comment: Analysis of a rod ejection accident is required for all current LWR designs. If this reactor design has advantages over competing concepts because of its particular kinetic parameters, then this will become clear in the course of the analysis. The behavior of the fuel will be important in this case.

ARP FQ/MST -32

RAI FQ-B32 / MST-B32: What are the technical bases for assuming that control rod ejection is not credible, and why do such reactivity insertions appear to be discounted? (FQ Section 4.3.1.1) {JV/F23}

Comment: For LWRs, control rod protection systems also exist, but design basis accidents include consideration of possible failure.

ARP FQ/MST -33

RAI FQ-B33 / MST-B33: The approach of establishing limits for fuel quality does not seem conservative. Why not make the best fuel that is economical and have a larger margin? (FQ Section 4.3.3) {LE/F15}

Comment: It may be useful to consider a cost/benefit analysis of the specifications in addition to the top-level requirements. The fuel quality requirements will be given separately for contamination, coating defects and probably other variables. The interaction of these variables can be complex under operating and accident scenarios. The logic for deriving the fuel requirements is sound. However, for example, if increasing coating quality can be done at relatively low cost, it could be included in the fuel specification to increase the safety margin.

ARP FQ/MST -34

RAI FQ-B34 / MST-B34: The entire fuel acceptance criterion is based on being able to provide fuel that is of equal quality to the German fuel. Rather than relying entirely on sampling of product to determine fuel quality, it may be prudent to establish on-line process monitoring standards. If on-line inspection is not practical, it may still be possible to set ranges for fluid flows, chemistry or other processing variables that can be monitored for all particles. Have on-line process monitoring or inspection techniques been considered? (FQ Section 5) {LE/F16}

Comment: It has been difficult for the US to produce fuel of equivalent quality to the German fuel in the past. Controlling the manufacturing process is crucial to obtaining high-quality fuel.

ARP FQ/MST -35

RAI FQ-B35 / MST-B35: Manufacturing quality assurance is essential. For each kernel and particle characteristic, can the numerical values, tolerances, measurements, methods and resolution of measurement techniques be included? (FQ Section 5.2.1.2) {LE/F17}

Comment: Eventually this information will be needed by the fuel manufacturer.

ARP FQ/MST -36

RAI FQ-B36 / MST-B36: The crystal structure of the SiC layer is given as key parameter controlling fuel performance in Section 3.3.3. Why isn't it listed as a parameter that will be monitored? (FQ Section 5.1.2.1) {LE/F18}

Comment: An adequate set of monitored fuel specifications is necessary to ensure the proper fuel quality.

ARP FQ/MST -37

RAI FQ-B37 / MST-B37: Are there any pre-irradiation thermal tests? Are there any tests to check the pre-irradiation bonding between the coating layers? What additional information could be obtained on small samples from large batches of fuel that could indicate fuel quality for parameters that are fundamental to performance? (FQ Section 5.2.2.2) {LE/F19}

Comment: Most of the fuel characteristics that will be monitored are for individual layers or properties. This question is asking if it is possible to batch test in a way that measures the aggregate particle properties necessary for fuel performance.

ARP FQ/MST -38

RAI FQ-B38 / MST-B38: The FQ white paper states "All irradiated fuel spheres will be subjected to heating tests simulating transient and accident temperatures, first at 1600 ^{o}C for 100 hours and then at 1800 ^{o}C for 100 hours." Could the material be annealed and the properties improved by holding the material at 1600^{o}C? Will this improve the performance at 1800^{o}C? (FQ Section 5.2.2.3) {LE/F20}

Comment: This question is also related to the path-dependence of material properties and the difficulty in determining which data is conservative for the design.

ARP FQ/MST -39

RAI FQ-B39 / MST-B39: There are very few failed particles in the database and it is not explained how the specific failure mechanism can be determined for each particle. There are so many particles in a sphere or compact, it is unclear if the failed particles could be identified to determine the failure mechanism. How are fuel particle failures used to benchmark a computational code if the failure mechanism for each particle is not identified? (FQ Section 5.3.5) {LE/F21}

Comment: Code verification is an important step in determining the test conditions for the fuel qualification program.

ARP FQ/MST -40

RAI FQ-B40 / MST-B40: There are a large number of material properties and failure mechanisms that contribute to fuel performance. Will a statistical analysis method, such as “design of experiments” be used to determine the importance of various factors and combinations of factors on fuel performance? Is so, please describe this method. (FQ Section 5.3.5) {LE/F22}

Comment: Many variables, including material properties and operating conditions, interact to determine fuel performance. Identifying the most important combinations of factors that affect fuel performance is large undertaking that could benefit from a logical and quantifiable method to screen the factors.

ARP FQ/MST -41

RAI FQ-B41 / MST-B41: Has the process summarized in FQ Section 3.2.1.2 been demonstrated in the US at the FDL? (FQ Sections 3.2.1.2 and 5.2) {HL/F2}

Comment: In Section 3.2.1.2 the German TROSO particle manufacturing process is summarized, noting perceived high quality of the particles produced by the Germans at that time.

ARP FQ/MST -42

RAI FQ-B42 / MST-B42: Will the QA program outlined for the PFP be applied to the FDL? (FQ Section 5.2.1.2) {HL/F3}

Comment: A summary of the quality assurance program for the PFP is given in section 5.2.1.2. Although this is a summary of the program, it nevertheless indicates the important parameters to be monitored and controlled. It is not clear from the discussion that this same program will be applied to the FDL.

ARP FQ/MST -43

RAI FQ-B43 / MST-B43: It is suggested that the transient data might be more limiting, and that the data base might be extended, either by experimental measurements or analytic means. Discuss the maturity of the analytic models that might be used to address this area. (FQ Section 5.2.2) {HL/F4}

Comment: The projection of TRSO particle behavior beyond the current experimentally measured base by means of analytic models requires a numerical algorithm that has been validated. The only code mentioned in the FQ white paper is PARFUME, and it is not clear if this code has been validated for this extrapolation, or if another code will be used.

ARP FQ/MST -44

RAI FQ-B44 / MST-B44: In mentioning the destructive PIE of irradiated fuel spheres and fuel compacts, no mention is made of the determination of transuranics as a function of particle position within the sphere. This data would be a very valuable benchmark for validating cross section and burnup codes, because of the double heterogeneity effect, which is unique to this fuel type. Is it possible to include this measurement in the PIE protocol? If it is included please state it more clearly. (FQ Section 5.2.2.2) {HL/F5}

Comment: The PIE of fuel compacts is described in this section, and includes the determination of fission product distribution. However, it is not clear if the trans-uranic content of the TRISO kernels will be determined as a function of position within the fuel compact. The desire to have this data will be useful to validate reactor physics codes that have a double-heterogeneity model. These models are necessary to carry out fuel element calculations, and a variety of models are used in the various codes used for this step.

ARP FQ/MST -45

RAI FQ-B45 / MST-B45: What range of carbon and oxygen will be included in the testing of UCO fuel? Has this range been manufactured before by other vendors? (FQ Section 5.3.1) {HL/F6}

Comment: The range of the carbon and oxygen fractions in the kernel of the TRISO particles implies a range of requirements on the manufacturing process. Thus, if some other manufacturer had fabricated fuel using the same range of carbon to oxygen, a good starting condition would be available for the fabrication process.

ARP FQ/MST -46

RAI FQ-B46 / MST-B46: What technical issues are alluded to in the AGR-1 test goals? (FQ Section 5.3.1) {HL/F7}

Comment: The description of the AGR series of tests is somewhat rudimentary, and this might be acceptable for the tests to be carried years from now. However, the first test described in AGR-1 requires more detail.

ARP FQ/MST -47

RAI FQ-B47 / MST-B47: (a) Describe how the MTR fuel test conditions match the conditions expected in the NGNP with respect to the entire nuclear, physical, and chemical environment. (b) Explain how irradiation at only two testing temperatures will be limiting. (FQ Section 5.2.2.3) {JV/F24}

Comment: It is not clear that for the testing for “Full Burnup Irradiation Target” two temperature test conditions are sufficient. Thermal mechanical fuel cycling may actually show that shifting between temperatures can be more demanding than staying in a single fuel (temperature) zone.

ARP FQ/MST -48

RAI FQ-B48 / MST-B48: Explain how the testing of fully burned fuel, as opposed to partially burned fuel, will give the only necessary data for the distribution of gaseous and volatile fission products throughout the fuel lifetime. (FQ Section 5.2.2.3) {JV/F25}

Comment: Migration and nuclear transformation of the gaseous fission products may affect tested results. Also, a note in the FQ white paper says that partial burnup testing may not be performed in conjunction with the NGNP project.

ARP FQ/MST -49

RAI FQ-B49 / MST-B49: Prior HTGR/HTR fuel qualification programs (US, UK, Germany, Japan, China) have made efficient use of fuel testing in real-time HTGR/HTR neutron environments available in experimental or prototype HTGR/HTR facilities, coupled with fuel testing in accelerated neutron environments, in material test reactors (MTRs). Explain the rationale for not including as major elements in the NGNP fuel qualification program:

- real-time testing of candidate NGNP fuel systems in existing HTGR/HTR irradiation facilities;
- safety testing of irradiated candidate fuel elements from these real-time environments, and
- qualification/confirmatory testing and monitoring in the NGNP prototype plant.

(FQ Section 5.1, page 73, bullets 4 and 5) {MJK(DC)/F1} [1-ii,2-ii]

Comment: The combination of irradiation testing under real-time HTGR/HTR neutron environments coupled with accelerated testing in MTRs has a proved to be an effective process to evaluate candidate fuel systems under representative irradiation conditions in a reasonable period of time. Real-time qualification testing in an HTGR/HTR environment seems to be downplayed for both the pebble-bed and prismatic fuel concepts in the FQ white paper. The only significant irradiation testing in this planned is under accelerated MTR environments.

The German fuel development program of the 1980s and 1990s had access to the AVR along with a number of European MTRs. This access to real-time and accelerated irradiation environments proved to be an invaluable asset to their development efforts. The success of this effort is evidenced in that all of the experimental fuel performance data (Chapter 3 and Appendix A) presented as evidence for the NGNP pebble bed fuel concept was generated within that program.

Currently there are two experimental HTGR/HTRs operating - one is the 30 MW_{th} HTTR in Japan and the other is the 10 MW_{th} HTR-10 in China. These experimental facilities provide the only available irradiation environments representative of the prismatic and pebble bed HTR concepts. The NGNP Program should initiate cooperative programs between the U.S., Japan, and China to provide irradiation testing access to these experimental facilities.

ARP FQ/MST -50

RAI FQ-B50 / MST-B50: Now that the South African (SA) Pebble Bed Modular Reactor (PBMR) Project has been terminated, how does the NGNP pebble bed concept go forward? A major portion, if not all, of the only detailed plan available in the FQ white paper now appears to be no longer applicable. Has an alternative business interest come forward to pick up where SA left off or will the NGNP pebble bed concept be eliminated? (FQ Section 5.2, pages 74-87) {MJK/F2} [1(b)-ii]

ARP FQ/MST -51

RAI FQ-B51 / MST-B51: Discuss the methods available to monitor the coated particle characteristics and fuel-sphere/fuel compact characteristics and show explicitly just how the monitoring will take place. Will process controls be in place to insure that the coated particle characteristics fall within the proper range? Please elaborate as to which process controls are important in controlling coated particle characteristics such as SiC microstructure, iLTI and oLTI anisotropy, buffer layer density, Weibull properties (SiC characteristic strength and modulus), iLTI permeability, and coating layer thicknesses. Which methods in the fabrication process are employed to control mechanical, thermal, elastic and Weibull (SiC characteristic strength and modulus) properties? Again give specific examples. (FQ Section 5.2.1.2, pages 76-77) {MJK/F3} [1(b)-ii, 2-ii]

ARP FQ/MST -52

RAI FQ-B52 / MST-B52: Which characteristics identified for coated particles contribute directly to TRISO fuel particle irradiation performance and are they explicitly accounted for in the current fuel performance model(s)? What is the range of acceptability for the characteristics listed and how are these affected by the fuel normal operating conditions (temperature, burnup and fast fluence)? Provide details of how the limits of these characteristics were determined to ensure successful TRISO fuel performance? In what manner will fuel at the respective limits be selected and tested to insure they meet fuel particle performance requirements? (FQ Section 5.2.1.2, page 76) {MJK/F4} [1(b)-ii, 2-ii]

Comment: This RAI item pertains to evaluating the qualification and performance of NGNP candidate fuel concepts (see discussion in draft NUREG 1338, Feb 26, 1996, page 7). Of particular interest are the items listed below:

- Design thicknesses of fuel particle coatings and the bases for these thicknesses given fuel particle failures from manufacturing, normal operation, and accidents.
- Quality control of the manufacturing process for particle fuel and resulting tolerances on particle coatings.
- Fuel performance of specific coated particles and coating tolerances demonstrated from irradiation and safety tests.

ARP FQ/MST -53

RAI FQ-B53 / MST-B53: Provide additional information on the Burn Leach procedures as to whether differences exist between the procedures used for fuel compacts vs. those used for spherical fuel elements. Identify any follow-on chemical analyses performed to determine the absolute quantity of free uranium, or other heavy metal contaminants (fissile or fertile). What assumptions are made about the source of this contamination and discuss the justification/evidence for these assumptions? Address whether specific quantitative analyses are, or will be, performed to determine the isotopic content of the measured contamination? (Section 5.2.1.2, page 77, Fuel Spheres) {MJK/F5} [1(b)-ii, 2-ii]

Comment: Exposed uranium and other fissile/fertile materials are key factors in controlling the source term for either spherical fuel elements or cylindrical compacts that contain TRISO coated particle fuel. Whether the measured contamination levels consist of natural uranium, enriched uranium, thorium, or other fissile materials appear to be important factors in source term determination.

Initial low-levels of fertile material contamination (Th-232 and natural uranium) in the fuel matrix material and the subsequent breeding of fissile material isotopes have been shown to be a significant source of in-reactor fission gas release [Ref.].

Reference: H. van der Merwe and J. Venter, "A Method to Evaluate Fission Gas Release During Irradiation Testing of Spherical Fuel", Proceedings HTR2008: 4th International Topical Meeting on High Temperature Reactor Technology, 23 Sep.-1 Oct., 2008, Washington DC, USA. Paper 2008-58184]

ARP FQ/MST -54

RAI FQ-B54 / MST-B54: Statements made relative to accident testing appear to be contradicting. Please discuss this apparent contradiction and provide any additional data to illustrate your position. (Section 5.2.2, page 77, 2nd bullet) {MJK/F6} [1(b)-ii, 2-ii]

Comments: The statement made referring to the transient temperature profile being more limiting does seem to be correct. In the transient tests illustrated, the temperature profiles achieve peak temperatures of 1620ºC and 1700 ºC in ~30 hr based on the DLOFC accident scenario, followed by a cool-down to ~1200ºC over the next 270 hrs. This scenario compares to the isothermal heating tests where the temperature profile is much less severe, rising to 1250ºC over a period of ~30 hr then rising to 1600ºC in an additional ~8 hrs, or 1700ºC and ~10 hr. These soak temperatures can last up to several hundred hours. Based on the data provided, 25 of the 26 recorded failed particles observed in the 1600ºC and 1700ºC heating tests failed during transient testing. Only one of the 26 failures was recorded in an isothermal test at 1700ºC. Thus, the follow-on statement that "analytical models and a general understanding of the relevant phenomena indicate that the isothermal test should be more challenging to the fuel" does not appear accurate.

ARP FQ/MST -55

RAI FQ-B55 / MST-B55: Please elaborate further on the suggestion made that "Additional confirmatory data under actual service conditions may be provided by a post-irradiation test and inspection program to be conducted on fuel discharged from the pebble-bed design." Discuss any planning for real-time testing of either FDL or PFP fuel. (FQ Section 5.2.2, page 78) {MJK/F7} [1(b)-ii, 2-ii]

Comment: This suggestion would appear to be a "must," especially in view of the fact that no real-time testing of spherical elements are planned, or at least identified, in this fuel qualification plan. This point also applies to the prismatic fuel. The inclusion of a "Post-Irradiation Fuel Inspection Program" for either NGNP reactor concept should also be a "must" requirement. Such programs were invaluable for all previous experimental and prototypical HTGR plants. See also RAI FQ-B55 / MST-B55.

ARP FQ/MST -56

RAI FQ-B56 / MST-B56: Provide the pre-irradiation as-fabricated quality data on recent UO2 TRISO fuel particles fabricated into: a) spherical fuel elements in South Africa's FDL (described on page 80); and b) fuel compacts at ORNL for inclusion into the AGR-2 irradiation test (described on page 89) now underway at the ATR in Idaho. Discuss the as-fabricated quality data relative to the NGNP pebble bed as-fabricated requirements (Table 16) and prior German fabrication experience (Tables 2 and 3). Inclusion of this data will provide important information regarding the status pebble bed fuel manufacturing capability today. (FQ Section 5.2.2.2, page 79) {MJK/F8} [1(b)-ii, 2-ii]

Comment: The FQ white paper provides no reference to as-manufactured quality data of UO_2 TRISO fuel particles fabricated in recent years in South Africa. These fuel particles have in at least two campaigns been fabricated into: a) spherical fuel elements in South Africa's FDL (described on page 80); and b) fuel compacts at ORNL for inclusion into the AGR-2 irradiation test, now underway. Both of these campaigns appear to be part of the approach outlined in FQ Sections 5.2.2.1 and 5.2.2.2 on pages 78 - 82.

At the HTR-2010 conference in Prague (October 2010), results were presented on "Recent Advances in HTR Fuel Manufacture" [Ref.]. The FQ white paper presents as-manufactured fuel quality results on HTR pebble bed fuel element fabrication based on the German experience from the 1980's, the HTR-10 fuel element production in China, and recent results from South Africa's FDL production of spherical elements (see figure below). The South African fuel fabrication work appears to be part of the effort (Testing of Laboratory-Produced Fuel Spheres) described on page 80 of the FQ white paper.

This important information should be included in the FQ white paper together with detailed discussions as to how well the pre-characterization data meet NGNP as-fabricated quality requirements (page 62, Section 4.2.3.1 and Table 16, page 72) and fuel element characteristics (listed on pages 76 and 77). Comparisons to previous German production campaigns should also be provided. Failure to include these data impedes understanding of the current production capability for UO_2 TRISO fuel and spherical fuel elements for the NGNP pebble bed concept.

Reference: H. Nabielek, C. Tang, and A. Müller, "Recent Advances in HTR Fuel Manufacture", paper 094, HTR 2010 Conference, Prague, CZ (October 2010).

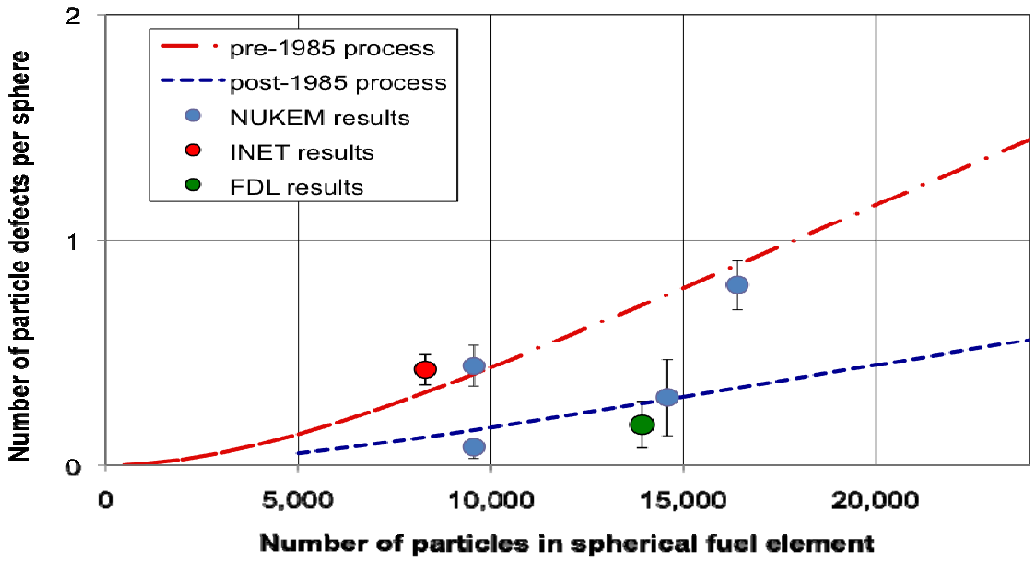


Figure Caption. Number of particle defects in manufacture as a function of the number of particles in a spherical fuel element. The red circle represents Chinese 2001 results and the green circle represents South African 2009 results. Black circles represent German results obtained by NUKEM during 1981-1988 and show the post-1985 improvement of manufacturing quality ("late NUKEM").

ARP FQ/MST -57

RAI FQ-B57 / MST-B57: Provide detailed information on the differences in the neutron spectra experienced in MTR irradiation facilities (such as the HFR in Petten, the IVV-2M in Russia and the ATR in Idaho) as compared to that anticipated in the NGNP pebble bed or the NGNP prismatic concepts. (FQ Section 5.2.2.2, page 80, and Section 5.3.1, page 89) {MJK/F9} [1(b)-ii, 2-ii]

Comment: This is of particular importance relative to accelerated neutron environment concerns and the fact that no real-time irradiation testing is discussed or planned in the FQ white paper. Generally MTR irradiation facilities have the capability to tailor the neutron spectra to meet their customer's irradiation needs. This possibility should be explored with the respective MTR facilities and adjustments made to insure a more representative HTGR neutron energy spectrum. This factor is important in insuring that the proper fission and activation product distributions are achieved in the accelerated irradiation tests compared to the real-time HTGR neutron environment. Significant differences can lead to unrealistic fission/activation product inventories within the TRISO coated fuel particles.

ARP FQ/MST -58

RAI FQ-B58 / MST-B58: Provide the rationale for irradiation testing only nine FDL fuel spheres to establish an early indication of the effectiveness of the NGNP pebble bed fuel manufacturing process. (FQ Section 5.2.2.2, page 80, Testing of Laboratory-Produced Fuel Spheres) {MJK/F10} [i(a)-ii]

Comment: Based on the published South African FDL fuel element quality data [Ref.], the as-fabricated burn leach data fall between the AVR 21-2 and HFR-K5/-K6 as-fabricated quality data. Translating this into failure fraction numbers, as was done on page 29, the expected defect fraction with 50% confidence failure fraction is ≤1.3 $x10^{-5}$, and with a 95% confidence, the failure fraction is ≤2.2 $x10^{-5}$.

Nine elements, each with ~14,400 particles per element, represent a total population of ~129,600 particles. A successful irradiation with no observed failed fuel in-reactor would yield a failure fraction with 50% confidence of ≤5.35 $x10^{-6}$, and with 95% confidence ≤2.31 $x10^{-5}$. These results indicate that nine irradiated fuel elements is an insufficient population to demonstrate NGNP pebble bed as-fabricated fuel quality requirement at the upper 95% confidence level. However, increasing the number of elements to ten would provide a sufficient population to meet the requirements, provided no in-reactor failures are observed.

Reference: - H. Nabielek, C. Tang, and A. Müller, "Recent Advances in HTR Fuel Manufacture", paper 094, HTR 2010 Conference, Prague, CZ (October 2010).

ARP FQ/MST -59

RAI FQ-B59 / MST-B59: Provide details of the planning and the methodology that will be employed for the Heating Tests identified in Section 5.2.2.2. (FQ Section 5.2.2.2, pages 81-82) {MJK/F11} [i(b)-ii, 2-ii]

Comment: No mention is made of how many irradiated fuel elements will be heated. The only indication that more than one test is to be performed is the term "Fuel spheres shall undergo …"

Details of the methodology are also insufficient based upon the large testing database available from the German accident testing program from the 1980's and 1990's. All isothermal heating tests proposed should consider following the same heating sequence (or an equivalent sequence) as developed and used in the German FDP (Ref. – Schenk, Pitzer, and Nabielek, Jül-2234, September 1988, [Fig. 8, page 13]). Such multi-step heating sequences allows for:

- Fission gas release measurements at room temperature;
- Cleaning/moisture removal at ~300ºC;
- Equilibration of internal gas pressure in TRISO fuel particles at temperatures of 1050ºC and 1250ºC; and
- Heatup to selected accident condition temperature and isothermal soak at this temperature for the required test period.

The heating test facility should be continuously purged with He during the entire accident test simulation, and this purge gas shall be monitored continuously for ^{85}Kr release from the test fuel. This means from the start of the test at room temperature, through the heat-up sequence, the actual isothermal soak at the correct temperature/duration, and finally the cool-down to room temperature.

ARP FQ/MST -60

RAI FQ-B60 / MST-B60: Describe a detailed sampling plan and an accompanying statistical analysis that validates the selection of 15 spherical fuel elements are sufficient to establish the as-manufactured fuel quality of test elements from the NGNP pebble bed fuel production facility. (FQ Section 5.2.2.3, page 83) {MJK/F12} [1(b)-ii]

Comment: Typically fuel elements would be selected from each of the production lots for evaluation. NUKEM, GmbH, employed a sampling plan that generally called for the selection of five random elements from each production lot. Thus, whether 15 elements are sufficient does not make much sense without knowledge of the number and size of the typical production lots for this fuel manufacturing facility. In some of the AVR production campaigns, like AVR 19 where 24,600 elements were produced, as many as 70 elements (five each from 14 production lots) were destructively analyzed. For the smaller campaigns like for the HTR Modul Proof test where ~100 elements were manufactured, only 10 were destructively analyzed.

The actual number of elements to be destructively examined in order to validate as-fabricated fuel quality will largely be a function of the U_{free}/U_{total} value and the heavy metal per fuel element (assuming reference UO_2 TRISO particle design). If the equilibrium NGNP pebble bed fuel element has ~6.2 g of uranium and ~11,200 particles based on the FQ white paper (adjusted fuel design, page 84), then estimates for the number of elements to be examined can be made based on anticipated U_{free}/U_{total} values. For U_{free}/U_{total} values of 6 x10^{-5}, 3 x 10^{-5}, and 1 x10^{-5}, the corresponding number of failed particles per element, on average, are ~2/3, ~1/3 and ~1/9, respectively. Using this information, sampling tables can be generated, as shown below, that provide an estimate of the failure fraction and confidence level that can be established. If for example, the failure fraction probabilities identified on page 29 [expected failure fraction ≤1.3 x10^{-5} (50% confidence) and ≤2.2 x10^{-5} (95% confidence)] are associated with an U_{free}/U_{total} value of ~1 x10^{-5}, are to be established, then ~45 equilibrium fuel elements from the production facility would have to be destructively examined (via Burn Leach) to validate the as-fabricated fuel quality level.

No. of Fuel Elements Examined*	U_{free}/U_{total} Limit	Expected number of Failed Particles (on average)	Failure Fraction (95% Confidence)	Failure Fraction (50% Confidence)
15	60 x10^{-6}	10	≤1.0 x10^{-4}	≤6.3 x10^{-5}
15	30 x10^{-6}	5	≤6.3 x10^{-5}	≤3.4 x10^{-5}
15	10 x10^{-6}	~2	≤3.7 x10^{-5}	≤1.6 x10^{-5}
25	60 x10^{-6}	~17	≤9.1 x10^{-5}	≤6.3 x10^{-5}
25	30 x10^{-6}	~8	≤6.3 x10^{-5}	≤3.1 x10^{-5}
25	10 x10^{-6}	~3	≤2.8 x10^{-5}	≤1.3 x10^{-5}
45	60 x10^{-6}	30	≤8.1 x10^{-5}	≤6.1 x10^{-5}
45	30 x10^{-6}	15	≤4.6 x10^{-5}	≤3.1 x10^{-5}
45	10 x10^{-6}	5	≤2.1 x10^{-5}	≤1.1 x10^{-5}

* Equilibrium Production-Line Fuel Sphere with 7 g UO2 (6.17 g HM) and containing ~11,200 particles (adjusted fuel element design, page 84).

ARP FQ/MST -61

RAI FQ-B61 / MST-B61: Compared to previous German campaigns, the irradiation of only 12 NGNP pebble bed Production Line fuel elements appear to be a small sample size to qualify a full-scale fuel element production facility. Discuss the rational for choosing this sample size and any backup plans in the event that the proof test performance goals are not achieved in these accelerated MTR irradiation tests. Provide the rationale and justification for not requiring, at a minimum, the irradiation testing of a similar number of Production Line fuel elements under real-time HTGR/HTR irradiation conditions. Does the lack of such a plan to include irradiation testing in real-time HTR environment cause any concern? (FQ Section 5.2.2.3, page 84) {MJK/F13) [1(b)-ii]

Comment: Because of the lack of an experimental or prototype HTGR/THE irradiation facility in the US, establishing a cooperative program between the US NGNP Program and Chinese Government, where NGNP pebble bed Production Line fuel elements could be routinely tested in the HTR-10 experimental reactor, would appear to be of prime interest. This same point can be made for a similar cooperative program between the US NGNP Program and the Japanese Government to irradiated NGNP prismatic fuel compacts under real-time conditions in the HTTR experimental reactor.

The irradiation of only 12 spheres, each containing 11,200 UO_2 TRISO coated particles, may not be a statistically significant sample. To irradiate the same particle population as for elements containing 14,400 particles, will require a minimum of 16 fuel elements be irradiated.

ARP FQ/MST -62

RAI FQ-B62 / MST-B62: The white paper states (page 98) that “Pretest predictions and after-test calculations will be performed for each irradiation test and some of the safety tests.” Please provide these pretest predictions for the completed AGR-1 irradiation test and the AGR-2 irradiation currently underway. Discuss the results of pretest predictions in relation to the observed in-reactor fuel performance data based on monitored short-lived fission gas species. Indicate whether the formal ATR pretest predictions are derived from the same suite of fuel performance models and codes designed to predict NGNP prismatic fuel performance under normal operating conditions. (Section 5.3.5, page 98) {MJK/F14} [2-ii]

Comment: With the exception of the IAEA sponsored CRP-6, no references to any documents containing ATR pretest predictions were made in the FQ white paper. Discuss the rationale for not including these performance predictions here. In most cases, these computer codes and the performance models have existed for many years and in some cases over decades.

ARP FQ/MST -63

RAI FQ-B63 / MST-B63: The lack of pre-irradiation characterization data on the NGNP prismatic fuel compacts for the AGR-1 and the AGR-2 tests in the FQ white paper is surprising. Pre-irradiation characterization data and as-fabricated fuel quality data for the fuel compact lots of AGR-1 and AGR-2 have been published elsewhere [Refs. 1 & 2].

· Provide the fuel pre-irradiation characterization data and the measured as-fabricated quality data for the AGR-1 and AGR-2 fuel compact lots. Discuss the comparison of the AGR-1 and AGR-2 specification as-fabricated quality specifications (Table 2, Reference 1) to the NGNP prismatic fuel performance requirements listed in Table

16 (page 72). Discuss how these data relate to the in-reactor performance of the AGR-1 fuel.

· Compare the as-fabricated fuel quality data for those compacts containing South African UO_2 TRISO fuel particles to the NGNP pebble-bed fuel requirements and prior German manufacturing data.

These data would provide a more thorough understanding of the status of manufacturing UCO TRISO fuels and NGNP prismatic fuel compacts. (Section 5.3.3, page 93) {MJK/F15} [1(b)-ii,2-ii]

References:

1. J. A. Phillips, C.M. Barnes and J.D. Hunn, "Fabrication and Comparison of Fuels for Advanced Gas Reactors," Proceedings of HTR-2010, Prague, Czech Republic, Oct. 18-20, 2010, paper 236.

2. IAEA TECDOC-CD-1645, Section 5.3, pages Table 7)

Comment: The pre-irradiation characterization data and as-fabricated quality data for the compacts containing UCO TRISO fuel particle in irradiation tests AGR-1 and AGR-2 have been available for a number of years. These results have been published in at least two international sources. Failure to include this data and discuss with respect to as-manufactured fuel quality requirements is a significant oversight. The two tables presented below were obtained from Reference 1. They present the as fabricated quality of the prismatic fuel compacts containing UCO TRISO fuel variants irradiated in theAGR-1 test, and compacts with either UCO TRISO fuel particles or UO_2 TRISO fuel particles now under irradiation in the AGR-2 test.

Table 3. Comparison of burn leach defects (in) particles before compacting (Reference 1).

Fuel Type	Burn-leach Defects	Sample Size	Ratio	95% CL
AGR-1 Baseline	0	120,688	0	≤2.5E-5
AGR-1 Variant 1	1	121,117	8.3E-06	≤4.0E-5
AGR-1 Variant 2	1	50,265	2.0E-05	≤9.5E-5
AGR-1 Variant 3	1	120,660	8.3E-06	≤4.0E-5
AGR-2 UCO	5	217,159	2.3E-05	≤4.8E-5
AGR-2 UO2	1	120,000	8.3E-06	≤3.9E-5
German particles [9]	102	3,300,000	3.1E-05	≤3.6E-5

Table 4. Comparison of defects found in deconsolidated particles by LBL (Leach-Burn-Leach) [Reference 1].

Fuel Type	Defects Found	Sample Size	Ratio (U_{free}/U_{total})	95% CL
Uranium Contamination (pre-burn leach)				
AGR-1 Baseline	0	99,470	0	≤3.1E-5
AGR-1 Variant 1	0	74,699	0	≤4.1E-5
AGR-1 Variant 2	0	99,100	0	≤3.1E-5
AGR-1 Variant 3	0	99,032	0	≤3.1E-5
AGR-2 UCO	3	317,625	9.4E-06	≤2.5E-5
AGR-2 UO2	3	246,840	1.2E-05	≤3.2E-5
SiC Defects (post-burn leach)				
AGR-1 Baseline	2	49,735	4.0E-05	≤1.3E-4
AGR-1 Variant 1	0	49,799	0	≤6.1E-5
AGR-1 Variant 2	1	49,555	2.0E-05	≤9.6E-5
AGR-1 Variant 3	0	49,516	0	≤6.1E-5
AGR-2 UCO	0	254,100	0	≤1.2E-5
AGR-2 UO2	0	123,420	0	≤2.5E-5

ARP FQ/MST -64

RAI FQ-B64 / MST-B64: An overpower transient will heat fuel particles from the inside. The fuel testing described heats the particles uniformly from the outside. This will affect the stress distribution in the coating layers and could impact performance. Can it be shown that the heating test performance is representative of fuel particle performance during an overpower transient? (Appendix A) {LE/F11}

Comment: A difference in the temperature distribution in the particle (hot kernel with cooler matrix in an overpower transient versus uniform temperature increase in the heating tests) will cause two different thermal stress distributions. The thermal stress could drive failure mechanisms such as fuel particle coating cracking or fuel particle layer debonding.

ARP FQ/MST -65

RAI FQ-B65 / MST-B65: In performing heatup tests on irradiated fuel to simulate heatup accident conditions, the heat is supplied from the outside the fuel compact. In the real accident situation, the heat is generated by nuclear decay inside the fuel kernels. Describe how these differences between actual conditions and test conditions affect kernel, coating, and matrix temperatures through a fuel compact and how these differences are considered in applying the test results to accident analysis. (Appendix A) {HL/F9}

ARP FQ/MST -66

RAI FQ-B66 / MST-B66: In discussing NRC requirements for fuel and fuel qualification, it would be useful to describe the basis for each of the fuel-related General Design Criteria and address the applicability of those GDCs to the NGNP. If a particular GDC is not directly applicable to the NGNP design, then identify analogous criteria for the NGNP and state how those criteria will be satisfied. (Section 2) {MJK/S2}

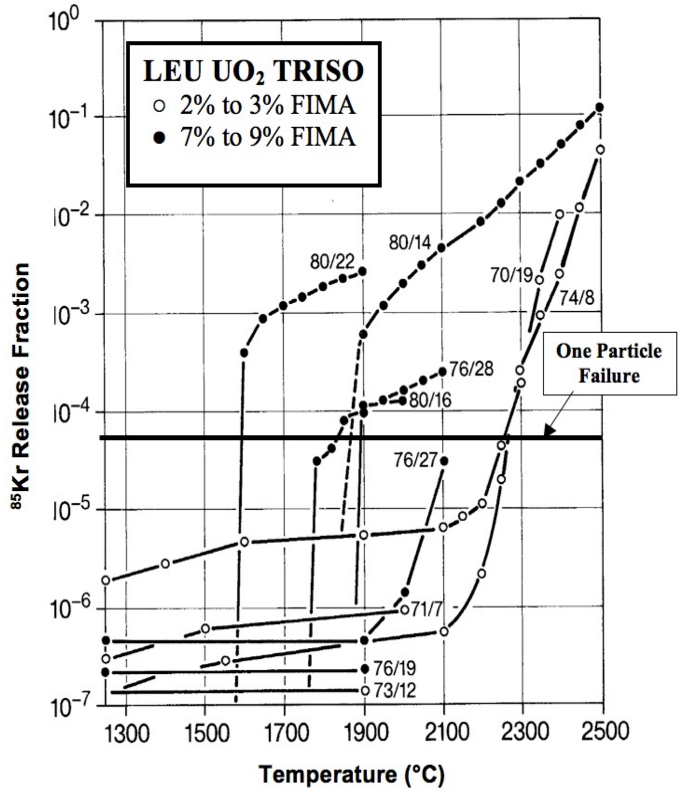
ARP FQ/MST -67

RAI FQ-B67 / MST-B67: The "heating test krypton release results" presented in Table 6 for 1700ºC and 1800ºC have different exposed kernel fractions (at 50% confidence interval (CI) and 95% CI) than similar data presented in Table 8 and Tables A-4 and A-5. This is the result of including additional heating test data in Table 6 from non-reference fuel test specimens irradiated in MTR irradiation tests (SL-P1 and FRJ2-P27). This is why the numbers of particles listed in Table 6 are different for the 1700ºC and 1800ºC heating tests. The resulting confusion makes it difficult to track the exposed kernel fraction data in Chapter 3 with that of Chapter 4 and Appendix A. It is not clear that the value of the heating test data conducted on non-reference fuel specimens is sufficient to warrant their inclusion. Please clarify how the NGNP Project interprets and uses these data. (FQ Sections 3.2.3.1 and 3.2.3.2, Tables A-4 and A-5) {MJK/FS3.1}

ARP FQ/MST -68

RAI FQ-B68 / MST-B68: Please clarify the following statement in the FQ white paper: "The degradation of fuel performance at elevated temperatures is regular and gradual. No sudden changes in behavior (cliff-edge effects) as a function of irradiation temperature, burnup, or accident temperature were seen." (FQ Section 3.2.3.2, bullet 2, bottom of page 37) {MJK/FS3.2}

Comment: Sudden bursts or changes in release rates were observed in ramp tests of irradiated AVR spheres to high temperatures. See for example the Kr-85 release fraction data for AVR elements 76/28, 80/22, 80/14 and 80/14 in the figure copied below [W. Schenk and H. Nabielek, Jül-Spez 487, January 1988, Fig. 57 pg. 195.]. The sudden bursts were a result of complete particle failure and occurred without prior warning. The requested clarification should (a) clearly specify the ranges of relevant parameters (e.g., irradiation temperatures, burnup levels, fluence levels, accident temperatures, etc.) over which no sudden changes in fuel behavior (cliff-edge effects) have been seen, (b) indicate the types of fuel behavior considered in this context (e.g., coating layer failures, diffusive release through intact coating layers, etc.), and (c) identify supporting technical references as appropriate.



Fractional release of ^{85}Kr measured during accident simulation testing of GLE 3 spherical fuel elements irradiated to various burnups in the AVR [W. Schenk and H. Nabielek, Jül-Spez 487, January 1988, Fig. 57 pg. 195].

ARP FQ/MST -69

RAI FQ-B69 / MST-B69: Please correct or clarify the statement on FQ page 37 that "no exposed-kernel failures were observed in any of the MTR irradiations." While it is true that no exposed-kernel failures were observed in any of the MTR irradiations conducted on full-size 60 mm-diameter spherical elements, nine failed LEU UO_2 TRISO particle failures were in fact recorded in-reactor from fuel particles irradiated in non-reference fuel specimens (20 mm-diameter spheres, cylindrical compacts and coupons) in MTR irradiation tests SL-P1 and FRJ2-P27. (FQ Section 3.2.3.2, bullet 3, bottom page 37) {MJK/FS3.3}

ARP FQ/MST -70

RAI FQ-B70 / MST-B70: Please clarify the intended meaning of FQ Figure 11 and the data it represents in terms of possible NGNP accident conditions. Any data point not plotted as "zero" on the linear ordinate would seem to have no relevance to modular HTGR designs like NGNP. Data in the NGNP-relevant range of 10^{-9} to 10^{-6} would appear here as "zero" on the linear ordinate. More meaningful would be a figure like that provided here in RAI FQ-B68 / MST-B68 (see above) [Ref.], which shows the release fraction for ^{85}Kr measured continuously during ramp heating tests of German irradiated AVR fuel elements. (FQ Section 3.3.3) {MJK/FS3.4}

Reference: W. Schenk and H. Nabielek, Jül-Spez 487, January 1988, Fig. 57 pg. 195.

ARP FQ/MST -71

RAI FQ-B71 / MST-B71: The following statement on page 41 of the FQ white paper should be clarified or corrected: “TRISO-particle fuels have been … used as the fuel in seven power and experimental reactors.” TRISO-particle fuels have in fact been used in only five power and experimental reactors [AVR, Dragon, FSV, HTTR and HTR-10]. While Peach Bottom did contain some test fuel with TRISO coatings in its FTE Program, the THTR employed only fuel with BISO-HTI coatings. (FQ Section 3.3.1, page 41) {MJK/FS3.5}

ARP FQ/MST -72

RAI FQ-B72 / MST-B72: The following statement on page 46 of the FQ white paper seems premature and weakly supported at this stage of UCO fuel development: “The heating test data for the German UO_2 fuel are considered to be generally applicable to the UCO fuel being developed by the NGNP/AGR Fuel Program.” While the AGR-1 fuel fabrication campaign appears to have succeeded in producing high-quality HTGR fuel with good operating performance under AGR-1 irradiation testing conditions, more data on operating and accident condition performance would be needed to justify any application of heating test data on UO_2 fuel to the UCO fuel of interest. At present, there appears to be no test data on U.S. UCO TRISO fuel that suggest the applicability of past German accident condition test data. Please describe the existing test data, if any, that the NGNP Project interprets as supporting the applicability of UO_2 TRISO fuel heatup test data to U.S. UCO TRISO fuel. (FQ Section 3.3.3, page 46) {MJK/FS3.6}

ARP FQ/MST -73

RAI FQ-B73 / MST-B73: The basis for the failure fraction values in Table 11 under normal operation is unclear. All the reference 60 mm-diameter spherical fuel elements containing LEU UO_2 TRISO fuel irradiated in MTRs (HFR-K3, FRJ2-K13, FRJ2-K15, HFR-K5 and HFR-K6) represent a total population of ~286,240 particles. [This number is larger than the MTR data provided in Table 4 because the test FRJ2-K15 (which contained AVR 21-2 fuel elements) is included.] Based on this total population with “0” defects, the 50% and 95% upper confidence intervals for a binominal distribution are 2.42×10^{-6} and 1.05×10^{-5}, respectively. The failure fraction numbers quoted in Table 11 require “0” failures in a population of ~79,672 particles. There is no indication of what set of test elements make up this population. Possibly, it represents a specific subset of the elements irradiated in the MTR tests. Please explain how these data were obtained. (FQ Section 4.2.3.2, page 62) {MJK/FS4.1}

ARP FQ/MST -74

RAI FQ-B74 / MST-B74: Failure fraction data for heating tests presented in FQ Table 12 is again different from that presented in FQ Tables 6, 8, A-3, A-4, or A-5. It is not clear which are the appropriate numbers to be used for normal operating conditions and accident conditions. The failure fraction data should be correct and provide consistent indications of fuel performance for both normal operating and accident conditions. Please clarify. (Section 4.2.3, Table 12) {MJK/FS4.2}

ARP FQ/MST -75

RAI FQ-B75 / MST-B75: Based on the performance data presented in FQ Chapter 3, Chapter 4, and Appendix A, there is little confidence in the NGNP pebble-bed failure fraction values presented in Table 13 and plotted in Fig. 22. Provide a consistent basis for the correct set of failure fraction numbers along with details on how they relate to prior German UO_2 fuel as-fabricated quality, irradiation performance, and accident testing. (FQ Table 13 and Fig. 22, pages 63-64) {MJK/FS4.3}

ARP FQ/MST -76

RAI FQ-B76 / MST-B76: Please provide more detail on the normal operating conditions and accident conditions for the prismatic NGNP concept. The closely related MHTGR 350 MW design has been around since the mid-1980s and the GT-MHR 650 MW design since the mid-1990s. From the "anticipated" maximum service conditions provided in the FQ white paper, it appears that the prismatic UCO fuel will experience a much more severe environment than the pebble bed UO_2 fuel. This is summarized in the following table. (FQ Section 4.3.2) {MJK/FS4.4}

Parameter	**Prismatic NGNP (Table 14)**	**Pebble-Bed NGNP (Table 10)**
Max Fuel Temperature – Normal Operations (ºC)	1400	1048
Maximum Time-Averaged Fuel Temperature (ºC)	1250	644
Fuel Temperature – Accident Conditions (ºC)	1600	1483
Fuel Burnup (% FIMA)	17	8.75
Fast Fluence ($x10^{25}$ n/m^2, E>0.18MeV)	5	2.39

ARP FQ/MST -77

RAI FQ-B77 / MST-B77: In FQ Table 16, the fuel performance requirements for the prismatic UCO TRISO fuel list the heavy metal (HM) contamination requirement as ≤1.0 $x10^{-5}$ (Expected – 50% CL) and ≤2 $x10^{-5}$ (Design – 95% CL). Does this number represent the U_{free}/U_{total} fraction as explained for the German spherical element? The NGNP design value for the German spherical element is 6 $x10^{-5}$ and compares well with the total NUKEM, GmbH, fabrication data which was demonstrated in the production of ~60,000 spherical elements in production-scale facilities. The HM contamination value for the prismatic NGNP fuel is 3 to 6 times smaller than the German design value. What is the basis for this requirement and are there any modern (post NPR) US fuel compact production data that substantiate the feasibility for this level of production quality? (FQ Section 4.3.3, Table 16, page 72) {MJK/FS4.5}

ARP FQ/MST -78

RAI FQ-B78 / MST-B78: Does the heavy metal (HM) contamination requirement in FQ Table 16 also include Th-232 HM contamination in the fuel components, namely the fuel compact or fuel element matrix materials? Studies by South African researchers have shown that the primary source of fission gas release, in the absence of defective fuel particles, in MTR irradiation tests (HFR-K5/K6) is the breeding of U-233 from thorium contamination in the matrix material of spherical elements [Ref.] that contain high quality TRISO fuel particles (U_{free}/U_{total} values of ~1.35 x10^{-5}). Will there be a requirement on thorium contamination for NGNP fuel? What were the HM contamination values on the high-quality fuel compacts prepared for the AGR-1 and AGR-2 irradiation experiments, including uranium (natural and enriched), thorium, and any other fissile or fertile materials? (FQ Section 4.3.3, Table 16) {MJK/FS4.6}

Reference: van der Merwe, J.J., Verification and Validation of the PBMR models and Codes Used to Predict Gaseous Fission Product Releases from Spherical Fuel Elements. MSc. Thesis, Rand Afrikaans University, South Africa, 2003

ARP FQ/MST -79

RAI FQ-B79 / MST-B79: Please clarify how the FQ Table 16 requirement for ^{110m}Ag release for NGNP fuels applies to accident conditions. Based on prior German isothermal heating test performed on an irradiated HFR-K3 sphere containing high-quality LEU UO_2 TRISO particles, the ^{110m}Ag release was >10^{-2} upon reaching the soak temperature of 1600 ºC. [Ref.] This element was irradiation at operating temperatures in the range of 1000ºC to 1200 ºC to a burnup of 7.5% FIMA and a fluence of ~4 x10^{25} n/m^2 (E> 16fJ). These conditions are significantly below those listed in Table 14 for the prismatic NGNP concept. (FQ Section 4.3.3, Table 16) {MJK/FS4.7}

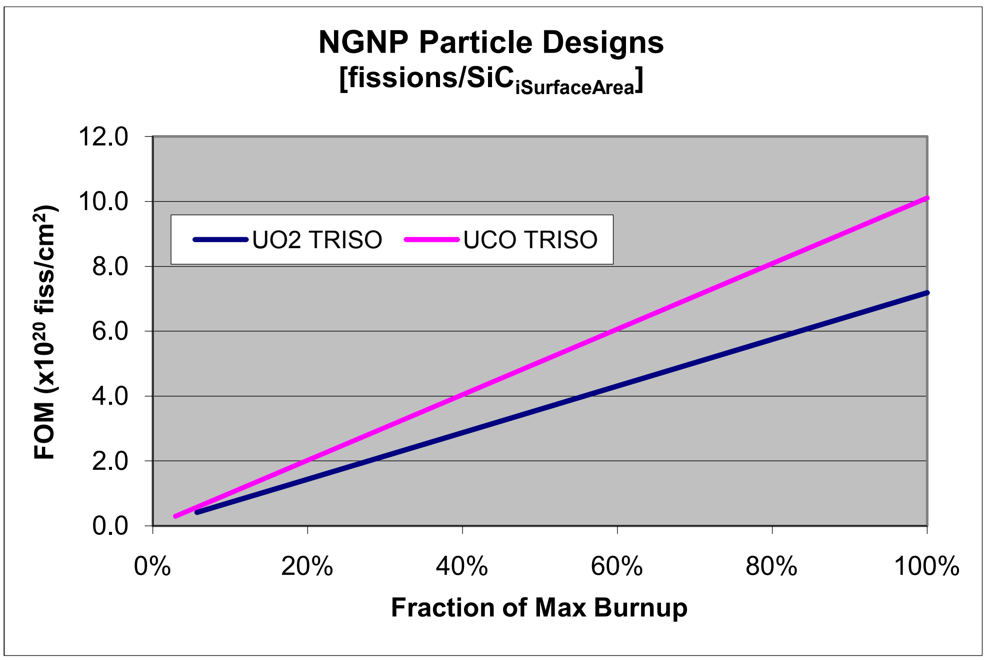
Reference: W. Schenk, G. Pott and H. Nabielek, J. Nucl. Mat. 171 (1990) pp. 19-30

ARP FQ/MST -80

RAI FQ-B80 / MST-B80: Please comment on the validity and significance of the observations presented in the comments that follow. (FQ Section 4.3.1.2, page 67) {MJK/FS4.8}

Comments: The UCO TRISO particle design envisioned for the NGNP concept is quite different and will undergo significantly different operating conditions than the UO_2 TRISO particle design in the NGNP pebble-bed concept. The UCO fuel kernel, nominally 425 µm-diameter, will have an enrichment of 14% U-235. The UO_2 fuel kernel is nominally 500 µm-diameter with an enrichment of 4.2 to 4.5% in the startup core and 7.8% subsequently. Although the TRISO coating design was not presented for the UCO particle design, the assumption is that it will be similar to the TRISO coating applied to the UO_2 fuel kernel. From a cursory evaluation of the operation conditions each of these TRISO fuel particle designs (Tables 10 and 14) will experience, it appears that the UCO particle in the NGNP prismatic concept will encounter a much more severe operating environment than the UO_2 particle in the pebble bed concept.

The fission density in the UCO fuel kernel will be significantly higher than that in the UO_2 fuel kernel. At the peak burnups of each, the fission density in the UCO kernel (at 17% FIMA) will be ~11.3 times that of the UO_2 kernel (at 8.75% FIMA). Assuming that each concept adopts a similar TRISO coating design (95 μm-thick Buffer, 40 μm-thick iLTI, 35 μm-thick SiC and 40 μm-thick oLTI), then the SiC layer in the UCO fuel particle will have a smaller inner surface area than that of the UO_2 particle (~23% smaller). Under normal operating conditions at peak burnup, the number of fissions/cm^2 of inner SiC surface in the UCO particle is ~45% higher than for the UO_2 TRISO particle. Thus, the flux of fission products to the SiC surface will also be ~45% higher for the UCO particle. The figure below illustrates how this difference in fission product flux will vary with accumulated burnup for each particle design. Coupling the higher fission density and the fission product flux with the differences in operating conditions in the prismatic [higher operating temperatures (up to 400°C) and ~2X in fluence] vs. the pebble-bed concepts means that the UCO fuel particle design will experience a significantly more severe operating environment than the UO_2 fuel particle design.



ARP FQ/MST -81

RAI FQ-B81 / MST-B81: Does the fuel design for the NGNP prismatic concept employ fertile particles? Does the prismatic fuel design employ fissile particles of a single enrichment or multiple enrichments? Previous U.S. prismatic HTGR designs, up thorough the mid-1990s, employed a two particle system consisting of both a fissile particle and a fertile particle, the latter containing either thorium or natural uranium. Recent GA pre-conceptual Modular Helium Reactor concepts (GA-A25401 and GA-A5402, April 2006) also employed a two particle system with an enriched UCO TRISO fissile particle and a natural UCO TRISO particle as the fertile particle. If a fertile particle is no longer employed, how are flux profiles flattened during normal operation? Are multiple enrichments, multiple compact packing fractions, and/or burnable poisons employed to achieve desired power shapes? (FQ Section 4.3) {MJK(DC)/FS4.9)

ARP FQ/MST -82

RAI FQ-B82 / MST-B82: Quantify how thermocouple (TC) failures in the AGR tests affect uncertainties in the irradiation temperatures of the fuel and fuel element materials. (FQ Section 5.3) {DC}

Comment: The response should quantify the added uncertainties in the temperatures of fuel and fuel element materials (i.e., local capsule temperature histories, capsule time-average peak temperatures, and capsule time-average volume-average temperatures) that result when multiple TCs fail in AGR tests. Of particular interest are the fuel temperature uncertainties associated with the specific TC failures identified in the completed AGR-1 test and the ongoing AGR-2 test. The response should include or reference a description of test thermal models and how they are used to support the evaluation of temperatures and temperature uncertainties in the AGR irradiation tests.