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REVIEW AND EVALUATION OF RECENT PUBLICATIONS BEARING ON THE FUELS SECTIONS OF THE DRAFT MHTGR PSER

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NOTICE

The Nuclear Regulatory Commission (NRC) is conducting a preapplication review of the modular high-temperature gas-cooled reactor (MHTGR) design, an advanced reactor plant design sponsored by the U.S. Department of Energy (DOE). Most of the information submitted by DOE on this design is labelled by DOE as "Applied Technology" information. DOE states in the label that any distribution of such information "to third parties representing foreign interests, foreign governments, foreign companies and foreign subsidiaries or foreign divisions of U.S. companies shall be approved by the Associate Deputy Assistant Secretary for Reactor Systems, Development and Technology, U.S. Department of Energy. Further, foreign party release may require DOE approval pursuant to Federal Regulation 10 CFR Part 810, and/or may be subject to Section 127 of the Atomic Energy Act."

Because of this statement, NRC has been treating Applied Technology information as if it was proprietary and have been restricting distribution of the information. Since 1985 when the reviews of these designs began, this information has not been placed in the public document room as part of the distribution of a DOE submittal or an NRC report on this design.

This technical evaluation report (TER) was completed by an NRC contractor and was classified as an "Applied Technology" document because it was based on documents classified by DOE as "Applied Technology" documents. In a letter of July 23, 1993, the NRC requested DOE to identify the Applied Technology information in the TER. DOE responded in its letter of August 26, 1993.

The enclosed report is the TER minus the Applied Technology information identified by DOE in its letter of August 26, 1993. Applied Technology information includes the listing of the references which contain such information. Therefore, this report is not classified "Applied Technology" and will be placed in the public document room for the public. Where information has been removed, a vertical line is placed on the right-hand side of the page. Extensive information was removed from sections in Chapter 3 of the report. These sections are also identified in the table of contents with a vertical line on the right-hand side of the page.

The public may contact the following person at DOE to request a copy of the complete TER including the Applied Technology information:

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ABSTRACT

Summaries are presented of thirteen recently published documents in the area of MHTGR fuel performance that may have an impact on the evolution of the Draft PSER for the MHTGR into the final SER. The applicable portions of the Draft PSER are Sections 4.1 and 4.2 which deal respectively with Reactor System Characteristics and Fuel Design. Some suggestions are provided on how this new information may be applied to revision of the Draft PSER. In addition, recent studies conducted for both NRR and RES are noted that may impact other portions of the Draft PSER.

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1. OBJECTIVES AND SCOPE

The objective of this task is to provide recommendations for updating Sections 4.1 and 4.2 of the draft Preliminary Safety Evaluation Report (PSER, 1989) for the Modular High Temperature Gas-Cooled Reactor (MHTGR) concept. Section 4.2 particularly, which deals with Fuel Design, is a critical part of the overall safety assessment. A significant body of new information in this area has appeared in the period of time between formulation of the draft PSER and the present. Evaluation of this new information and assessing its relevance are necessary steps for finalizing the draft PSER.

Section 2 of this report contains a brief description of Sections 4.1 and 4.2 of the draft PSER. Highlighted are the most significant conclusions contained in the draft PSER and also the items which appear to be most sensitive to change based on information that has recently become available. Section 3 contains a synopsis of each new report together with an assessment of how it may affect the PSER. Sections 4 and 5 discuss, respectively, recommendations for updating the PSER.

The following reports have been reviewed and evaluated for possible effect on an updated PSER:

"MHTGR Fuel Performance and Supporting Data Base," GA-A19877 (Section 3.4)

"Evaluation of MHTGR Fuel Reliability," NUREG/CR-5810 (Section 3.10)

2. SUMMARY OF PSER SECTIONS 4.1 AND 4.2

Sections 4.1 and 4.2 of the draft PSER are examined in this section with respect to intended purpose, organization, and sensitivity to change in the light of the newly available information.

2.1 Summary of Section 4.1," System Characteristics"

This section of the PSER provides an overview of the reactor system (within Chapter 4, entitled REACTOR) including (1) general configuration of the reactor vessel (RV), steam generator (SG) and cross-duct, (2) general features of the concrete reactor building housing the RB and SG, (3) the reactor core subsystem (RCSS), including the types and sizes of fuel elements, (4) description of the annular core configuration and the direction of the coolant flow through the core, and (5) the general means for reactivity control.

As such, a brief overview of the reactor system is provided as an introduction to the subsections which follow. This is a brief, descriptive overview subsection, which possibly needs to be verified for updatedness, but otherwise contains no safety judgements.

2.2 Summary of Section 4.2, "Fuel Design"

Section 4.2 follows the standard format used for all the subsections in Chapters 4-10 which deal with reactor systems that may effect safety. The standard format used is as follows:

1. Design Description and Safety Objectives,
2. Scope of Review,
3. Review and Design Criteria,
4. Research and Development,
5. Safety Issues, and
6. Conclusions.

Evidently, identification of the key safety issues for the particular reactor system, as enumerated in Part 5, is the principal purpose of each subsection. Part 1 (i.e., Section 4.2.1) should provide a sufficient description of the Fuel System to indicate its safety functions and its expected behavior for the satisfactory performance of those functions. Part 2 describes the scope of the review, which will indicate an expansion in the final PSER to include the items enumerated in the Table of Contents.

The intent of Part 3 (i.e., Section 4.2.3), Review and Design Criteria, is not clear. As currently constituted, this part lists the applicable General Design Criteria (GDCs) in 10 CFR 50, Appendix A, relating to proof of fuel performance. In addition, it is stated that the radionuclide design criteria should follow the general intent of 10 CFR 50.46 and Section II of Appendix K, 10 CFR 50. Section 4.2 of the Standard Review Plan (SRP) is cited as providing guidance for acceptance criteria for the performance of the fuel. However, other than citing these guidelines, there is no indication as to how they apply to fuel design nor any indication if the current design conforms to these general guides.

Part 4 of Section 4.2 (i.e., Section 4.2.4), Research and Development, states that the "...adequacy of the RTDP for fuel development is an essential requirement for staff acceptance of the MHTGR concept." The staff concluded in the draft PSER that, "...the RDTP must be revised to demonstrate that a coherent and proven correlation exists between the fuel design's safety related capabilities and all possible postulated (accident) conditions." Therefore, review of the RDTP would be an essential exercise for finalizing the PSER.

Part 5 (i.e., Section 4.2.5) lists the principal MHTGR safety concerns related to the fuel identified for the draft PSER. These are listed and briefly described below.

2.2.1 Fuel Performance Models

Two main concerns cited are briefly interpreted as follows: (1) it needs to be shown that the fuel models tested on prior fuel designs apply as well to the current reference design; and (2) a question was raised regarding the validity of out-of-reactor heating tests for predicting in-pile accident condition behavior.

2.2.2 Fuel Performance Statistics from Laboratory Testing

Concern is expressed here regarding the ability to statistically verify the required low defect fractions for as-manufactured fuel by means of the planned experiments.

It is further stated that assurance of as-manufactured quality needs to be demonstrated in a way that is consistent with guidelines presented in 10 CFR 50, Appendix B, and SRP Section 4.2. Some comments regarding this section are the following:

1. Confusion may be present between the defect fraction of as-manufactured fuel and defect rates resulting from service conditions. These are two distinctly different considerations. Appendix B of 10 CFR 50 deals mainly with assurance of manufacturing methods. In contrast, the main thrust of SRP Section 4.2 is in-service performance.

2. Concerns regarding statistical methodology seem to be unwarranted. The fuel product is tested largely by pass/fail tests for which simple and well-established methods apply.

2.2.3 Manufacturing Quality

This section states that the QA and QC plans as well as the fuel acceptance criteria need to be reflected in the RTDP. Particularly, it is stated, the QC plan must contain an appropriate sampling scheme for particles and compacts. A comment on this section is:

- A significant problem relates to selection of the appropriate sampling scheme for fuel compacts. Does testing one compact constitute a sample of one, or a sample of about 5000, the number of particles in a compact? In addition, the availability of suitable QC tests for fuel compacts is a technical problem noted by Wichner and Barthold (1992).

2.2.4 Weak Fuel Particles

The staff defined "weak" fuel as particles with manufacturing defects as such that they do not fail in normal service, but fail "unexpectedly" during accidents. The request was made that failure models account for fuel weaknesses caused by manufacturing defects. The DOE response was that the current failure models account for such defects [i.e., the models are based on accepted (standard) fuel which includes both an allowable fraction of defects and manufacturing weaknesses.] This definition of "standard fuel" however differs from that of several DOE reports. A clarification of this point is essential.

2.2.5 Normal Operation Fuel Performance

This section recommends irradiation testing of the full scale fuel element (i.e., the fuel block). DOE's response was that capsule tests satisfactorily predicted FSV fuel performance hence MHTGR capsule tests should do likewise. (Specifically, capsule F-30, which was the proof test for FSV fuel, containing 13 full sized compacts, was cited as satisfactorily predicting FSV fuel behavior.)

In addition, concern was expressed that accelerated service tests may not be conservative (e.g., accelerated dose rate may lead to lower damage per unit fluence) or may alter failure modes. Comments follow:

1. Since completing the fuel element by insertion of fuel compacts into the fuel block involves no threat to the fuel, testing of the fuel element seems unnecessary, except for metrology, visual, and confirmation of fissile loading, as required by QA/QC procedures. (Analogously, LWR fuel bundles are not irradiation tested since, likewise, the fuel pins are not threatened by insertion into the assembly.) On the other hand, compact fabrication poses a serious threat to fuel particles. Therefore, it is important that the final irradiation validation tests on fuel be performed on the compacts.

2. The degree of conservatism, if any, in accelerated irradiation testing is an important issue which appears not to have been resolved. The technical issue is complex. Higher dose rates may result in lower damage per unit of fluence, as is the case with the steel alloy used for LWR pressure vessels. However, higher dose rates also result in higher temperature gradients, higher temperatures, and as a result, higher rates of fission product transport to the SiC. Therefore, the net effect of accelerated dose rates is still an open question. As a result, the NPR fuel program planned to include at least one capsule test to be conducted in real time (i.e., for up to three-years).

2.2.6 Fuel Element (FE) Cracking under Thermal Stress

The PSER quotes the modified DOE position on FE cracking, which briefly is,

1. Permit probability of limited cracking.
2. Limit FE stresses to below the mean strength of graphite.
3. Cracking probability should be sufficiently low such that the probability of functional damage to the FE is within the "risk allotment" of the core.

The NRC staff deferred judgement pending examination of the FSV FEs. (Is examination of the FSV FEs proceeding and to what extent?)

2.2.7 Ability of the Fuel to Withstand Accident-Induced Temperatures and Environments

2.2.8 Effects of Fuel Composition on Performance

2.2.9 Effect of Exposure to External Chemical Attack on Fuel Performance

This section states that accident testing of fuel should include representative environments of steam, oxygen, and nitrogen in concentration ranges dictated by accident sequence analyses.

It is further stated that the key impurities should be identified that need to be kept from entering the core, such as, chlorine and sodium hydroxide. Comment follows:

- It is not clear how impurities such as chlorine or sodium hydroxide can enter the core. This is possibly a non-issue.

2.2.10 Applicability of FRG Data

This section states that the extent and effect of the dependence of the DOE fuel behavior models on FRG data should be clarified. Comments follow:

1. The major differences between FRG and U.S. fuel design are (1) kernel composition of UO_2 relative to UCO for U.S. fuels, (2) the spherical fuel element shape relative to the cylindrical compact and hexagonal block fuel element in the DOE concept, and (3) minor differences in particle dimensions and protective coating layers.

2. Behavioral differences caused by different fuel fabrication equipment and techniques are more subtle. Since to a large degree fuel behavior depends on the extent and nature of minor manufacturing non-idealities, failure rates of FRG and U.S. fuel could differ significantly.

3. The planned FIMA at discharge is significantly higher for U.S. fuel relative to FRG fuel.

4. In sum, basing fuel behavior models on a combination of U.S. and FRG data may be sound on a theoretical level. However, validation tests need to be performed on the reference U.S fuel. Furthermore, because of the sensitivity of the fuel to subtle manufacturing variabilities, the validation testing should be performed on fuel manufactured by the planned commercial scale equipment.

2.3 Staff Conclusions for PSER Section 4.2

The staff noted that:

1. The DOE safety program relating to fuel behavior needs to be expanded and successfully executed.

2. A conclusion regarding the need for a conventional sealed containment vessel is deferred to the future.

3. SUMMARY OF NEW INFORMATION RELEVANT TO THE DRAFT PSER

3.1 Effect of Water Vapor on Fission Gas Release

3.2 Experiment HFRB-1: Analysis of the Water Injection Experiments

3.3 Preliminary Evaluation of Petten Fuel Hydrolysis Data

3.4 "MHTGR Fuel Performance and Supporting D   ase," Goodin (1989)

This brief report is written as a sort of a tutorial with boosterism overtones. It is not the type of technical report which would have an impact on licensing. Its message is (1) fuel "quality" has steadily improved over the past 20 years, and hence fission product retention has likewise steadily improved, and (2) current fuel performance models conservatively predict degree of radioactivity retention for both normal and accident conditions.

Isolated pieces of information are presented to support these contentions, some of which are cited here.

Figure 3.4-1 illustrates that the current MHTGR design has succeeded in reducing the normal operations exposure envelope of the fuel relative to both the FSV experience and the range of test capsule conditions, at least in terms of temperature and fast fluence.

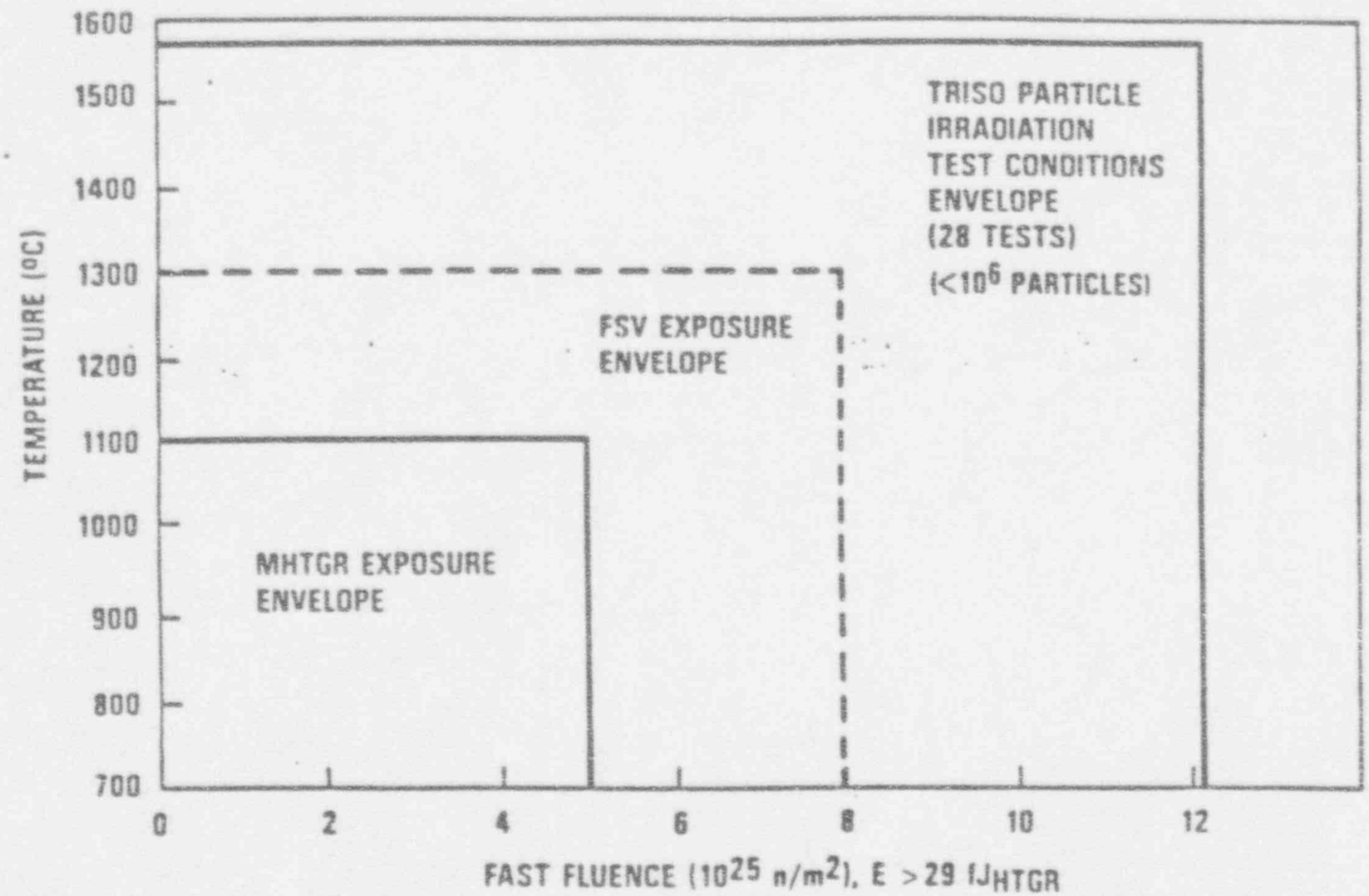

Fig. 3.4-1. TRISO irradiation data base extends far beyond MHTGR service conditions.

Figure 3.4-2 presents a useful summary of fuel irradiation test history including both German and U.S. test capsules. The intended impression is that the small MHTGR operating envelope has been well covered by numerous test capsules that go well beyond in fluence and temperature conditions. However, many types of fuel are included, both loose particles and in compacts. Also some of the capsules were intended for accident conditions; therefore, the accident conditions envelope should also be shown.

Figure 3.4-3 illustrates that radioactivity retention by FSV fuel, during this time period at least, was better than both model predictions and the "expected" release rate cited in the FSV FSAR.

Figures 3.4-4 and 3.4-5 illustrate the superior performance of fuel particles in German spherical fuel elements under two sets of simulated accident conditions: (1) temperature ramp tests up to 2500°C which show no particle failures below 2100°C, and (2) annealing tests which show no particle failures at up to 500 h of heating.

3.5 MHTGR Fuel Process and Quality Control Description

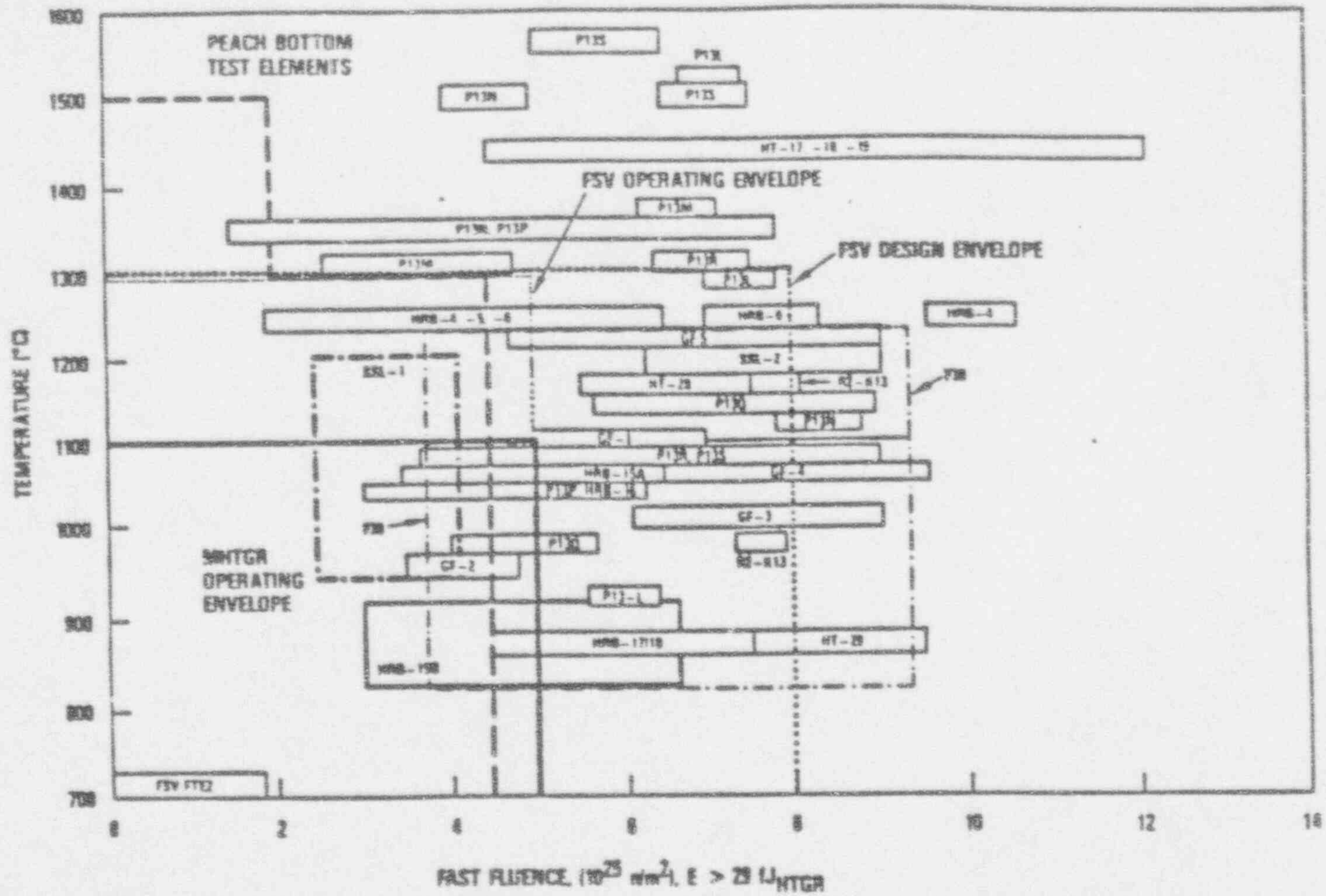

Fig. 3.4-2. TRISO irradiation data base includes irradiation and operating reactors.

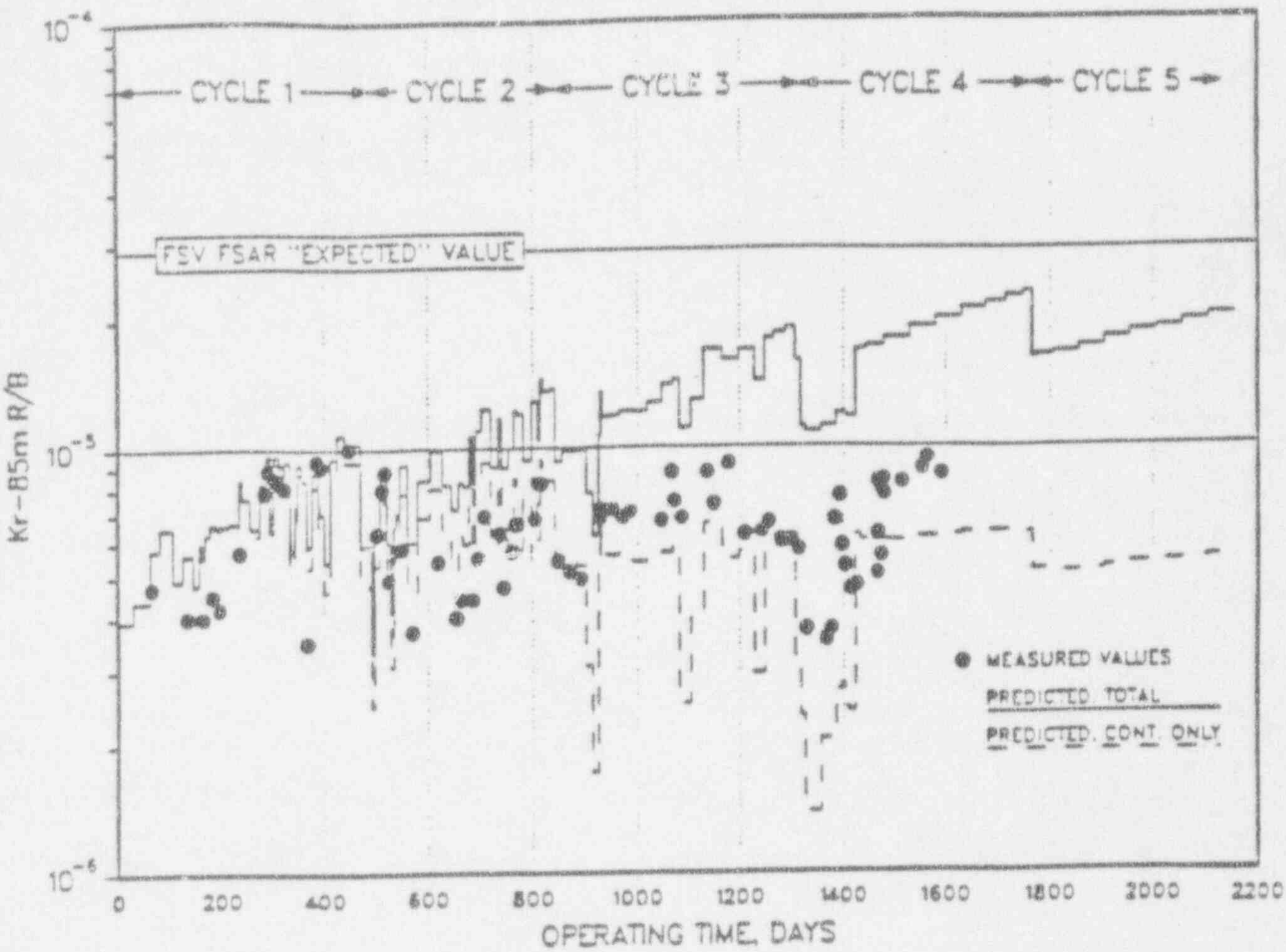

Fig. 3.4-3. Circulating activity measurements indicate that performance models based on accelerated testing are conservative.

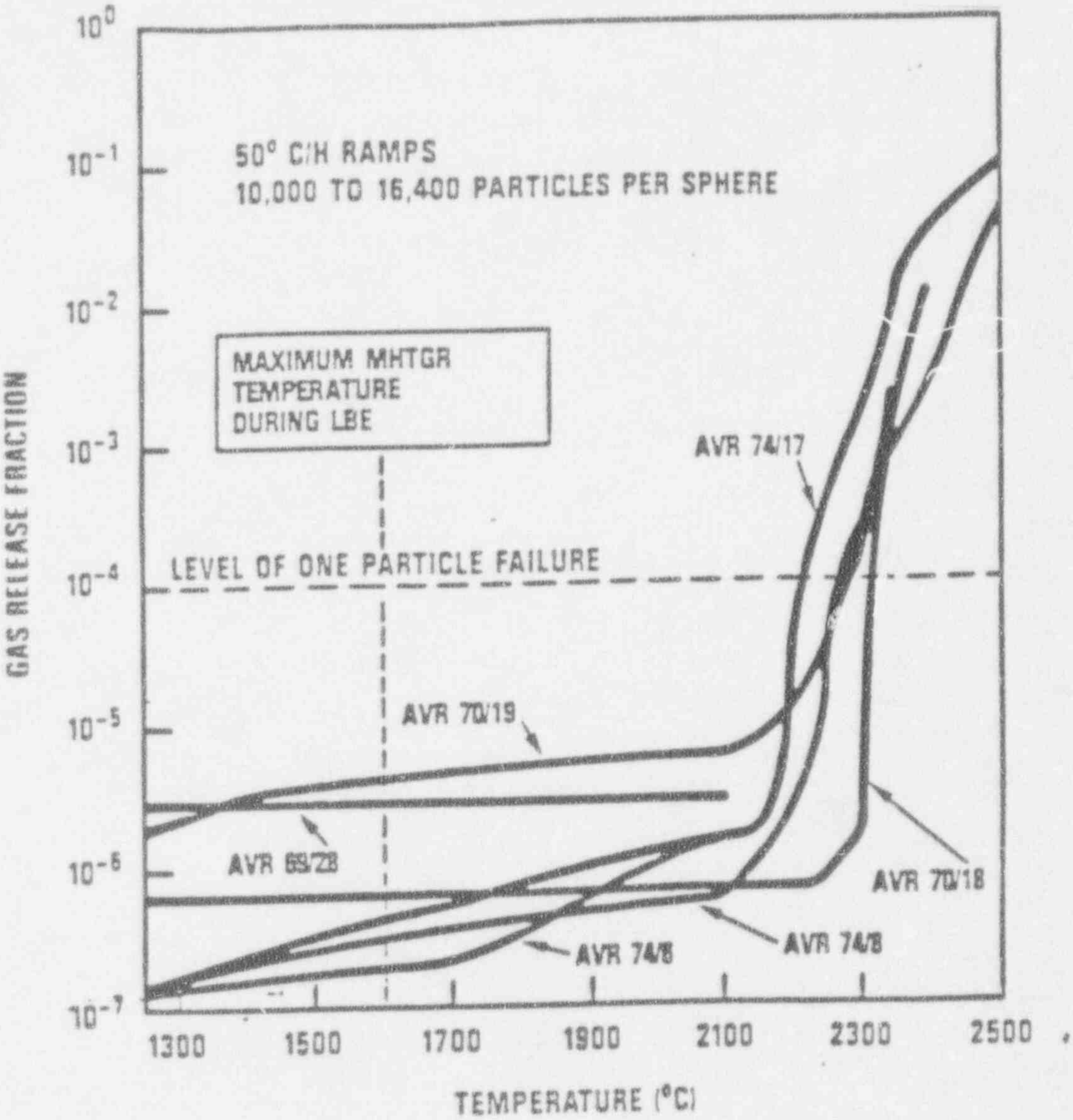

Fig. 3.4-4. FRG ramp tests to 2500°C show TRISO fuel contains radionuclides beyond MHTGR maximum conditions.

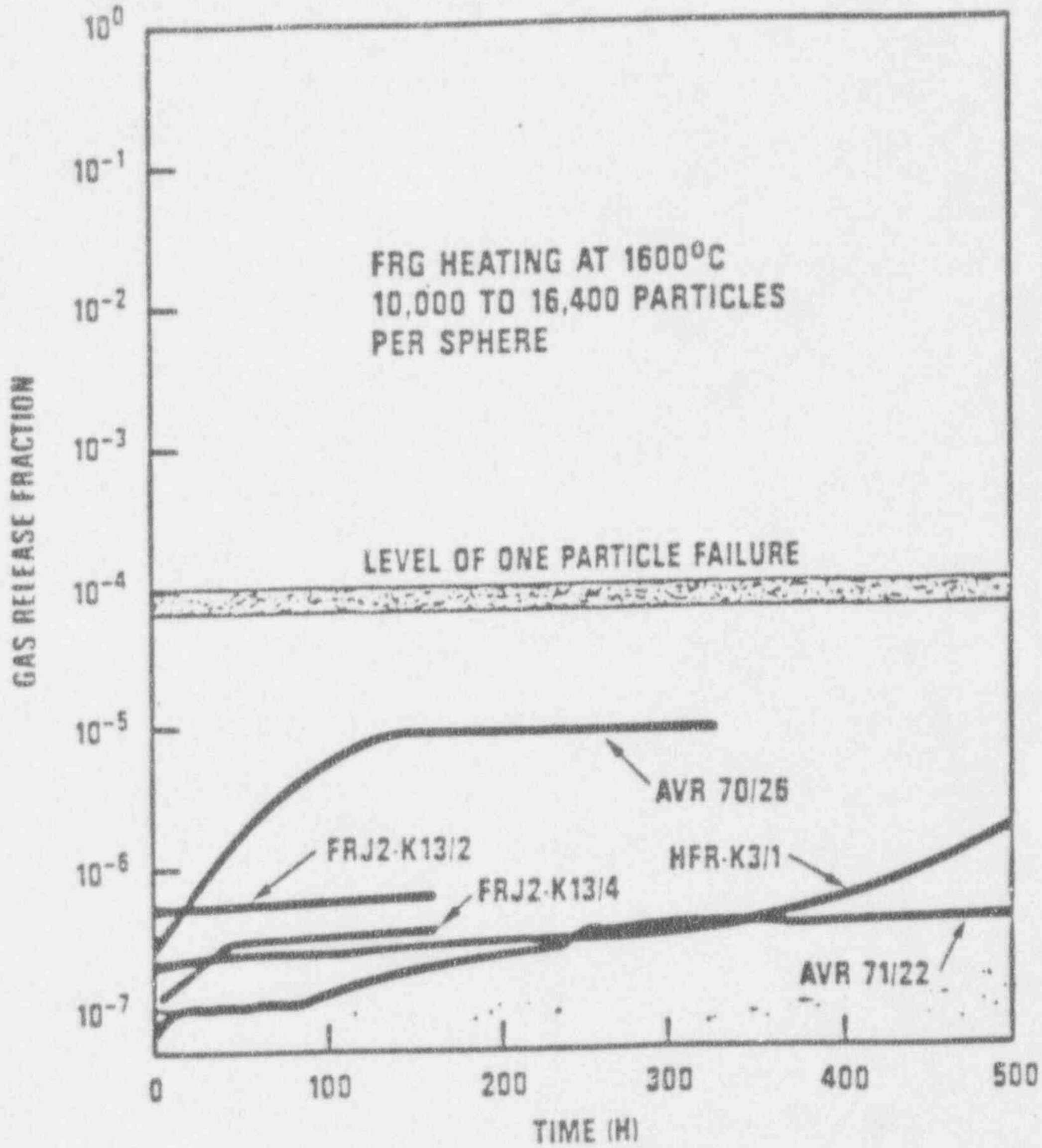

Fig. 3.4-5. FRG TRISO fuel heated under MHTGR conditions shows negligible gas release.

3.6 MHTGR Fuel/Fission Product Technology Development

3.7 Regulatory Technology Development Plan for the MHTGR

3.8 Technical Support Document of the MHTGR Fuel Production Specification

3.9 MHTGR Fuel Product Specification

3.10 "Evaluation of MHTGR Fuel Reliability," Wichner and Barthold (1992)

The principal objective of this study was to evaluate the basis of the proposed NRC concept of "weak fuel." In this concept the safety analysis is required to test the effect of higher source terms to the reactor building than the expected values predicted by fuel behavior and transport models. Motivations for the concept are: (1) the DOE proposal to use a non-sealed reactor building in lieu of a sealed containment vessel, (2) expression of fuel failure models in purely statistical terms, and (3) basing these models on data for fuel designs other than the current reference design.

The weak fuel concept in essence requires parametric testing of the source term to the reactor building through some range. The magnitude of the range is a reflection of the uncertainty in the fuel failure model. In its simplest application, the weak fuel concept assumes some selected higher fuel particle failure fraction during an accident than fuel models predict.

Evaluation of the basis of this concept required review of fuel manufacturing methods (Section 2), fuel failure mechanisms (Section 3), and QC procedures (Section 5). The principle conclusion of the study was that there are potential manufacturing defects that may lead to early fuel failure which may be overlooked by currently available QC procedures. Thus, there appears to be a sound reason for parametrically testing higher source terms to the containment than predicted by current models.

The following three types of manufacturing defects were identified as leading to early failure and which may escape detection by current QC method: (1) fuel particle damage caused by compact fabrication; (2) coating anomalies, e.g., HM dispersion, that may result in excessive SiC corrosion, and (3) fuel particle faceting. Further, due to the complex physics and chemistry of the fabrication process, there may be other failure mechanisms, enhanced by subtle manufacturing variances, that can contribute to early failure that were not recognized by this study.

The first two potential defects result from process flaws which should be identified by process control techniques and so documented by the QA system. However, should they occur through some system flaw, they may be missed by current QC methods. In particular, the lack of a suitable QC test for the fuel particles in the finished compact is deemed a significant handicap. The third defect type, particle faceting, has the effect of elevating mechanical stress on the coating layers thus leading to early failure.

In summary, the caution requested by the NRC with respect to the source term to the containment building, as expressed by the weak fuel concept, appears to have a sound mechanistic basis. The conservatism so imposed may be reduced or eliminated by improved confidence in fuel behavior models and improved QC methods.

Improved confidence in fuel behavior models may be achieved by augmenting the data base of current empirical models, and possibly restricting use of data for non-reference fuel designs. Alternatively, an improved reflection of manufacturing anomalies and their impact on failure mechanisms may serve the same purpose.

3.11 U.S./FRG Accident Condition Fuel Performance Models

3.12 Amendment 11

3.13 Review of Amendment 12

3.14 Recent NRR and RES Documents

In addition to the above-reviewed documents, recent work for the NRR under FIN L-1918 and for the RES under FIN A9477 should be recognized as potentially significant for an updated version of the PSER. Particularly, the following documents should be noted:

The letter report by Kueck and Gwantley (1992) describes the method for determining the safety classification of equipment for both the MHTGR and the NPR version. In addition, this report places the classification method in perspective relative to current industry practice.

The TER by Gwantley and Wichner (1992) discusses factors relating to vessel, cross-duct, and steam generator failure probabilities. These three vessel components make up the primary system boundary. Highlighted is the vessel support system, which is critical for the assessment of stresses in the cross-duct.

The letter report by Wichner (1992) to the NRR summarizes the MHTGR fuel design. The most current capsule data available at that time are summarized.

The likelihood of RCCS failure as a result of vessel depressurization into the reactor cavity was assessed by Smith (1992) in a TER to the NRR. A companion report by Chester (1993) assesses the effect of shock impacts on the RCCS.

A TER by Ball and Wichner (1992) performed for the RES evaluates containment design options described in the DOE report DOE-HTGR-88311.

A TER by Barthold (1993), which is currently in a final revision phase, describes and evaluates computer codes that are used to calculate MHTGR dose consequences.

The recent NUREG/CR by Smith (1993), performed for the RES, provides a realistic assessment of reactivity effects that result from steam ingress to the primary system. The significance of this study is that these new estimates indicate a far smaller reactivity response to steam ingress than earlier estimates that did not include the effect of ingress rate.

4. RECOMMENDED REVISIONS TO SECTION 4.1

As noted above in Section 2.1, part 4.1 of the draft PSER currently provides a fairly brief overview of the MHTGR system. In this report format, more complete and focused descriptions of system parts may be provided in Sections 4.2 through 4.5, which deal respectively with Fuel, Nuclear Design, Thermal Hydraulics, and Reactor Internals.

All of these subsections are within Chapter 4 entitled, Reactor, which is taken to mean are components within the reactor vessel. Closely related is Chapter 5 entitled, Vessel and Heat Removal Systems, which includes consideration of the vessel, and the vessel support system. Also closely related to Chapter 4 are Chapters 11 and 12, which cover radionuclide control under normal operation, and Chapter 15 which gives results of accident conditions.

In this context, Section 4.1 should provide an overview of the reactor system within the reactor vessel, with care to cover safety-related areas that are detailed in following subsections.

This is fairly close to the current contents of Section 4.1. An updated section 4.1 perhaps should consider adding discussion of safety related components within the vessel, citing information developed by Kueck (1992). Providing the safety classification of each in-vessel component should be considered. In addition, a somewhat more logical arrangement would be to incorporate the general description of the fuel, that is now included in Section 4.2.1, into Section 4.1. This would permit discussions in Section 4.2.1 to be less general descriptive and more safety focused.

The statement in the first paragraph regarding the objectives for the relative locations of the reactor vessel and the steam generator should be reviewed. The purpose is not to reduce convective cooling of the core, as stated.

5. RECOMMENDED REVISIONS TO SECTION 4.2

Reference should be made to Section 2.2 of this report which briefly summarizes Section 4.2 of the PSER.

5.1 Possible Revisions to Section 4.2.1

The general description of the fuel, as given in the initial four paragraphs of Section 4.2.1 and Figs. 4.3 and 4.6 may be more appropriate in Section 4.1, which is devoted to a general description of the system. Section 4.2.1 should possibly be reserved for detailed features which directly bear on safety issues.

The discussion of fuel failure modes should be more completely dealt with, possibly by following the outline appearing in Wichner and Barthold (1992). This should apply to both failure mode in normal service and accident condition failure modes. In addition, description of the types of as-manufactured and in-service failures needs to be discussed in a complete and organized way. Information in Fig. 4.5 should be clarified. The definition of "standard particle," used in the figure to depict a particle with no manufacturing defects, should be rendered consistent with other sources, e.g., Scheffel and Tang (1989).

The discussion on the interrelation of manufacturing defects with expected in-service behavior should be re-examined for completeness. Possibly some discussion of the fuel manufacturing process taken from Bresnik (1991) may be included, with emphasis on the types of manufacturing defects that can be produced and their effect on fuel behavior. Wichner and Barthold (1992) also discusses this area.

The discussion on fuel failure and performance models may need updating using information in Goodin and Nabeilek (1985), and Goodin (1987, 1989).

5.2 Possible Revisions to Section 4.2.3

In this section, the PSER deals with application of design criteria to fuel manufacture in a very general way. It may be preferable to render this more specific by citing the top level goals which impact fuel behavior, and the particular criteria for fuel behavior which are intended to satisfy those goals. Information in Tang (1989) on fuel product specification could be added here. Wichner and Barthold (1992) present a discussion which indicates that some of the performance criteria may only marginally satisfy the stated top-level goals. This should be resolved.

5.3 Possible Revisions to Section 4.2.4

The PSER states that this section, which deals with fuel R&D, is particularly sensitive in view of the proposal to omit the traditional sealed containment vessel as one of the defense-in-depth barriers. The quote is "Thus the RTDP must be revised to demonstrate that a coherent and proven correlation exists between the fuel design's safety-related capability and all the possible and postulated conditions the fuel may be exposed to."

Therefore, it is essential to revisit this issue by evaluation of the newer document, Regulatory Technology Development Plan (RTDP), DOE-HTGR-86-064. This needs to be done in conjunction with an updated recognition of normal and accident-induced failure mechanisms.

5.4 Possible Revisions to Section 4.2.5, "Safety Issues"

This section discusses 10 safety issues relating to fuel behavior. Each needs to be re-evaluated in the light of newer available information. In addition, possible omissions should be noted and included.

A. Fuel Performance Models

At least three reports that are newer than the latest used in the PSER are currently available, Goodin and Mabeilek (1985) and Goodin (1987 and 1989).

B. Fuel Performance Statistics

Statistical methodology seems to be well established such that this item as a safety issue may not be necessary. (One related consideration, however, may be significant. Namely, do tests on a compact count as one test or as 5000, the approximate number of particles in the compact?)

C. Manufacturing Quality

This short section on QC methods needs to be updated using information in Scheffel and Tang (1989) and Bresnik (1991). An evaluation of QC methods also appears in Wichner and Barthold (1992).

D. Weak Fuel Particles

The conservative concept of the "weak fuel particle" proposed by the NRC was evaluated by Wichner and Barthold (1992) which may modify the discussion in the PSER. The text indicates that this issue needs to be re-evaluated and concluded.

E. Normal Operation Fuel Performance

This issue is significant for safety because it affects the quantity of radioactivity outside of the fuel immediately available for release to air during an accident. However, no recent document deals explicitly with this subject. Preliminary reports from recent capsule irradiations on putative reference fuel (capsules HRB-21, NPR-1, NPR-2, and NPR-3) indicate far poorer results that anticipated. Wichner (1992b) describes some early results. The most current information on these tests needs to be acquired for the final SER. It is not clear how issues raised as a result of the poor performance in these tests will be resolved.

F. Fuel Block Cracking

The PSER deferred judgement in this area pending examination of Fort St. Vrain fuel elements. However, no new information seems to have appeared.

G. Ability to Withstand Accident-Induced Environments

The PSER calls for accident condition testing of fuel in the temperature range up to 2000°C. Such tests are currently in process and have not yet been reported on, except for equipment description and calibration. The PSER also judges that some of these tests should include air and moisture environments. For the SER, the scope of these current tests should be reviewed (outlined in the RTDP) and the most current test results acquired.

H. Effect of Fuel Composition on Performance

This section notes that tests on high-enriched fuel form a large share of the data base for formulation of fuel behavior models. Since chemical attack on the SiC layer is an important failure mechanisms, the question is raised whether or not the different fission product yields for the LEU fuel would create different results. This issue may be resolved by examination of the RTDP and judging the adequacy of the testing program.

I. Effects of Exposure to Chemical Attack

The principal concern relates to the effects of moisture on exposed fuel. This issue is the subject of recent reports by Myers (1991a, 1991b) and Richards (199Oa, 1990b). Hydrolysis testing of fuel has not yet been completed, and reports will continue in this series.

The PSER concerns regarding the effects of sodium hydroxide and chlorine need to be reviewed for validity. In addition, the PSER calls for accident testing in an air atmosphere. It is not clear if such tests are currently planned.

The recent report by Smith (1993) should be noted in discussion of hydrolysis environments.

Some discussion should perhaps be included in the SER on the subject of steam attack on materials other than exposed fuel. For example, the possible weakening of intact fuel by steam resulting in altered response to subsequent accident conditions may be an issue.

J. Applicability of FRG Data

The recent documents by Goodin (1987, 1989) describe the manner in which FRG data are applied to accident condition model development. In addition, the report by Martin (1993) summarizes the current accident condition data base.

However, the main thrust of the discussion in this section of the PSER needs to be re-examined. Use of FRG data is strongly advocated, but this must be done in a carefully selected manner in view of the significant differences between FRG and US reference fuel.

5.5 Further Comments to PSER Section 4.2

The following comments on possible revisions to PSER Sections 4.2.1 through 4.2.4 and 4.2.6 by one of the authors (W. P. Barthold) were made available too late for incorporation into the text. These comments are included here as submitted.

"4.2.1 Design Description and Safety Objectives

In the second paragraph of page 4-3, it should read "higher concentrations of fissile material" and no "heavier ...."). In the same paragraph is stated that the zoning ensures that "a maximum fuel temperature of 1250°C is not exceeded," but the calculated maximum is 1330°C. No hot channel factors included!

In the third paragraph is stated that "the fuel safety objectives for the MHTGR are more demanding (than for FSV) because the fuel-particle coatings are considered by the safety analysis to be the primary fission-product containment barrier." However, this is also true for FSV.

The 4th paragraph states that the SiC coating is known as TRISO. It should read that theparticle with this coating is known as TRISO particle.

The last paragraph should be reworded. It says that radionuclides are retained within the particle coatings under all postulated conditions. And then proceeds saying that offsite doses come from radionuclides that escaped the fuel kernel barriers. Instead, it should state that tha RN are retained within "intact" coatings.

On page 4-4 the term "unprotected particles" is introduced that should be avoided (use, for example, the term exposed kernel).

The discussion of manufacturing defects and particle failures should be strengthened. In its present form, it can be misunderstood.

The statement that the IPyC is impermeable to gases needs to be qualified. The IPyC is not expected to be a barrier. Actually, it is expected to fail during normal operation.

The statement that pressure-induced failures are negligible except when the OPyC layer is missing is misleading. I don't know how well one can draw a distinction between a failed OPyC and a missing OPyC. Three percent of the OPyC are expected to fail during normal operation. This does not mean that 3% of the SiC layers will also fail. It is my understanding that all OPyC in HRB-21 have failed, but not the SiC layers.

4.2.3 Review and Design Criteria

In regard to your comments: it needs to be shown by the applicant how the current design conforms to the general guidelines, not by the NRC.

4.2.4 Research and Development

It is stated correctly that the review of a revised RTDP is essential for finalizing the PSER. This means it would have to be done before the PSER is issued - and should then not be referred to anymore in the PSER as a NRC task.

4.2.5 Safety Issues

The statement in the draft PSER that "the analysis and resulting correlations should not be based on an interpretation or extrapolation of earlier fuel design" implies that only experiments with the current fuel design would count. This has far-reaching implications. It would be at odds with later statements as to the use of, for example, German data. I think that a qualifier should be included that emphasizes validation with new data and calls for new data whenever older data are not applicable. There are many correlations for fuel performance analysis that are not very design-dependent.

A. Fuel-Performance Models

In regard to out-of-pile high-temperature tests, I think the NRC makes a valid point. After fuel is removed from the reactor, it can take years until it is placed into a furnace for hightemperature tests. During this time, some of the fission gases might escape from defective particles. However, what is measured in heatup tests are failures that occur during the heatup.

B. Fuel Performance Statistics from Laboratory Testing

I suggest to use in your comments under (1) the term "failure rates of defective fuel ..." rather than "defect rates resulting from ...".

I think the text under (2) addresses only part of the issue, namely fuel product statistics. What the PSER seems to be focusing on is fuel performance statistics. Issues that come to mind are the number of particles in a capsule test at a specific temperature, burnup, and fluence as well as the accuracy with which the experimental environment can be characterized.

C. Manufacturing Quality

I am not sure if I understand what it means that the QA/QC plans and acceptance criteria need to be considered in the RTDP, as stated in NUREG-1338. Clearly, one has to know all the parameters that characterize the fuel that has been irradiated to draw any meaningful conclusions from the test results. Is this the issue?

A separate issue is that of QC standards, If a QC technique is used to characterize the fuel, how well does it characterize the fuel (i.e., against which standard can this technique be calibrated?).

D. Weak Fuel Particles

The NRC definition is different from the one we used. We looked at it as a penalty to account for the lack of data and experience. The NRC mentions the tails of the distribution curve and wants a QA program to detect weak particles.

I suggest to reword the last sentence in your comments: "models are based on accepted (reference) fuel which includes both ..." rather than using the term "standard" fuel that implies no manufacturing defects.

E. Normal Operation Fuel Performance

I think the meaning of proof testing is misinterpreted. It is not to show weaknesses in fuel integrity by long-term exposure at NOC (page 4-10) but to demonstrate that what has been learned from separate effects tests done with lab-scale fuel is applicable to production-type fuel.

Testing of block vs compact fuel is a separate issue. It should be noted that there are potentially significant differences in regard to the fuel and graphite temperature distributions which in turn affect metallic fission product transport. I agree that the potential for damage by inserting fuel compacts into graphite blocks is very small. But there are other issues that need to be considered, too.

The reference to FSV testing mentioned in the PSER should be removed.

In regard to the degree of conservatism [your item (2)], there is an additional issue. The diffusion equation used to calculate metallic fission product transport does not contain a term that accounts for the temperature gradient as a driving force for transport. In COPAR (and TRAFIC) it is argued that this approximation is justified because of the very small temperature gradient from the particle center to the particle surface under normal reactor operating conditions. However, if the temperature gradient in the test is 25 times higher than in the reactor, this approximation might not be justified anymore. It should be noted that the temperature gradient term is included in the calculation of transport in the compact.

If the diffusion process is driven by concentration <u>and</u> temperature gradients but interpreted as only dependent on the concentration gradient, misleading results can be obtained.

G. Ability of Fuel to Withstand Accident-Induced Temperatures and Environments

It should be noted that accident temperatures are synonymous with depressurization accident temperatures for a shutdown reactor (i.e., no transient overpower events are considered).

If predicted temperatures can go as high as 1800°C, I think it is prudent to test up to 2000°C. The GA temperature calculations are all based on nominal calculations for what GA perceives as the most constraining accidents.

In regard to SiC "failure": enhanced diffusion is possible due to increased porosity in the SiC coating as a result of fast neutron bombardments.

H. Effects of Fuel Composition on Performance

In regard to (3) "representative fuels": MHTGR fuel has different enrichments due the varying dilution with graphite. The effect of thorium/uranium-233/Pa-233 because of its decay heat production might have an effect on out-of-pile fuel that is awaiting heatup; but it is probably insignificant.

I. Effect of Exposure to External Chemical Attack on Fuel Performance

Item (1): chlorine could be still present from the fabrication process.

2.3 Staff Conclusions

The NRC identifies a list of activities that need to be addressed for the finalization of the PSER. Among them is a review of the new RTDP, probably some data base assessment, model assessments, and QC assessments in more detail. The staff conclusions will be affected by the outcome of these evaluations."

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