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FUEL PERFORMANCE MODELS FOR HIGH-TEMPERATURE GAS-COOLED REACTOR CORE DESIGN

by
O. M. STANSFIELD, W. A. SIMON, and A. M. BAXTER

Prepared under
Contract DE-AT03-76ET35300
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ABSTRACT

Mechanistic fuel performance models are used in high-temperature gas-cooled reactor core design and licensing to predict particle failure and fission product release.

Failure of particles from the thermochemical effects of the fission product - SiC reaction and kernel migration is limited by the reactor design to less than 10^{-4} fraction and is insignificant with regard to fission product release. The fission product - SiC reaction is more limiting than kernel migration on the allowable operating temperature of the fuel. Heavy metal contamination is the source of about 60% of the circulating activity and is the major source of released fission gas. The second largest source is from failure of about 5×10^{-4} fraction of particles during service. Failure of particles with defective buffers contributes 35% of the circulating activity, and pressure vessel failure of standard particles contributes 5%. Clearly, reduction in fuel contamination and the amount of fuel with missing or defective buffers appears to be the most effective way to attain lower fission product release.

Fuel particles manufactured with defective or missing SiC, IPyC, or fuel dispersion in the buffer fail at a level of less than 5×10^{-4} fraction. These failed particles primarily release metallic fission products because the OPyC remains intact on 90% of the particles and retains gaseous isotopes. The predicted failure of particles using performance models appears to be conservative relative to operating reactor experience.

Future development will focus on improved characterization to better identify the design margin of safety to assist the design and licensing effort.

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FIGURES (Continued)

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I. INTRODUCTION

The reference fuel cycle for the high-temperature gas-cooled reactor (HTGR) employs low-enriched uranium and thorium (LEU/Th). The fissile fuel is a two-phase mixture of 20%-enriched UO_2 and UC_2, usually referred to as UCO, even though the oxygen to uranium ratio is nominally 1.7. The fertile fuel is ThO_2. Both fertile and fissile fuels are in the form of dense microspheres coated in a fluidized bed with a TRISO[a] coating (1) whose primary purpose is to retain fission products. The coated fissile and fertile particles are blended and bonded together with a carbonaceous binder into the form of fuel rods, which are placed into fuel holes in a helium-cooled graphite fuel element. Figure 1 illustrates the TRISO coating concept and how the fuel is packaged in the fuel element. Details of the TRISO particle design are given in Table I.

Changes in national and international economic, technical, and proliferation restraints have resulted in consideration of a number of HTGR variants with different design requirements. The resulting evolutionary changes in design parameters, e.g., power density, temperature, enrichment, and breeding ratio, have influenced fuel technology. Performance models that guided core design as well as fuel and process development were developed that reduced the extent of time-consuming and costly fuel testing programs. Use of these performance models to predict the expected fuel failure and fission product release allowed the development of optimized designs for the different applications and constraints.

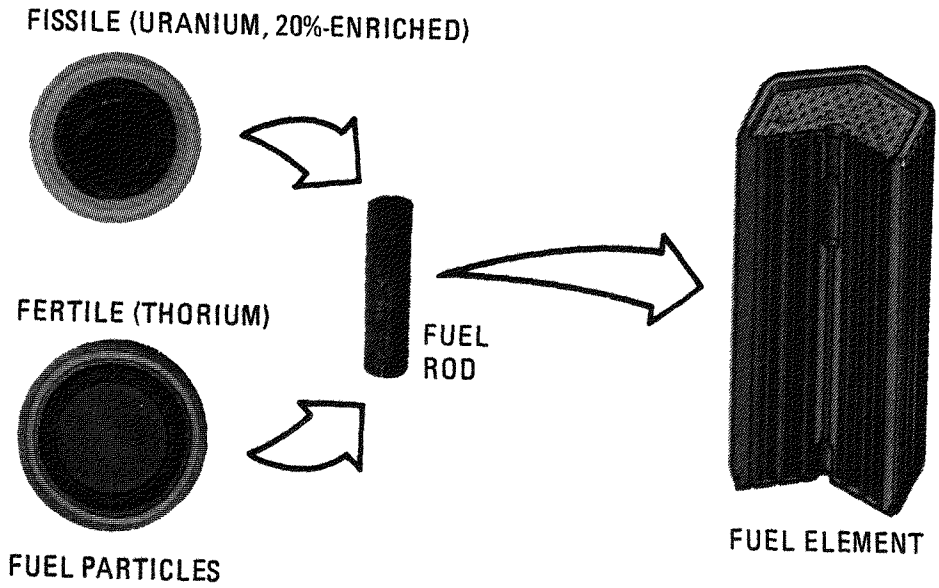

Fig. 1. HTGR fuel element components

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TABLE I
TRISO PARTICLE DESIGN

Property	Kernel	Buffer	Coating		
			Inner Isotropic (IPyC)	Silicon Carbide (SiC)	Outer Isotropic (OPyC)
LEU fuel (20% U-235 enriched)					
Composition	$UC_{0.3}O_{1.7}$	--	--	--	--
Density (Mg/m^3)	11.0	1.0	1.90	3.20	1.87
Mean diameter or thickness (μm)	350	115	35	35	40
Fertile fuel					
Composition	ThO_2	--	--	--	--
Density (Mg/m^3)	9.8	1.0	1.90	3.20	1.87
Mean diameter or thickness (μm)	500	80	35	35	40

The predicted fuel failure for the SC/C HTGR[b] is between 10^{-4} and 10^{-3} fraction. The fact that more than 10^4 particles can be simultaneously tested makes it possible to predict and measure such small failure fractions with high statistical confidence.

The HTGR fuel development effort has been international in scope, and although fuel failure models published by different contributors differ somewhat in detail, they have the same general form (2-19). A single generic performance model for each failure mechanism has been developed using this experience base and is used in the U.S. HTGR design effort.

The purpose of this paper is to provide a brief description of the models and their use in core design for predicting fuel performance under the normal equilibrium and transient conditions (temperature <1600°C) expected in HTGR operation. The model for fuel performance under accident conditions (temperature >1600°C) is described elsewhere (20).

II. DESCRIPTION OF PERFORMANCE MODELS

II.A. Source of Fission Product Release

Fission product release from HTGR fuel under normal and transient operating conditions is derived from the following five sources:

1. Coating damage during fuel manufacture, resulting in heavy metal contamination on coating surfaces and in the fuel rod matrix.

2. Pressure vessel coating failure in particles with defective or missing coating layers.

3. Pressure vessel coating failure in standard particles.

4. Failure of the SiC coating caused by reaction with fission products.

5. Failure due to kernel migration and interaction with the coating.

The precise mechanistic description of these failure mechanisms is very complex, but relatively simple approximations for predicting failure fraction have been developed and are described below.

II.B. Heavy Metal Contamination

Damage to fuel coatings can take place as the particles are transferred from one stage to another during coating and fuel rod manufacturing. If such damage is sufficient to expose the kernel, the heavy metal material, fissile or fertile, can be dispersed as contamination over the surfaces of particles and fuel rod matrix in subsequent processing.

The heavy metal (HM) surface contamination is typically the largest contributor to circulating fission gas activity because fission gases are rapidly released into the coolant. For example, 30% of Kr-85m produced in surface contamination at 1100°C is released before it decays (21, 22).

The amount of HM contamination in the manufactured fuel is controlled by process techniques and specified quality. The specified limit on HM contamination of $<10^{-4}$ (HM exposed/total HM in fuel) represents the acceptance of a practical manufacturing capability. The larger the amount of exposed fuel and associated fission product release, the more restrictive the requirements for fuel design and specification to minimize in-service fuel failure and to comply with core fission product release design criteria.

The contribution of HM contamination to circulating activity of the HTGR is modeled to allow prediction of the release of gaseous isotopes. The release rate of important isotopes is determined relative to the total birth rate in each portion of the core $(R/B)^c$. Contamination in the fuel releases gaseous isotopes at 1100°C in accordance with the empirical relationship for xenon and krypton isotopes shown in Fig. 2 (22, 23). In this and subsequent empirical relationships, the extensive data base has been omitted to show the design curve clearly. Detailed documentation of the data is found in the references.

The relationship shown in Fig. 2 makes a simplifying and conservative assumption that isotopes in the same periodic row that are gaseous at operating temperature have similar properties. Consequently, iodine and tellurium are assumed to behave like xenon, and bromine and selenium like krypton. Prediction of gaseous release in portions of the core at temperatures other than 1100°C is made by applying a temperature-dependent correction for R/B obtained from the empirical relationship shown in Fig. 3 (22, 23).

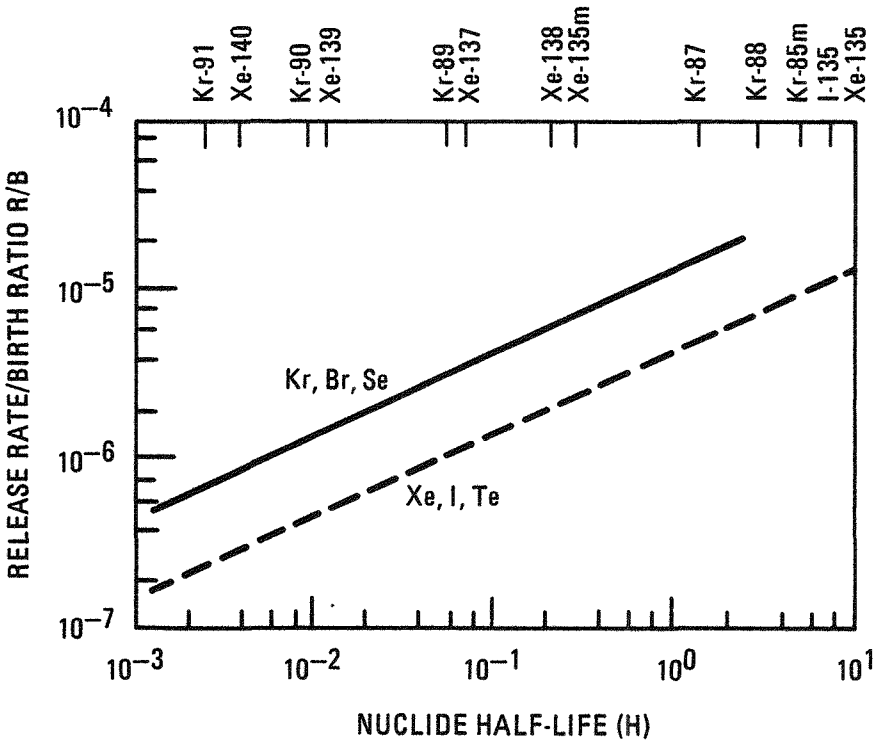

Fig. 2. Fission gas release from 10^{-4} fraction heavy metal contamination in as-manufactured fuel at 1100°C

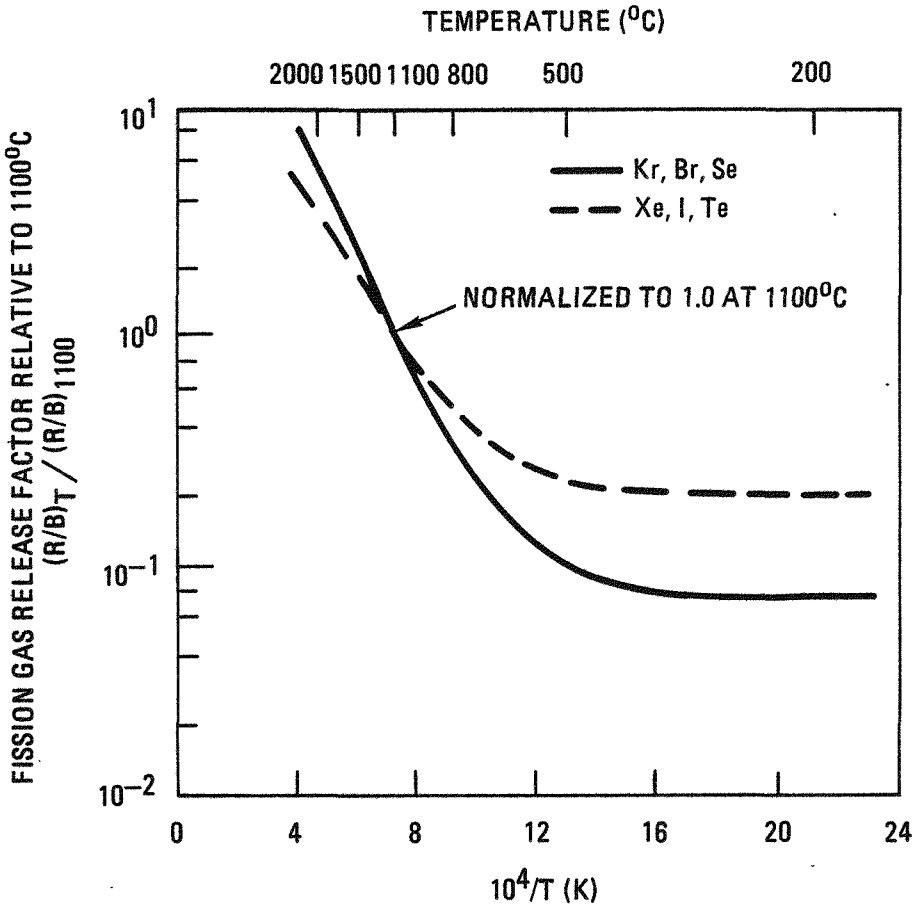

Fig. 3. Temperature dependence of normalized fractional fission gas release $(R/B)_T/(R/B)_{1100}$ from contamination in fuel

II.C. Missing or Defective Coatings

The term "missing or defective coatings" refers to particles having at least one intact coating and one or more missing or defective coating layers. An example of such a particle is a TRISO-coated particle having at least one intact PyC or SiC coating and a missing buffer layer. Particles having missing or defective buffer or PyC coatings do not release fission gas upon initial irradiation, but the intact coatings eventually become overstressed and fail prematurely as fission gas accumulates. Particles with missing or defective SiC layers can release volatile metallic fission products such as cesium, but if the OPyC layer is intact, short-lived gaseous fission products such as Kr-85m are retained. Less than 10% of the OPyC coatings on defective SiC fail under peak core conditions (24). Therefore, the contribution of a small population of defective SiC coatings to circulating gaseous activity is not significant in HTGR design. The fraction of missing or defective coatings is limited by fuel specifications in a manner consistent with practical manufacturing capability and core design requirements.

The model describing the behavior of defective TRISO particles is based primarily on pressure vessel analysis. This model predicts the increasing probability of failure with increasing burnup in particles with missing or defective buffer and OPyC coatings. A simplifying assumption of neutron fluence independence is made using a conservative bounding model, considering the failure fraction of each type of defect, as shown in Fig. 4. In this model, failure of all particles with missing or defective buffers

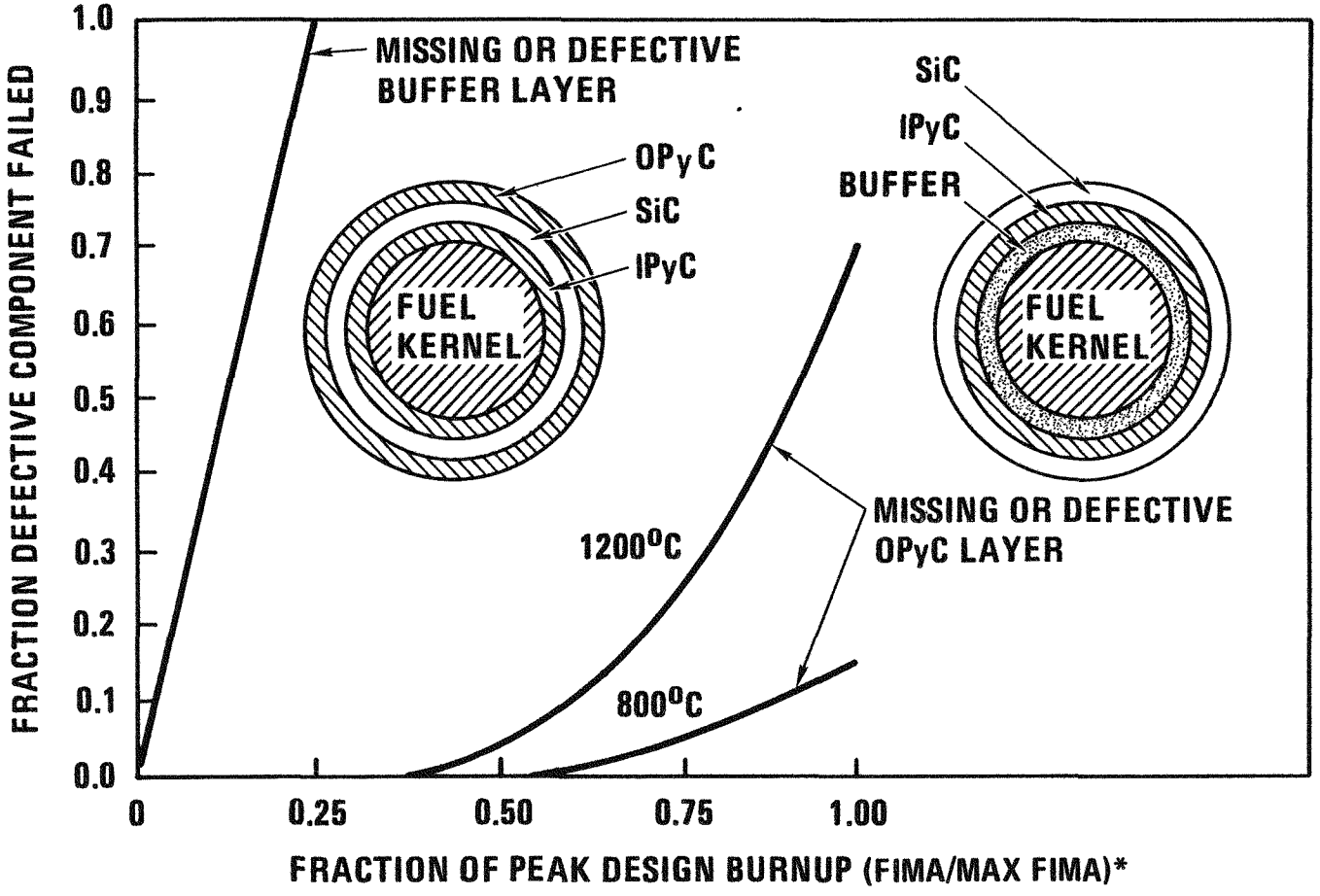

Fig. 4. Defective particle model for failure resulting in both gas and metal release

occurs at 25% of design burnup; missing or defective OPyC has a more delayed effect, with some temperature dependence. Coating failure from defective buffer and OPyC is less than 5×10^{-4} fraction and results in both gaseous and metallic fission product release, because no coating barrier remains after failure.

Defective particles whose failure results in only metallic release because of a retentive OPyC are those with (1) missing or defective SiC, (2) missing or defective IPyC, or (3) fuel dispersion into the buffer, which can lead to accelerated SiC attack by fission products. Particles with defective IPyC and fuel dispersion are modeled to fail linearly with increasing burnup, and particles with defective SiC fail at the onset of irradiation, as shown in Fig. 5. Failure from these two effects is predicted in less than 5×10^{-4} fraction of fuel particles.

II.D. Standard Particle Pressure Vessel Failure

Standard particles are those without the defects discussed in the previous section. Pressure vessel failure can take place in standard fuel because the statistical nature of the chemical vapor deposition coating process combines the largest kernels with the thinnest buffers in a small fraction of particles. The gas pressure buildup in these particles during irradiation is much greater than in the rest of the population, and the probability of pressure vessel failure is greatly enhanced. If there were no variation in particle component dimensions, a standard particle design could be established with no predicted failure. However, volume fraction

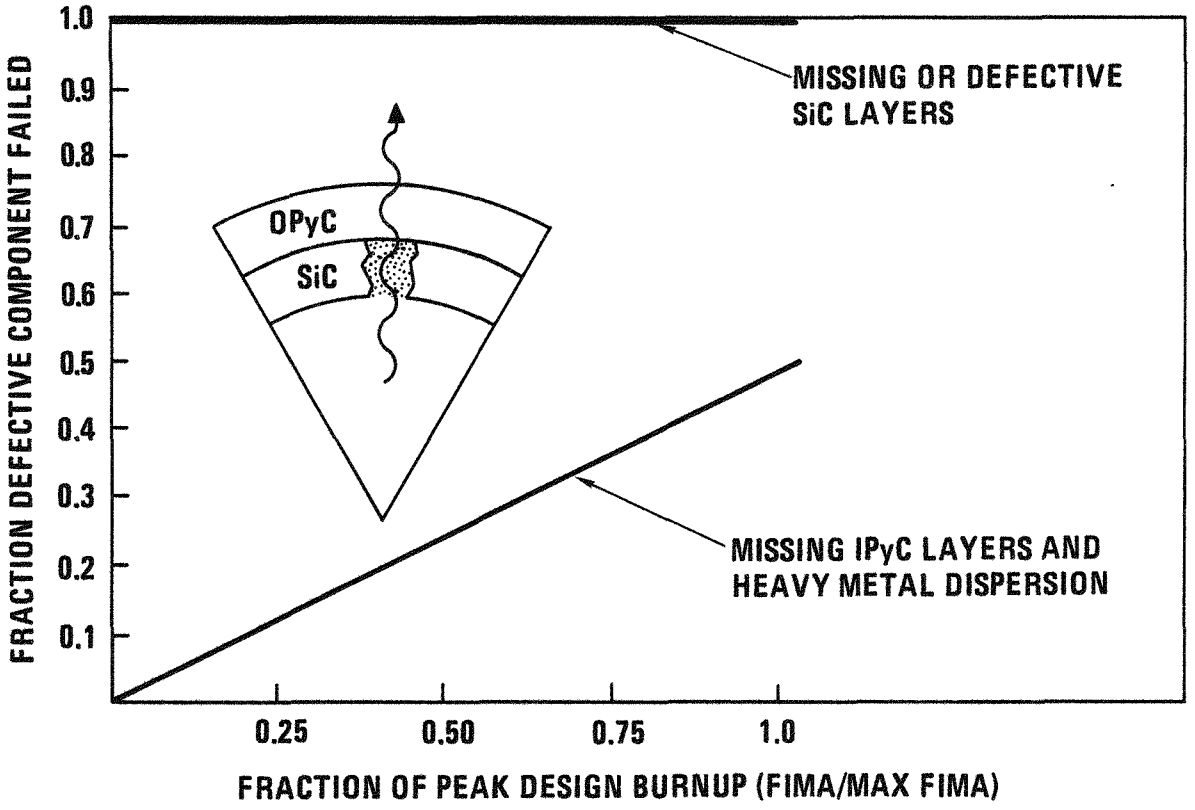

Fig. 5. Defective particle model for failure resulting in only metal release

limits imposed by high HM loading requirements make it impractical to avoid failure in standard particles entirely by use of coatings thick enough to overcome these statistical considerations. Consequently, a fuel particle design is defined by considering variation in particle dimensions and other critical coating properties. The probability of failure for a given design is calculated by using analytical stress models. The Monte-Carlo calculational routine in the model treats the observed variation in coating layer thickness and kernel volume (2, 17). Similar models have been developed and used in the British and West German HTR programs (15, 25).

The analytical model accounts for the buildup of fission gas pressure and kernel volume increase due to solid fission product production. Shrinkage of the OPyC and consequent compressive stress component on the SiC are also treated. When the tensile stress in the SiC resulting from internal gas pressure exceeds a single critical value (SiC fracture strength), the SiC and both PyC coatings are assumed to fail. Figure 6 gives an example of the pressure vessel failure predicted in standard fuel as a function of temperature and burnup.

A simplifying compromise in the model is the assumption of SiC failure upon exceeding a unique critical tensile stress obtained by normalizing model prediction to observed failure in irradiation tests (17). The merit of using the true statistical distribution for SiC strength as appropriate for a brittle material rather than a single value has been demonstrated (25). Additional development of the pressure vessel model is under way to remove conservatism, account for the statistical variation in coating

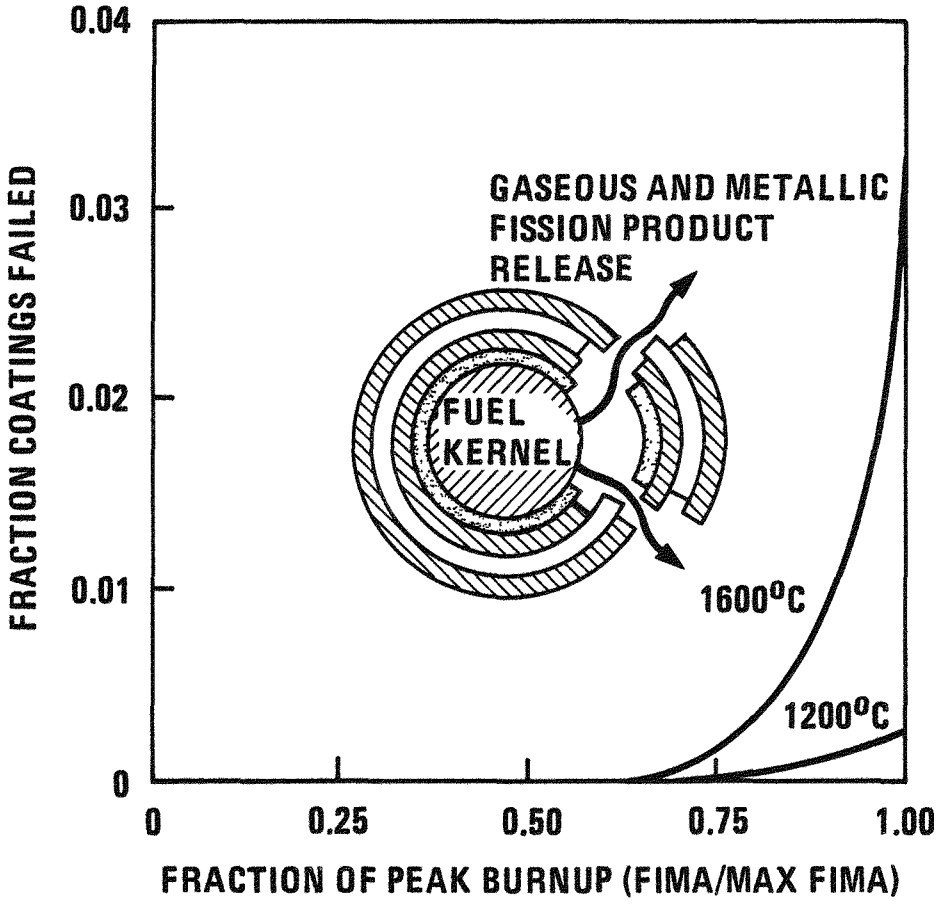

Fig. 6. Pressure vessel failure model illustrated at 1200° and 1600°C

strength, and make model predictions more realistic. During the interim period, the simplified model discussed above is used in core performance calculations to define a conservative envelope for fuel performance.

II.E. Fission Product - SiC Interaction

Fissioning of uranium and plutonium produces lanthanide and palladium fission products, which are known to react with the SiC coating if they are released from the kernel (26, 27, 28, 29). In UC_2 kernels, the lanthanides are released, migrate down the thermal gradient, and attack the SiC on the cool side of the particle. In oxide-based fuels, the lanthanide fission products such as cerium, praseodymium, and neodymium tend to be retained in the kernel as refractory oxide compounds. However, palladium, which does not form a strong carbide or oxide compound, is released from oxide and carbide kernels such as UC_2, UO_2, UCO, and ThO_2 and reacts with the SiC coating. Palladium attack of SiC contributes to coating failure by degrading the structural integrity of the layer. It is the limiting thermal failure mechanism for all fuel types.

Time to SiC coating failure is estimated with reaction rate models based on the kinetics of SiC attack by palladium. The reaction kinetics have been characterized by measuring the advance of a reaction zone in SiC as a function of time and temperature in a large number of particle batches under both high and low neutron flux and out-of-pile conditions (7, 14, 24, 26, 30). The SiC corrosion is a highly temperature-dependent, activated process with scatter in the data, and even though palladium is the primary

fission product of concern in oxide-based fuel, the kinetics data base includes SiC attack rates for lanthanides and palladium. The temperature dependence of the rate of SiC attack by fission products, based on compilation of all relevant data, is shown in Fig. 7.

The core design model uses the time-temperature history of fuel in conjunction with the temperature dependence of SiC corrosion rate to determine the penetration depth at any time. When less than 50% of the original SiC thickness remains intact at any local region in the SiC coating, failure with regard to release of cesium and other volatile metallic fission products is assumed to take place (26). The OPyC coating over the failed SiC coating is assumed to remain intact and retain fission gases (27). Some perspective on the significance of the SiC - fission product reaction in core design is provided in Fig. 7. The upper curve shows the approximate minimum reaction rates that would be sufficient to cause SiC failure under typical HTGR time-temperature conditions. This figure shows that the core thermal design provides a time-temperature history of fuel such that higher than measured reaction rates would be necessary to cause SiC failure.

II.F. Kernel Migration

Under the influence of a thermal gradient that exists during reactor service, both oxide and carbide fuel kernels migrate up the thermal gradient into the coatings. Kernel migration in carbide fuels is relatively well understood and has been shown to be controlled by solid-state diffusion of

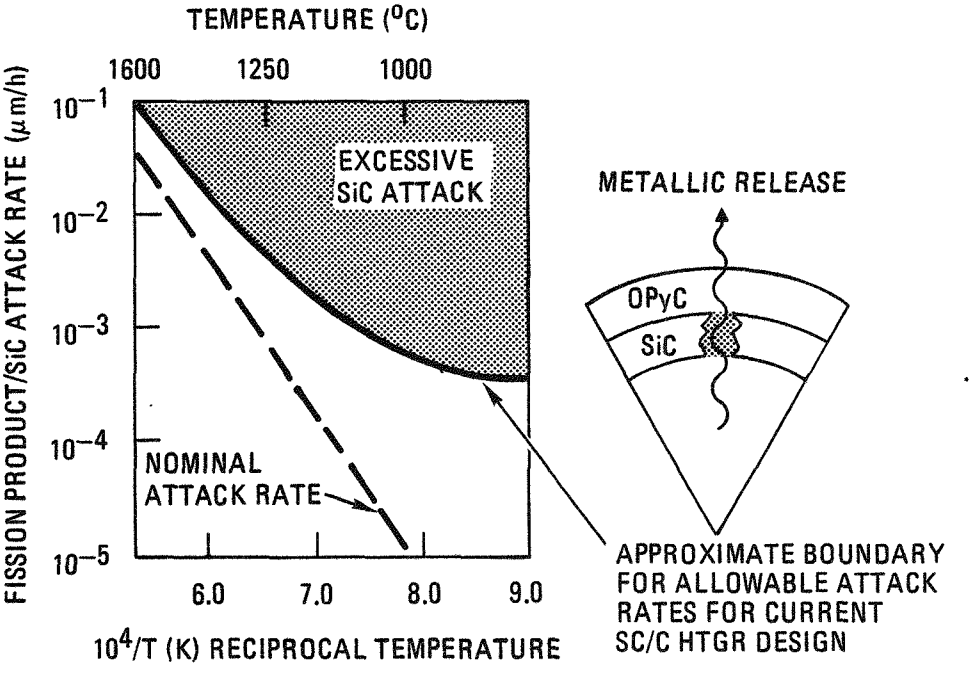

Fig. 7. Thermal design basis for metallic fission product - SiC attack

carbon in the fuel phase under the influence of a thermal gradient (31). Carbon is taken into solution in the kernel from the adjacent PyC on the hot side, transported across the fuel phase, and rejected as graphite on the cool side.

The amoeba effect in UCO, UO_2, and ThO_2 particles is not as well understood as it is in carbide particles. In ThO_2, as well as UO_2, carbon accumulates on the cool side of the kernel, and the kernel moves up the gradient. Mechanisms have been proposed for carbon transport in UO_2 at a rate controlled by $CO-CO_2$ gas phase interdiffusion and decomposition or solid-state oxygen diffusion (9). Reduction of CO/CO_2 pressure by means of an oxygen getter, such as UC_2 in the UCO kernel, should minimize migration by these mechanisms. On the other hand, carbon transport along grain boundaries of ThO_2 has been observed (32). Therefore, solid-state diffusion of carbon through oxide phase kernels to produce the amoeba effect is possible.

In the absence of a proven theoretical model, empirical correlations of ThO_2, UO_2, and UCO migration with temperature and temperature gradient have been made on the same basis as that for carbide fuels. This approach is consistent with the rate-controlling step being solid-state diffusion of carbon or oxygen under the influence of a thermal gradient. Using this model, a kernel migration coefficient, which is a temperature and temperature gradient normalized migration rate, can be defined as:

$$KMC = \left(\frac{dx}{dt}\right)\left(T^2\right)\left(\frac{\Delta T}{\Delta X}\right)^{-1} \quad , \qquad (1)$$

where KMC = kernel migration coefficient ($K\text{-}m^2/s$),

dx/dt = kernel migration rate (m/s),

T = absolute temperature (K),

$\Delta T/\Delta X$ = temperature gradient across the particle (K/m).

The temperature dependence of KMC for the reference HTGR fuel system is shown in Fig. 8.

The onset of kernel migration in ThO_2 is delayed by a time interval that decreases with increasing burnup and temperature (32). Above 2% fissions per initial metal atom (FIMA), the incubation time is assumed equal to zero. The empirical approximation of the incubation time for lower burnup conditions is shown in Fig. 9.

The rates of kernel migration at any thermal condition are deduced from the KMC. Because the time at each condition is known from core design analysis, the distance of migration through the coating can be determined. Failure of the SiC coating with release of metallic fission products is assumed if a migrating kernel penetrates both the buffer and the inner PyC to contact the SiC. The OPyC coating is assumed to remain intact so that the gaseous fission products are retained. Additional perspective with regard to core design is provided by the upper curve in Fig. 8, which shows the approximate KMC that would be sufficient to cause SiC failure under the time-temperature history of typical HTGR fuel. The measured KMC is less than the minimum required to fail SiC by kernel migration.

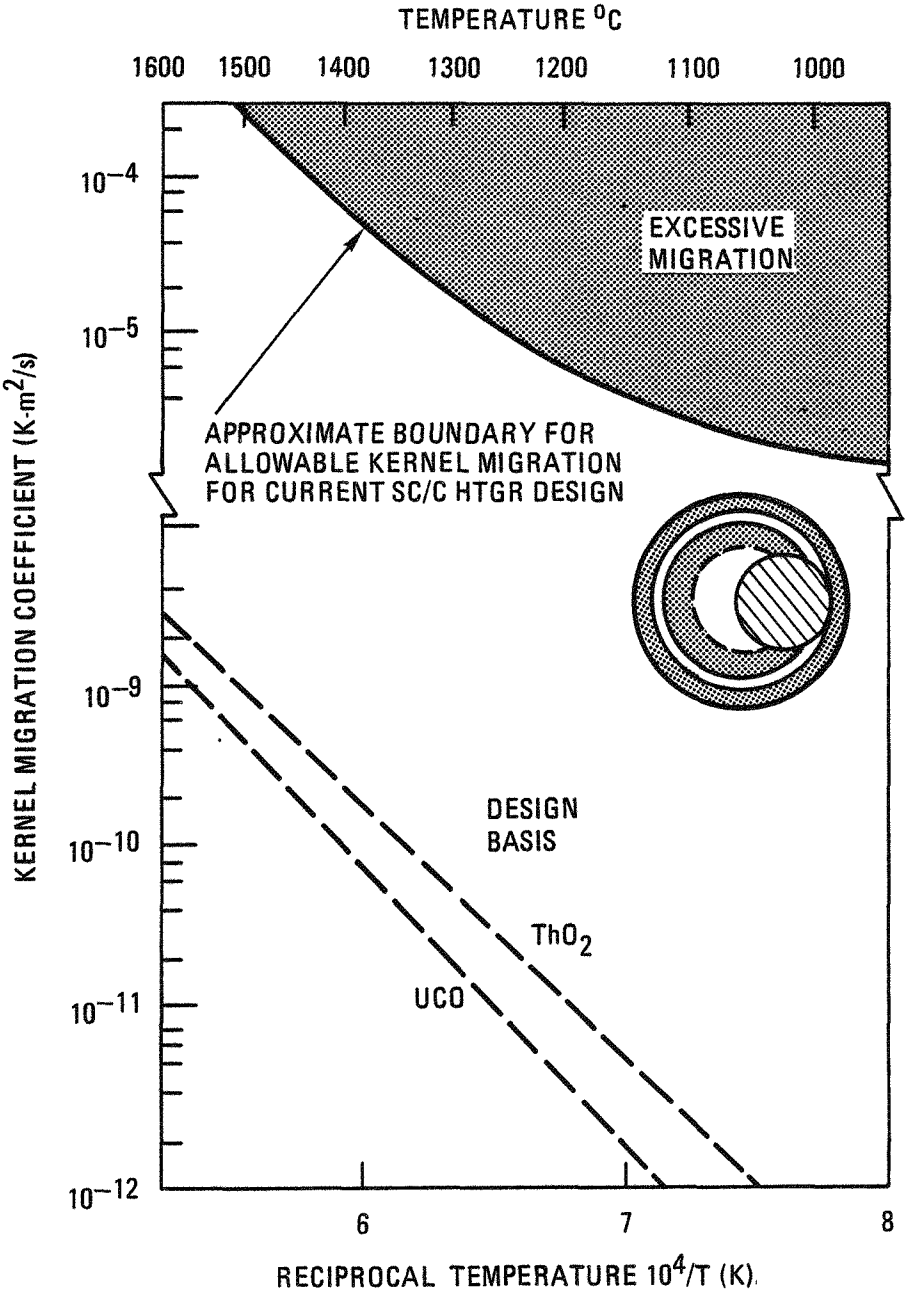

Fig. 8. Thermal design basis for kernel migration

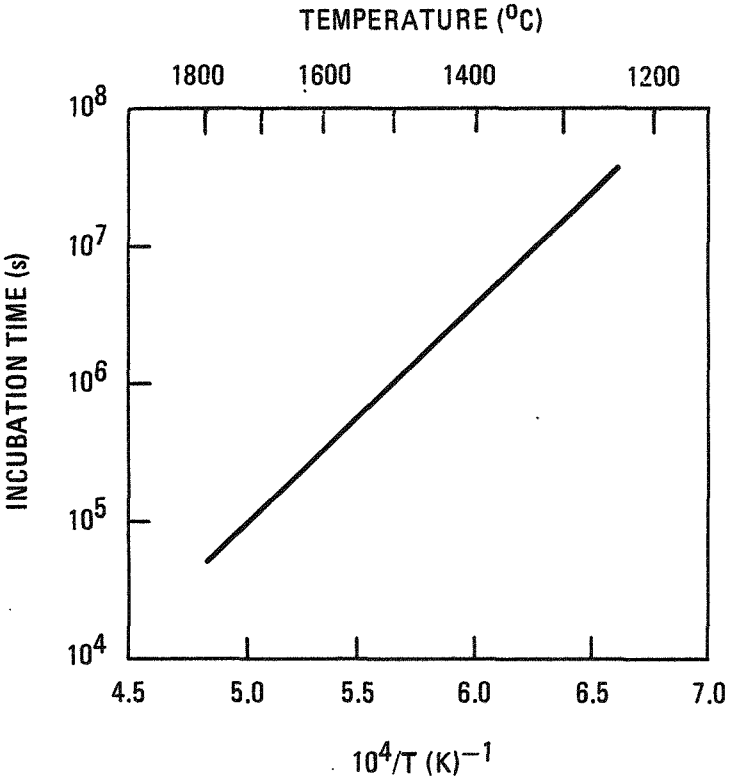

Fig. 9. Temperature dependence of the incubation time for onset of kernel migration in ThO_2 kernels with heavy metal burnup of $\leq$2% FIMA

In the SC/C HTGR design, the core temperatures have been purposely restricted so that fuel failure caused by thermal effects is insignificant ($<<10^{-4}$ fraction). Under these conditions, fission product - SiC interaction is more limiting than kernel migration in core design.

III. PREDICTED VERSUS OBSERVED FUEL PERFORMANCE

III.A. Irradiation Capsules

A vital part of the development of fuel performance models is the normalization process resulting from comparison of predicted and observed fission product release during irradiation testing. Changes in the models and associated assumptions can be made to improve agreement between the predicted and observed performance. Because circulating gaseous activity is of primary concern in HTGR design, the predicted and observed release of fission gases such as Kr-85m is the most important measure of fuel performance in irradiation tests.

Irradiation testing of fuel is carried out in capsules of different designs depending on the objective. Tests are usually conducted with gas purging to monitor fission gas release during irradiation (33). When several different fuel designs are to be evaluated in a limited time, one technique is to irradiate fuel rods containing the candidate fuels in a single cell to high burnup and fast neutron exposure under controlled temperatures. The capsule purge gas in this case can be monitored for fission gas activity during irradiation, but it represents an average release from

all fuel samples and, as such, the performance of fuel is individual rods cannot be determined. Therefore, after irradiation, the individual fuel rods are removed from the capsule and individual fission gas release determined by neutron activation in a TRIGA reactor facility (34). The fuel rods are heated to 1100°C while being irradiated, and the released fission gases are trapped. The trapped gas is quantitatively analyzed by a gamma spectrograph and the R/B calculated for Kr-85m and other gases.

The predicted gas release from irradiated fuel rods is determined for comparison with observed release by first estimating the coating failure fraction using the models discussed in the previous sections. The failed particle fraction is then multiplied by an empirical R/B determined for failed particles, as shown in Eq. 2:

$$R/B = (f_{fissile})(F_{fissile})\ (R/B)_f + (f_{fertile})(F_{fertile})\ (R/B)_f \quad , \qquad (2)$$

where R/B = average isotope release rate/birth rate for fuel sample or reactor core

$f_{fissile}$, $f_{fertile}$ = fissile and fertile particle failure fractions,

$F_{fissile}$, $F_{fertile}$ = fraction of fissions in fissile and fertile particles,

$(R/B)_f$ = R/B for failed particles.

The failed particle gaseous release factor $(R/B)_f$ is a complex function of kernel composition, burnup, and temperature. In addition, oxidation and hydrolysis reactions with impurities in the coolant can cause exposed

fissile kernels to become less dense and less retentive of fission products. For example, the Kr-85m release from failed UCO fissile fuel at operating temperatures is on the order of 0.005 fraction for unhydrolyzed fuel. In the hydrolyzed state, which is the usual conservative assumption, the release fraction is 0.025. The fertile ThO_2 kernel does not react with coolant impurities when exposed by a failed coating, and under typical operating conditions, the $(R/B)_f$ of a failed ThO_2 particle is ~0.02 for Kr-85m. A more complete discussion of the release factor is reported (21, 22, 23, 35, 36) and is beyond the scope of this article. With the appropriate factor for gas release, failure fractions can be estimated when average gaseous release from reactor core or fuel sample is known, or the in-service release can be predicted when the particle failure fraction is known.

Recent results from irradiation of LEU fuel in capsule HRB-15A give an example of the close agreement between predicted and observed gas release at the end of irradiation (37). The fuel rods were individually activated and gaseous release determined in a TRIGA test reactor after irradiation at 1100°C in the high-flux isotope reactor at Oak Ridge National Laboratory. The observed gaseous release for Kr-85m is compared with predictions for individual fuel rods in Fig. 10. About half of the predicted values for fuel rods in HRB-15A were within a factor of two of the observed release, and all values were within a factor of five. This is consistent with the uncertainty associated with assumptions in the model and the gaseous release measurements.

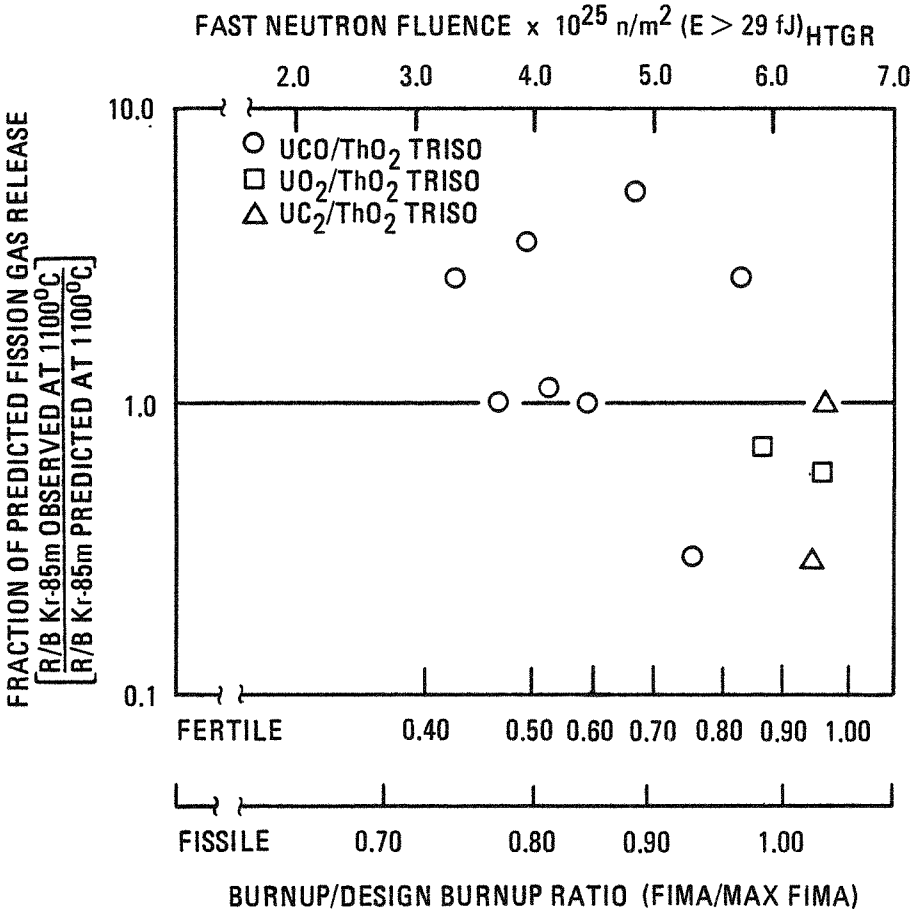

Fig. 10. Comparison of observed with predicted fission gas release from LEU TRISO fuel rods irradiated at 1100°C showing that performance models estimate fission gas release within a factor of five

Although the postirradiation activation technique provides a useful indication of performance model accuracy at the end of irradiation, a more complete test of the models is obtained if gas release during the course of irradiation can be measured and compared with prediction. This kind of comparison can be made when rods containing only a single fissile and fertile fuel particle batch are placed in an irradiation capsule cell that is purged and monitored for fission gas release (38). The predicted fission gas release can be obtained as discussed above and compared with observed release. An example of such a comparison is shown in Fig. 11.

The predicted rise in fission gas release early in the irradiation, shown in Fig. 11, was based on failure of defective particles. The subsequent, relatively minor increase was due primarily to increased release from U-233 bred from thorium exposed in defective particles or initial contamination. Although the predicted release was generally higher than the observed release, which showed typical fluctuation, the agreement between prediction and observation was relatively good in the form of the long-term exposure dependence.

Future irradiation will expand the data base for the reference LEU UCO/ThO_2 TRISO fuel system. Model prediction and observed performance will be compared to guide appropriate model adjustments and to verify final performance models.

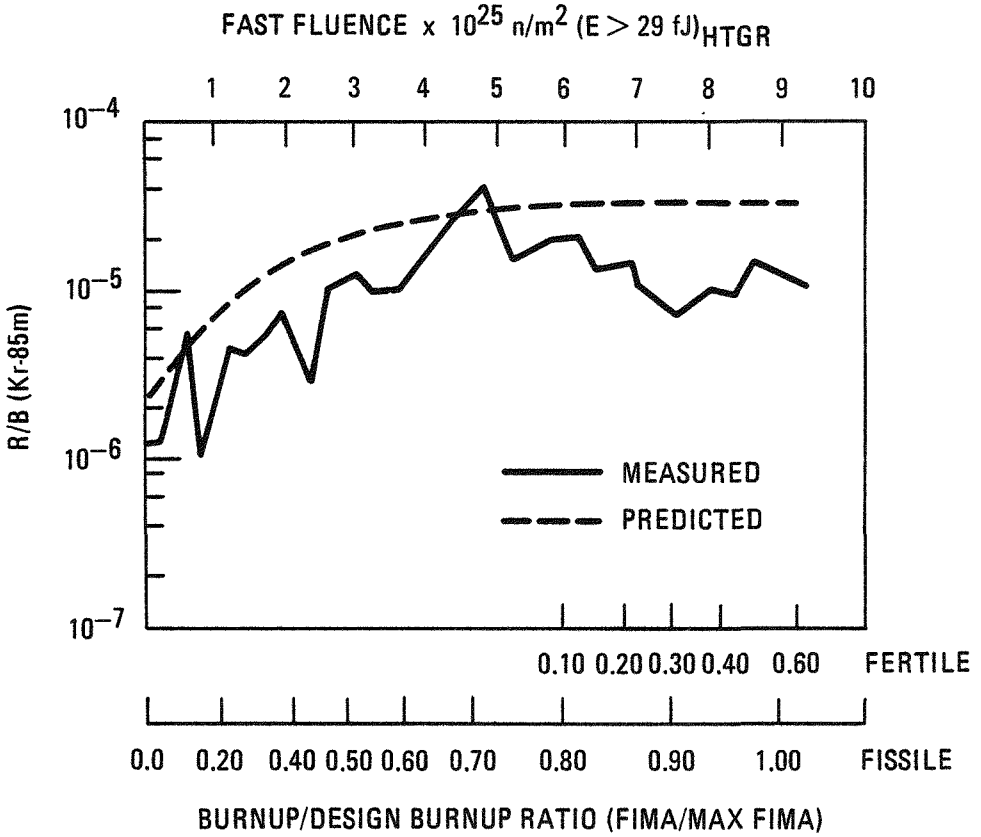

Fig. 11. Measured and predicted Kr-85m R/B versus fast fluence for capsule GF-4, cell II, containing HEU VSM UC_2 TRISO/ThO_2 fuel at 1000°C

III.B. Operating Reactor

The observed circulating activity in the Fort St. Vrain (FSV) 330-MW(e) HTGR operated by the Public Service Company of Colorado provided support for the validity of the performance models. The generic fuel failure models, modified to account for HEU mixed carbide fuel kernels (39) and a somewhat higher defect fraction for coatings, were used to predict circulating activity for the first two cycles. The average fast neutron exposure was ~1 x 10^{25} n/m^2 (E > 25 fJ), and the average burnup was 7% and 0.4% FIMA for fissile and fertile fuel, respectively. The predictions were made for two conditions: (1) no pressure vessel or defective particle failure and (2) defective particle failure in accordance with the model. The predictions were compared with observation of Kr-85m release, as shown in Fig. 12.

Short-term variations in gas release were caused by temperature changes with power and flow adjustments. However, the long-term trend in gas release was a gradual increase during cycle 1 from about 4.5 x 10^{-6} to 9 x 10^{-6} R/B Kr-85m. In cycle 2, the gas release was slightly lower than in cycle 1 because fuels with relatively high levels of contamination were removed during the standard refueling of one-sixth of the core and replaced with fuel with lower contamination levels more representative of current production (<1 x 10^{-4} fraction HM). The predictions made assuming failure of defective particles showed a more rapid increase with exposure than was actually observed, and at the end of cycle 2 the predicted release was about a factor of 7 higher than observed. However, when only the contribution

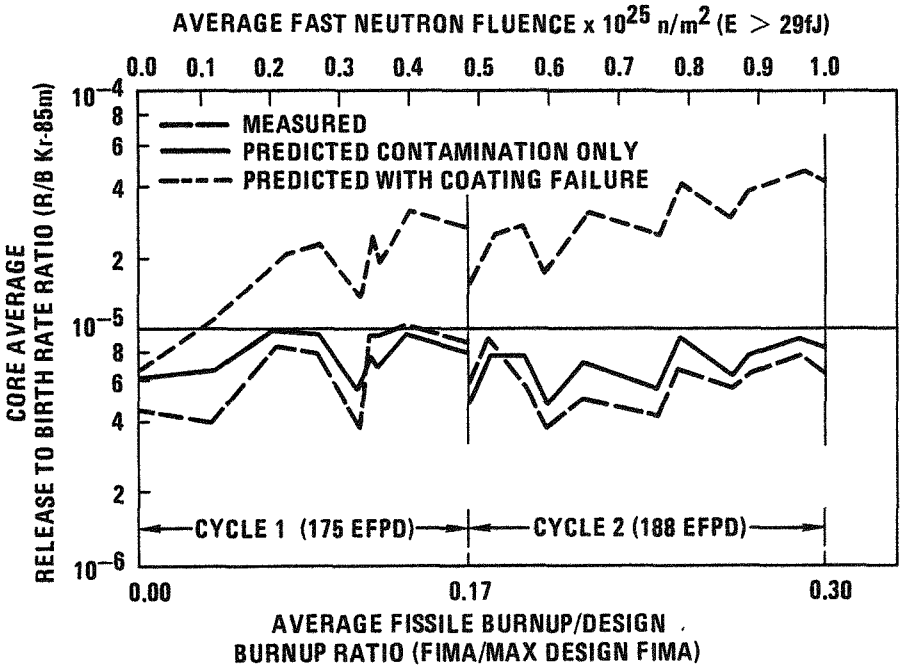

Fig. 12. Comparison of measured and predicted fission gas release in the FSV HTGR

from HM contamination was considered as a fission gas source, the predicted gas release was typically within about 30% of the observation. The evidence clearly shows the conservatism of the performance models and that, for the low-exposure conditions of cycles 1 and 2, failure of defective particles did not take place as predicted by the generic model. The predicted release from surface contamination alone was consistent with observed release.

As the burnup and fast neutron exposure increases, the probability for failure of defective particles increases. Under these conditions, the observed fission gas release may become more consistent with the generic model, which assumes defective particle failure very early in the service life. Thus far, the generic fuel performance model has provided a means for interpreting the FSV HTGR core fission gas release and making a conservative prediction of future core performance.

IV. APPLICATION OF PERFORMANCE MODELS IN HTGR CORE DESIGN

During normal steady-state power operation, the fuel in an HTGR core is exposed to temperatures up to 1250°C, fast neutron fluence up to 6.5 x 10^{25} n/m^2 (E > 29 fJ), and HM burnups up to 26% and 7% FIMA in fissile and fertile fuel, respectively. The fuel performance models discussed in the previous sections are employed along with the design exposure conditions to predict the fuel failure and associated fission product release from the core. The circulating gas activity is of primary concern in the licensing and operation of the HTGR. The design limit on circulating gaseous activity is dictated by a limit for site boundary dose ($\leq$5 mrem/yr whole-body dose)

and containment access time for maintenance (40 h/week with vented containment) ainment) (40). The design goal is a factor of four lower than the design limit to ensure releases as low as reasonably achievable (ALARA). For example, the limit on total circulating $Kr\text{-}88^d$ activity is 14,000 Ci, and the ALARA limit is 3,500 Ci.

As discussed previously, and demonstrated by experience in the FSV HTGR, the primary source of circulating activity in the HTGR is thorium and uranium contamination of the fuel rod matrix, including particles with coatings broken during the manufacturing process. The fuel specifications permit up to 10^{-4} fraction of thorium and uranium to be exposed as contamination during the manufacturing process. The release of fission gas from the contamination is calculated for the reactor by accounting for release from contamination in different parts of the reactor core based on the expected contamination and the temperature dependence of release. The predicted circulating activity for Kr-88 derived from contamination in one recent version of the 2240-MW(t) SC/C-HTGR core design was about 15% of the ALARA limit and 60% of the total release, as shown in Fig. 13. This observation has been important in directing fuel improvement work toward reducing contamination in the fuel as the most effective way to reduce fission product release from the core.

Predicted core average coating failure, based on the different failure models discussed previously and the design service conditions, is relatively small at about 10^{-3} fraction. This predicted failure fraction includes as-manufactured defective SiC coatings, which result in metal release; but

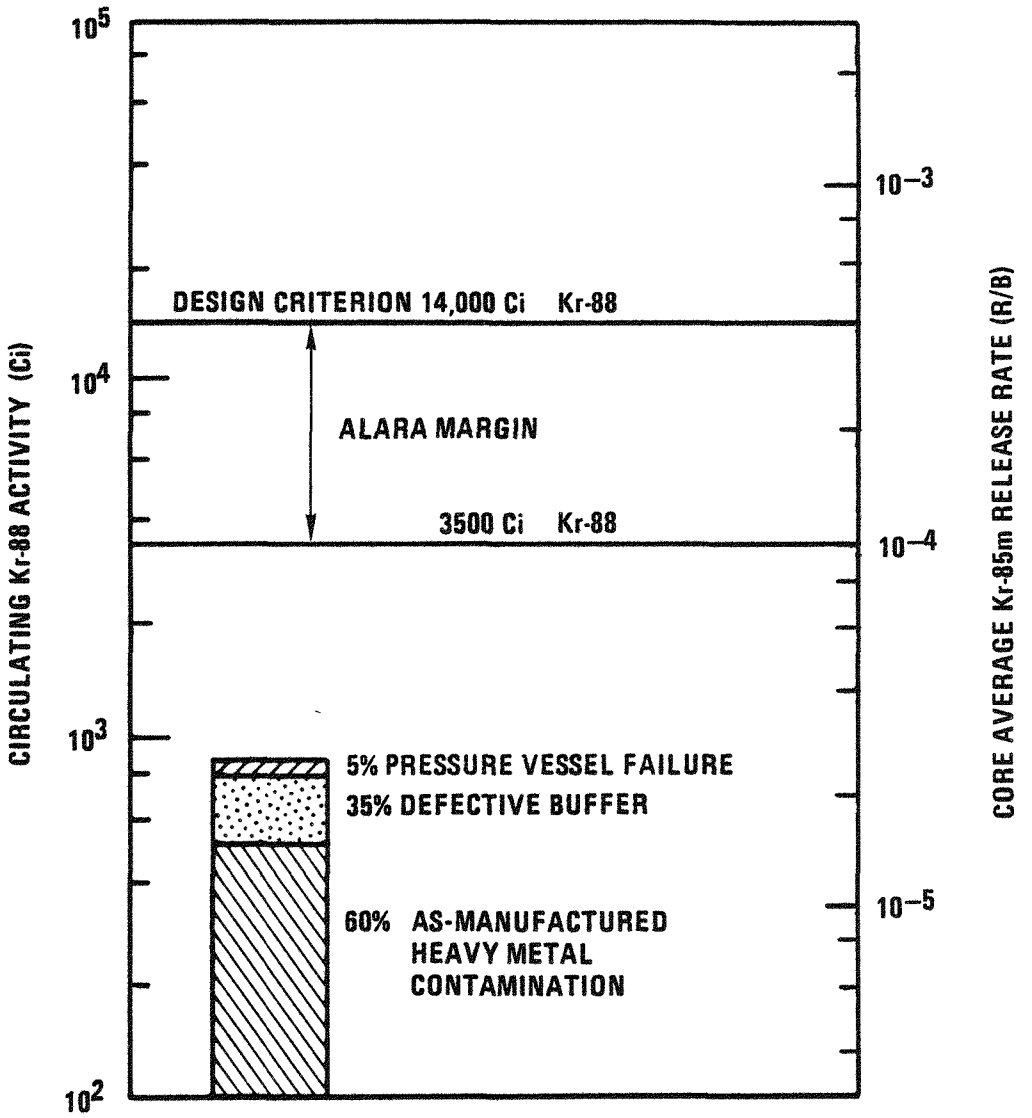

Fig. 13. Circulating Kr-88 fission gas activity design criteria for the 2240-MW(t) HTGR compared with predicted core average sources and corresponding Kr-85m R/B at equilibrium

because of the retentive nature of the OPyC coating on such particles, those that release fission gas, such as Kr-88, are limited to less than 6×10^{-4} fraction on a core average basis. In addition, failure of particles due to thermal effects such as SiC - fission product attack or kernel migration have been eliminated through limiting maximum temperature in the core design. Therefore, the SC/C-HTGR maintains a coolant circuit with exceptionally low radioactivity, which minimizes safety hazards and maintenance expense.

V. CONCLUSIONS

Gaseous fission product release under normal operating conditions is one of the primary concerns in the design and licensing of the HTGR. Empirical testing of a wide range of HTGR fuel variants since the late 1950's has contributed to development of mechanistic performance models that predict fission gas release from fuel as a function of exposure conditions. The contributions to fission product release in the HTGR can stem from:

1. Heavy metal contamination outside particle coatings.
2. Failure of defective particles.
3. Pressure vessel failure of standard particles.
4. Fission product - SiC reaction resulting in coating failure.
5. Kernel migration through coatings.

Mechanistic fuel performance models describing these five sources of fission product release are an important tool in HTGR core design because

they provide a means for optimizing overall core design to meet specific goals with regard to fission product retention and power production. The performance models can be verified in accelerated tests so that technical support for HTGR licensing can be developed in a timely manner.

When coupled with specific reactor design, the models help to establish allowable maximum fuel temperature-time conditions and areas for potential fuel and design improvements. Particles manufactured with defective SiC, IPyC, or fuel dispersion in the buffer fail at a level of less than 5×10^{-4} fraction, but release primarily metallic fission products because the OPyC remains intact on 90% of the particles and retains gaseous isotopes. Failure from thermal effects is limited to much less than 10^{-4} fraction, with fission product - SiC attack being more limiting on thermal design than kernel migration. Mechanical failure of particles with both gaseous and metallic fission product release is predicted to be less than 6×10^{-4} fraction, primarily as a result of failure in fuel with missing or defective buffers. About 35% of the predicted circulating activity results from failure of fuel with defective buffers and OPyC; only 5% comes from standard particles failed by pressure vessel effects. The primary source of circulating activity (60%) is derived from HM contamination outside particle coatings. A summary of the particle failure fractions calculated with the performance models on a core average basis is shown, along with the associated contribution to circulating activity in Table II.

TABLE II
FUEL PARTICLE FAILURE AND CIRCULATING ACTIVITY IN THE HTGR

SOURCE OF FISSION PRODUCT	CORE AVERAGE PARTICLE FAILURE FRACTION		RESULTING FRACTION OF CIRCULATING Kr-88 ACTIVITY
	FISSION PRODUCT METAL AND GAS RELEASE	FISSION PRODUCT METAL RELEASE	
HEAVY METAL CONTAMINATION	–	–	0.60
DEFECTIVE PARTICLE FAILURE			
BUFFER, OPyC DEFECTIVE	$<5 \times 10^{-4}$	$<5 \times 10^{-4}$	0.35
SiC, IPyC DEFECTIVE	$<4 \times 10^{-5}$	$<4 \times 10^{-4}$	0.00
STANDARD PARTICLE PRESSURE VESSEL FAILURE	$<10^{-4}$	$<10^{-4}$	0.05
FISSION PRODUCT – SiC REACTION	$\ll 10^{-4}$	$\ll 10^{-4}$	0.00
KERNEL MIGRATION	$\ll 10^{-4}$	$\ll 10^{-4}$	0.00
TOTAL	$\leq 6 \times 10^{-4}$	$\leq 10^{-3}$	1.00

The most effective way to reduce fission product release is to reduce fuel contamination and the number of particles with defective buffer layers.

The major features of the fuel particle performance models have been identified, and the predicted failure appears to be conservative relative to operating reactor experience. Future development will focus on improved characterization of the reference fuel properties for better identification of the design margin of safety and to assist the licensing effort.

VI. ACKNOWLEDGMENT

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REFERENCES

1. T. D. GULDEN, and H. NICKEL, "Coated Particle Fuels," Nucl. Technol., 206-213 (1977).
2. C. L. SMITH, "Fuel Particle Behavior Under Normal and Transient Conditions," DOE Report GA-A12971, GA Technologies Inc. (October 1, 1974).
3. M. TOKAR, "Evaluation of High Temperature Gas Cooled Reactor Fuel Particle Coating Failure and Models and DAT," NUREG-0111 (November 1976).

4. K. BONGARTZ and H. NABIELEK, "A Universal Model for Coated Particle Failure," TRANS 6th International SMIRT Conference, Paris, France (17-21 August 1981).

5. H. L. GEKO, and A. W. MEHNER, "Prediction of Coated Particle Behavior under Irradiation with the Code IAMESI and Comparison with Experiments," TRANS 6th International SMIRT Conference, Paris, France (17-21 August 1981).

6. R. L. PEARSON, R. J. LAUF, and T. B. LINDEMER, "The Interaction of Palladium, the Rare Earths, and Silver with Silicon Carbide in HTGR Fuel Particles," ORNL/TM-8059, Oak Ridge National Laboratory (April 1982).

7. T. N. TIEGS, "Fission Product Pd-SiC Interaction in Irradiated Coated Particle Fuels," ORNL/TM-7203, Oak Ridge National Laboratory (April 1980).

8. T. B. LINDEMER, and R. L. PEARSON, "Kernel Migration for HTGR Fuels from the System Th-U-Pu-C-O-N," J. Am. Ceram. Soc. 60, 5, (1977).

9. M. WAGNER-LOFFLER, "Amoeba Behavior of UO_2 Coated Particle Fuel," Nucl. Technol. 35, 372 (1977).

10. O. M. STANSFIELD, C. B. SCOTT, and J. CHIN, "Kernel Migration in Coated Carbide Fuel Particles," Nucl. Technol. 25, 517 (1975).

11. C. L. SMITH, "Migration of ThO_2 Kernels Under the Influence of a Temperature Gradient," Nucl. Technol. 35, 403 (1977).

12. C. L. SMITH, "SiC-Fission Product Reactions in HTGR TRISO UC_2 and UC_xO_y Fissile Fuel: I, Kinetics of Reactions in a Thermal Gradient," J. Am. Ceram. Soc. 62, 600 (1979).

13. C. L. SMITH, "SiC-Fission Product Reactions in HTGR TRISO UC_2 and UC_xO_y Fissile Fuel: II, Reactions Under Isothermal Conditions," J. Am. Ceram. Soc. 62, 607 (1979).

14. R. L. PEARSON, T. B. LINDEMER, and E. C. BEAHM, "Simulated Fission Product - SiC Interaction in TRISO-Coated LEU or MEU HTGR Fuel Particles," ORNL/TM-6991, Oak Ridge National Laboratory (November 1980).

15. H. WALTHER, "A Model for Stress Analysis in Coated Fuel Particles," DP 683, OECD Dragon Project (October 1969).

16. J. L. KAAE, "A Mathematical Model for Calculating Stress in Pyrocarbon and Silicon Carbide Coated Fuel Particle," J. Nucl. Mater. 29, 249 (1969).

17. T. D. GULDEN, et al., "The Mechanical Design of TRISO-Coated Particle Fuels for the Large HTGR," Nucl. Technol. 16, 100 (1972).

18. W. J. KOVACS, K. BONGARTZ, D. T. GOODIN, "TRISO Coated HTGR Fuel Pressure Vessel Performance Models," GA Unpublished Data.

19. D. T. GOODIN, "Accident Condition Performance of Fuel for High Temperature Gas Cooled Reactors," J. Am. Ceram. Soc. 65, 238 (May 1982).

20. D. T. GOODIN, "Fuel Performance Under Hypothetical Accident Conditions," GA Unpublished Data.

21. R. D. BURNETTE, W. E. BELL, and N. L. BALDWIN, "Fission Product Retention Characteristics of HTGR Fuel," Proc. Int. Conf. Nucl. Fuel Perf., Session 10, Paper 16, p. 16.1, British Nuclear Society, London (October 15-19, 1973).

22. B. F. MYERS, et al., "The Behavior of Fission Product Gases in HTGR Fuel Material," GA-A13723 (October 1977).

23. M. J. HAIRE, and D. W. McEACHERN, "Gaseous Radioactivity Levels in the Primary Coolant of an HTGR," GA-A12946 (October 1, 1974).

24. "HTGR Fuel Technology Program Semiannual Report for the Period Ending September 30, 1982," GA-A16919, p. 3-46 (November 1982).

25. K. BONGARTZ, "Improvement of a Method for Predicting Failure Rates of Coated Particles During Irradiation," Nucl. Technol. 35, pp. 379-385 (September 1977).

26. C. L. SMITH, "SiC Fission Product Reactions in HTGR TRISO UC_2 and UC_xO_y Fissile Fuel: I, Kinetics of Reactions in a Thermal Gradient," J. Am. Ceram. Soc. 62, No. 11-12, pp. 600-606 (November-December 1979).

27. C. L. SMITH, "SiC Fission Product Reactions in HTGR TRISO UC_2 and UC_xO_y Fissile Fuel: II, Reactions Under Isothermal Conditions," J. Am. Ceram. Soc. 62, No. 11-12, pp. 607-613 (November-December 1979).

28. H. GRUBMEIER, A. NAOUMIDIS, and B. A. THIELE, "Silicon Carbide Corrosion in High Temperature Gas-Cooled Reactor Fuel Particles," Nucl. Technol. 35, pp. 413-427 (September 1977).

29. F. J. HOMAN, et al., "Stoichiometric Effects on Performance of High Temperature Gas Cooled Reactor Fuels from the UCO System," Nucl. Technol. 35, pp. 428-442 (September 1977).

30. R. L. PEARSON, R. J. LAUF, and R. J. LINDEMER, "The Interaction of Palladium, the Rare Earths, and Silver with Silicon Carbide in HTGR Fuel Particles," ORNL/TM 8059, Oak Ridge National Laboratory (April 1982).

31. T. D. GULDEN, "Carbon Thermal Diffusion in the UC_2-Carbon System," J. Am. Ceram. Soc. 55, 14 (1972).

32. C. L. SMITH, "Migration of ThO_2 Kernels Under the Influence of a Temperature Gradient," Nucl. Technol. 35, pp. 403-412, (September 1977).

33. D. P. HARMON and C. B. SCOTT, "Development and Irradiation Performance of LHTGR Fuel," DOE Report GA-A13173, GA Technologies Inc. (October 31, 1975).

34. E. E. ANDERSON, et al., "An In-Core Furnace for the High Temperature Irradiation Testing of Reactor Fuels," Nucl. Technol. 11, p. 259 (1971).

35. M. L. POINTUD and P. CHENEBAULT, "Emission of Fission Gases by Failed Coated Oxide Fuel Particles," Nucl. Technol. 35, pp. 494-500 (September 1977).

36. B. F. MYERS, N. L. BALDWIN, and W. E. BELL, "Fission Gas Release from Fuel Particles and Fuel Rods," Nucl. Technol. 35, pp. 501-508 (September 1977).

37. J. W. KETTERER, et al., "Capsule HRB-15A Postirradiation Examination Report," GA Unpublished Data.

38. W. J. KOVACS and B. J. SEDLAK, "Postirradiation Examination of Capsule GF-4," DOE Report GA-A16064, GA Technologies Inc. (October 1980).

39. C. B. SCOTT and D. P. HARMON, "Irradiation Performance of Fort St. Vrain High-Temperature Gas Cooled Reactor Fuel in Capsule F-30," Nucl. Technol. 35, pp. 442-454 (September 1977).

40. S. D. SU and A. W. BARSELL, "Derivation of Criteria for Primary Circuit Activity in an HTGR," GA-A16086, in the Proceedings of the IAEA Specialists' Meeting on Coolant Chemistry, Plateout, and Decontamination, Jülich, Federal Republic of Germany (November 1980).

FOOTNOTES

[a]TRISO refers to a four-layer composite coating with three materials: (1) low-density pyrocarbon layer on the kernel to accumulate fission gas and attenuate recoils; (2) high-density SiC structural layer to retain metallic and gaseous fission products; and (3) high-density pyrocarbon layers designed to protect the SiC and retain fission gases.

[b]SC/C HGTR = steam cycle/cogeneration HTGR.

[c]R/B = release rate/birth rate.

[d]Because of its greater radiological consequences, Kr-88 is used as a guide in design analysis rather than Kr-85m, which is used in experimental work for historical reasons.

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