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Evaluation of MHTGR Fuel Reliability

Prepared by
R. F. Wichner, W. P. Barthold

Oak Ridge National Laboratory

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Abstract

Modular High-Temperature Gas-Cooled Reactor (MHTGR) concepts that house the reactor vessel in a tight but unsealed reactor building place heightened importance on the reliability of the fuel particle coatings as fission product barriers. Though accident consequence analyses continue to show favorable results, the increased dependence on one type of barrier, in addition to a number of other factors, has caused the Nuclear Regulatory Commission (NRC) to consider conservative assumptions regarding fuel behavior. For this purpose, the concept termed "weak fuel" has been proposed on an interim basis. "Weak fuel" is a penalty imposed on consequence analyses whereby the fuel is assumed to respond less favorably to environmental conditions than predicted by behavioral models. The rationale for adopting this penalty, as well as conditions that would permit its reduction or elimination, are examined in this report. The evaluation includes an examination of possible fuel-manufacturing defects, quality-control procedures for defect detection, and the mechanisms by which fuel defects may lead to failure.

Contents

	Page
Abstract	iii
List of Figures	vii
List of Tables	ix
List of Abbreviations and Acronyms	xi
Acknowledgments	xiii
Objectives and Scope	xv
1 Introduction	1
1.1 The MHTGR Concept	1
1.2 Radionuclide Containment	1
1.3 The Weak Fuel Concept	1
2 HTGR Fuel Manufacture	3
2.1 MHTGR Fuel	3
2.2 The Fuel Particle	3
2.2.1 The Fuel Kernel	4
2.2.2 TRISO Coated Particle	5
2.2.3 Buffer Coating	6
2.2.4 The Inner Pyrolytic Carbon Layer (IPyC)	7
2.2.5 The Silicon Carbide Layer (SiC)	7
2.2.6 The Outer Pyrolytic Carbon Layer (OPyC)	9
2.2.7 The Outer Protective Layer (PPyC)	9
2.2.8 Seal Coatings	11
2.3 Compact Fabrication	11
2.4 Manufacturing Defects	11
2.5 Status of Fabrication Technology for High-Quality Fuel	12
2.6 Evaluation	12
3 Fuel Failure Mechanisms	15
3.1 Introduction	15
3.2 Manufacturing Defects	15
3.2.1 Commonly Cited Manufacturing Defects	15
3.2.2 Other Manufacturing Defects that May Affect Fuel Failure	16
3.3 Fuel Failure Mechanisms in Normal Operation	18
3.3.1 Categories of Fuel Particles	18
3.3.2 Normal Service Failure Mechanisms	18

3.4 Fuel Failure Mechanisms Under Accident Conditions 20
3.5 Conclusions Regarding Fuel Failure Mechanisms 21

4 Fuel Design Requirements 23

4.1 Definitions and Development 23
4.2 Core Performance and Fuel Design Criteria 24
4.3 Evaluation of Fuel Design Requirements 27

4.3.1 Goal 3 Requirement 27
4.3.2 Goal 1 Requirement 27
4.3.3 Comparison of Fuel Element and Fuel Particle Requirements 28

4.4 Summary of Fuel Design Requirements Evaluation 28

5 QA/QC Methods 31

5.1 Past Practice 31
5.2 Proposed Practice 31

5.2.1 Fuel Quality Control 32
5.2.2 Administrative Controls 34
5.2.3 Records Control 36

5.3 Sample Size Considerations 36

5.3.1 Required Sample Size 37
5.3.2 Factors Influencing Sample Size 38

5.4 Evaluation 38

6 LWR Fuel Reliability Perspective 41

6.1 LWR vs MHTGR Fuel Parameters 41
6.2 Development of Improved LWR Fuel Reliability 41

6.2.1 LWR Fuel Failure Modes 41
6.2.2 Evolution of Improved LWR Fuel Performance 42

6.3 QA/QC Procedures for LWR Fuel 43
6.4 LWR Perspective Relative to MHTGR Fuel 44

7 Summary and Conclusions 47

7.1 Summary 47
7.2 Conclusions 48

References 51

Appendix A. Comparison of Fuel Design Requirements and Top-Level Goals 53

List of Figures

Figure		Page
2.2-1	The MHTGR fuel particle	3
2.2-2	Flow sheet for manufacture of UCO kernels	5
4.1-1	Determination and definitions of fuel criteria	23
4.2-1	Fuel product specification units	26
5.2-1	Organization for fuels QA program	36
5.3-1	Relation between sample size and detectable defect fraction	37
6.2-1	Fuel reliability index (FRI) for an LWR vendor	43
6.3-1	Typical relationship of QA and QC activities in LWR fuel manufacture	44

List of Tables

Table		Page
2.2-1	Fuel kernel characteristics	4
2.2-2	Coating process conditions	6
2.2-3	Attributes of the buffer layer	7
2.2-4	Attributes of the inner pyrolytic carbon layer	8
2.2-5	Attributes of silicon carbide layer	9
2.2-6	Attributes of outer pyrolytic carbon layer	10
2.2-7	Attributes of outer protective coating	10
4.2-1	Maximum allowable releases from fuel element during normal operation averaged corewide (Goal 1 or 3 requirement)	24
4.2-2	Maximum allowable releases from fuel element during long-term transients averaged corewide (Goal 3 requirement)	24
4.2-3	Maximum allowable releases from fuel element during short-term transients averaged corewide (Goal 3 requirement)	25
4.2-4	Maximum allowable manufacturing defects of fuel particles in fuel element	25
4.2-5	As-manufactured and EOL fuel particle failure fractions for release of fission gases and metals, projected for MHTGR	27
5.2-1	Typical steady-state MHTGR fuel production quantities	32
5.2-2	Available quality control techniques	33
5.2-3	Proposed raw materials sampling plan	34
5.2-4	Proposed MHTGR particle production sampling plan	35
5.2-5	Proposed MHTGR fuel compact production sampling plan	35
5.2-6	QA record retention responsibilities	36
6.1-1	Comparison of LWR and MHTGR fuel element parameters (typical values)	41
6.2-1	LWR fuel failure mechanism	42
6.3-1	QC tests on LWR fuel	45

List of Abbreviations and Acronyms

EAB	exclusion area boundary
BAF	Bacon anisotropy factor, a QC test for the PyC
FSV	Fort St. Vrain reactor
HEU	highly enriched fuel
IPyC	inner pyrocarbon layer
LEU	low enriched fuel
MHTGR	modular high temperature reactor
NOC	normal operating conditions
NPR	new production reactor version of the MHTGR
OPyC	outer pyrocarbon layer
PyC	pyrocarbon
PPyC	protective pyrocarbon layer
SER	safety evaluation report
TRISO	refers to multiple coated fuel particles including an SiC layer
UCO	refers to a kernel composition of UO_2 and UC_2

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We wish to acknowledge the generous assistance of several Quality Assurance (QA) managers for Light-Water Reactor (LWR) fuel vendors for providing much of the information summarized in Sect. 6. This information was extremely useful for providing background regarding the nature and role of QC techniques in a mature fuel production industry. In particular we wish to thank Mortimer M. Glotzer, Manager, Quality Assurance, Nuclear Fuel Manufacturing and Carl J. Volmer, Manager, Quality Assurance, Advanced Nuclear Fuels Corporation.

Objectives and Scope

The objective of this study is to review Modular High-Temperature Gas-Cooled Reactor (MHTGR) fuel reliability in normal service and under postulated accident conditions. The term "reliability" means confidence that the fuel will behave in service according to behavioral model predictions. The principal motivation is an evaluation of the appropriate Nuclear Regulatory Commission (NRC) approach to the desire of the Department of Energy (DOE) contractor to house the reactor in a nonsealed reactor building instead of the traditional sealed containment vessel. The DOE design team has adopted such an approach based on extensive analyses of both normal operating and accident conditions. These analyses show that the top-level plant operational and safety goals (Top-Level Goals 1 and 3) are satisfied by such an approach.

Satisfactory results regarding radiological containment are based on (1) judicious selection of core design and operating conditions and (2) selection of high-quality TRISO coated particle fuel. Thus, the lack of a sealed containment vessel and presumption of high-quality fuel combine to place a heightened importance on the reliability of the fuel.

The interim, conservative NRC response has been to adopt a "weak fuel" penalty to consequence evaluations for concepts with no sealed containment. This conservatism presumes a poorer response of the fuel to environmental conditions than is predicted by the behavioral models. The continued need for such a penalty and measures that could reduce it are evaluated in this report.

In essence the question is, "How much confidence in the fuel models is appropriate for the NRC to assume when the safety net of the sealed containment vessel is removed?" The response is a judgment call that must be based on examination of a number of related issues addressed in the various sections of this report.

The evaluation starts with a brief overview of the fuel-manufacturing process described in Sect. 2. The mechanisms by which the fuel particles may fail are summarized in Sect. 3. Section 4 explores the important link between the fuel-design requirements (i.e., manufacturer's objective) and the capability for satisfying the top-level reactor goals. The current Quality Control (QC) plans for fuel manufacture are reviewed in Sect. 5. A perspective of the mature Light-Water Reactor (LWR) fuel fabrication industry is provided in Sect. 6 regarding successful methods that may profitably be noted for the MHTGR.

These are the subject areas that need to be critically analyzed for evaluation of the "weak fuel" issue. Some areas entail traditionally complex issues that are briefly summarized; other areas are known to be in transition due to current program activities. In view of the importance of the fuel reliability question, a periodic reevaluation of the situation may be warranted.

1 Introduction

The objective of this study is to review Modular High-Temperature Gas-Cooled Reactor (MHTGR) fuel reliability and its relationship to the current design, which does not employ a sealed containment vessel. Fuel "reliability" is here defined as fuel performance according to behavioral model predictions under both normal and accident conditions. The principal motivation is an evaluation of the appropriate Nuclear Regulatory Commission (NRC) approach to the desire of the Department of Energy (DOE) contractor to house the reactor in a nonsealed reactor building instead of the traditional sealed containment vessel.

1.1 The MHTGR Concept

The MHTGR design emphasizes passive and inherent safety features, many of which are common to all high-temperature gas-cooled reactors. For example, use of graphite as a moderator and a low power density result in a slow and tempered response to a loss-of-coolant accident (LOCA), and selection of ceramic materials eliminates the possibility of a core meltdown. The inert helium coolant eliminates the potential for phase change due to accidental core overheating. Design selections were made to ensure that NRC safety goals, Environmental Protection Agency (EPA) Protective Action Guidelines, and a set of user/utility requirements are met with sufficient margin. Specific design selections contributing to passive safety are (1) a modular arrangement with a small, individual unit size of 350 MW(t); (2) a passive, air-cooled emergency vessel cooling system that operates continuously; and (3) a below-grade location to minimize seismic effects and possible consequences of other external events. Because of the expected high level of safety, no emergency preparedness plans for evacuation and sheltering are being prepared. An extremely small emergency planning zone (EPZ) is proposed that is restricted to the exclusion area boundary (EAB) of 425 m (Silady and Millunzi 1990). This requires that the restrictive dose limits imposed by EPA (EPA 1975) for the EPZ, which is normally set at a radius of about 16 km, be met at the much smaller EAB.

The net effect of these inherent and selected safety features is a design that, according to DOE predictions, surpasses safety requirements by wide margins for a range of postulated accidents. Because of this projected performance, the DOE has taken the position that the MHTGR should not be required to have a conventional containment vessel as an additional barrier to fission product release.

1.2 Radionuclide Containment

Central to the above assertion is the projected high level of fuel reliability assumed in the consequence analyses. The term reliability means fuel performance that is in accord with the behavioral model predictions used in consequence analyses. As such, it includes as-manufactured quality, performance in normal service, and anticipated response to adverse accident conditions. A requirement of 5×10^{-5} has been set for the defect fraction of as-manufactured fuel. Although the required fuel quality level has been produced in the laboratory, it has not yet been attained on a production scale with the selected fuel design. In addition, irradiation tests of the current fuel design manufactured in the laboratory have just begun. At this time, behavior under normal and accident conditions is based on capsule irradiation tests performed in the U.S. and Germany on a variety of closely related (but different) fuel designs.

1.3 The Weak Fuel Concept

As a cautionary measure, the "weak fuel" concept was proposed in the draft Safety Evaluation Report (SER) (Williams 1989). "Weak fuel" is a concept in which the fuel is assumed to respond less favorably to environmental conditions than is predicted by the behavioral models. As such, it is a penalty applied to consequence estimates for MHTGR designs that do not include a conventional, sealed containment vessel. In its simplest form, weak fuel may take the form of assuming either a premature failure of fuel particles or a degree of failure during an accident beyond that predicted by the fuel models.

As far as is known, no indication of weak fuel has been evident in any operating High-Temperature Gas-Cooled Reactor (HTGR) or in any capsule irradiation test involving TRISO fuel particles. This data base includes about 28 TRISO particle irradiation tests involving ~10^6 particles, as well as 5 helium-cooled reactors built in Europe and the United States. Preliminary indications of fuel behavior in recent in-pile capsules (HRB21, NPR1, NPR1a, and NPR2) may be representative of weak fuel.

Several factors, in addition to the absence of a sealed containment vessel support the adoption of this conservatism at the current time. The weak fuel concept also reflects the novelty of the UCO fuel design. The fuel performance models are not based on this design but are inferred from

closely related fuel concepts. In addition, there is less than a full understanding of all the basic mechanisms affecting fuel behavior. While failure mechanisms have been extensively researched, they are quite complex and include chemical, mechanical, solid state, and diffusive transport effects. This lack of full comprehension of fuel failure mechanisms, especially under the environmental stresses imposed by various postulated accidents, lessens confidence in the predictions of the largely empirical behavioral models.

It should be noted that MHTGR fuel reliability depends on (1) selection of appropriate fuel design requirements to satisfy the top-level goals, (2) proper fuel design and fuel specifications to ensure performance according to the requirements, (3) fuel fabrication and process control methods that ensure manufacture according to specifications, (4) quality control and quality assurance procedures, and (5) accurate predictions provided by models describing fuel behavior. Assessment of fuel reliability needs to consider all of these areas.

This study is organized into five major sections. A brief overview of MHTGR fuel manufacturing procedures is given in Sect. 2. This evaluation seeks to determine if features of the manufacturing process exist that warrant the weak fuel burden. In Sect. 3, an attempt is made to summarize what is known regarding fuel failure mechanisms. A brief summary of the functional fuel design requirements needed to satisfy the top-level plant protection and safety goals is presented in Sect. 4. An outline of preliminary QA/QC options identified by DOE is provided in Sect. 5. To provide a broader perspective on fuel reliability, trends in Light-Water Reactor (LWR) fuel quality and manufacture are discussed in Sect. 6. While completely different from HTGR fuel, examining the evolution of fuel quality in a related and fully developed industry such as LWR fuels provides a perspective that may provide useful insights. Section 7 provides a summary and preliminary conclusions regarding the weak fuel burden.

2 HTGR Fuel Manufacture

2.1 MHTGR Fuel

The MHTGR uses 19.9% enriched fuel consisting of TRISO coated particles that are contained in short graphite compacts inserted into the fuel holes of the graphite fuel blocks.

This fuel differs from that produced for the Fort St. Vrain (FSV) reactor in regard to enrichment (LEU vs HEU fuel); fuel form [UCO fuel instead of mixed (Th, U)C_2, ThC_2, and UC_2 fuel]; and particle design (kernel and coating dimensions).

The UCO fuel form consists of a mixture of UO_2 and UC_2 phases distributed throughout the kernel. The presence of UC_2 serves to reduce the oxygen potential within the kernel, thereby reducing the tendency for SiC damage due to oxidation. UC_2 reduces the gas pressures generated as a result of oxygen release from UO_2 following fission; therefore, the tendency for fuel failures due to kernel migration and excessive internal pressure are reduced.

Despite the change in fuel enrichment and kernel composition, the basic fuel manufacturing process remains the same, namely:

- fuel kernel fabrication in an external gelation process,
- coating of the kernels in a vertical furnace where they are simultaneously heated and fluidized by an upward flow of carrier gas containing compounds that decompose on the particles and form the coating layers, and
- fabrication of fuel compacts in an injection molding process.

Some modifications have been made in the fabrication process to yield a fuel with a much lower initial defect fraction than that produced for the FSV reactor.

2.2 The Fuel Particle

The HTGR coated fuel particle consists of a UCO fuel kernel that is surrounded by a pyrolytic carbon buffer layer, an inner pyrolytic carbon layer (IPyC), a silicon carbide layer (SiC), an outer pyrolytic carbon layer (OPyC), and a protective outer pyrolytic carbon layer (PPyC) with several seal coating layers in between (Fig. 2.2-1). The coated fuel particle is a highly sophisticated fission product containment system with a design based on empirical and mechanistic justifications.

The following is a brief description of the attributes of the fuel kernel and coating layers and the fabrication processes employed to produce fuel particles.

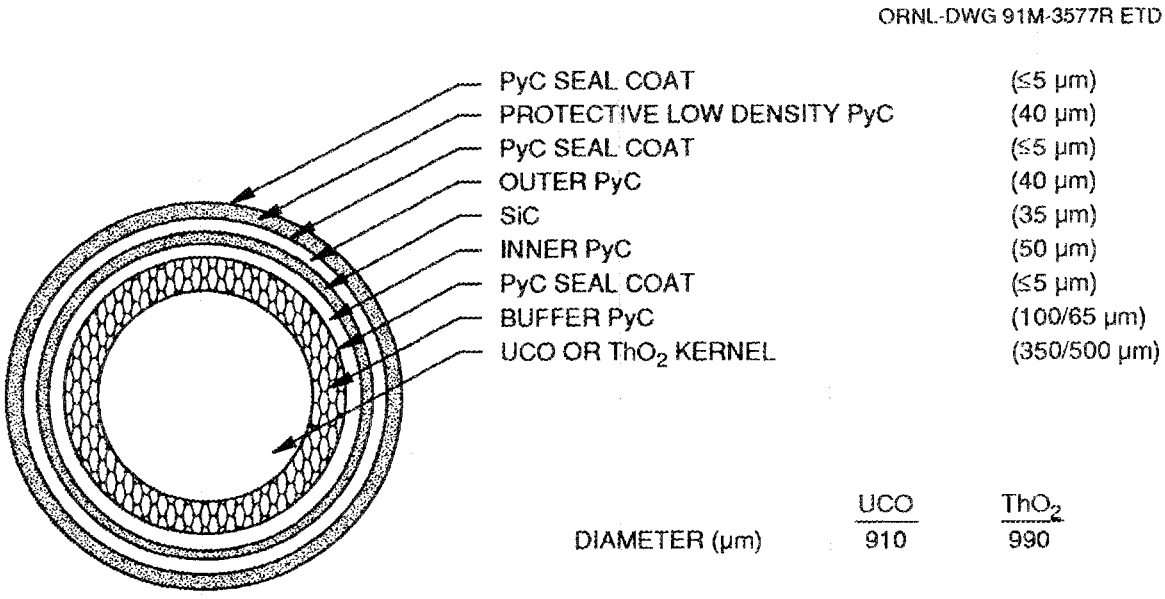

Figure 2.2-1 The MHTGR fuel particle

2.2.1 The Fuel Kernel

2.2.1.1 Attributes

It is generally assumed that the coatings are the primary barriers to fission product release, with the kernel having less significance as a barrier (Gulden and Nickel 1977). However, the kernel, which plays an important role in reducing the release of fission gases from broken particles, is designed to provide a transport delay for fission products. The transport delay is ~28 d (Wichner 1991), so ^{131}I, the longest-lived nuclide in this category, undergoes about four half-lives decay prior to release from the kernel. This delay and resulting decay of short-lived fission gases is an integral part of the models for fission product release from fuel. A poorly made kernel of excessive porosity would release higher fractions of the fission gases than predicted by the models.

Many of the kernel functions relate to the required heavy metal loading. However, the behavior of oxygen released in fissions of UO_2 in high-burnup fuel in a high-temperature environment relates to the UC_2/UO_2 ratio. In addition to the potential for excessive CO pressures in the kernel that could cause a pressure vessel failure of the particle, CO could also potentially cause an oxidative decomposition of the SiC layer by reacting with SiC and forming a protective layer of SiO_2 at temperatures below 1400°C, and by decomposing into SiO, a gas, at higher temperatures.

Table 2.2-1 summarizes the fuel kernel characteristics, showing the important kernel design parameters, their functions, and consequences of specification violations.

2.2.1.2 Fabrication

Fuel particle manufacturing technology is described in several review reports including Bresnick (1991), Huschka and Vygen (1977), Yoshimuta (1990), and Haas et al. (1981). Several variations of the process have been developed, divided roughly into external and internal gelation methods following droplet formation of a uranyl nitrate solution in an organic liquid. Internal gelation is reported (Haas et al. 1981) as superior for large particles (>1 mm) because the gelation reagent need not diffuse inward from the outer surface. However, no discernable difference in properties is noted between the two methods for kernel sizes in the 350-μm range selected for the MHTGR. Internal gelation has been selected for the NP-HTGR. While no final selection has been made for the commercial HTGR, late information suggests that external gelation may be favored (Bresnick 1991).

Table 2.2-1 Fuel kernel characteristics

Important design parameters	Function	Consequences of specification violation
UC_2/UO_2 ratio	Optimum composition of 85 wt % UO_2, 15 wt % UC_2 minimizes fission metal mobility and internal gas pressure due to liberation of oxygen from UO_2	• Excessive CO pressure can cause particle failure • Potential for oxidative decomposition of SiC
Dimensions	Ensures required minimum heavy metal loading and particle lifetime in presence of multiple coating layers	Excessive kernel size leads to high internal gas pressure
Impurities	Keep impurity level low to reduce likelihood that contaminants are introduced during processing and reduce potential for SiC attack	Higher than specified levels of transition metal impurities (Fe, Cr, Ni) can degrade structural integrity of SiC layer
Density	Highest achievable density is desired to optimize heavy-metal loading and reduce fission-gas release per failed particle early in life	High-kernel porosity leads to poor fission-gas retention and reduced HM loading in particles and may require higher particle packing fractions to meet core-wide HM loading requirements
Sphericity	High sphericity reduces irradiation-induced stresses in coating layers	Deformed particles show stress concentrations that can lead to particle failure

A variation of the external gelation method that is being considered (Bresnick 1991) is shown in Fig. 2.2-2. To form the liquid that contains uranium, UO_3 (or U_3O_8) is first taken into solution by dissolving it in a weak nitric acid to form uranyl nitrate (UNH). This solution is mixed with tetrahydrofurfuryl alcohol (THFA), and this mixture is added to a polyvinyl alcohol (PVA) dispersion in water to form a broth consisting of $UO_2(NO_3)_2.6H_2O$ + THFA + PVA.

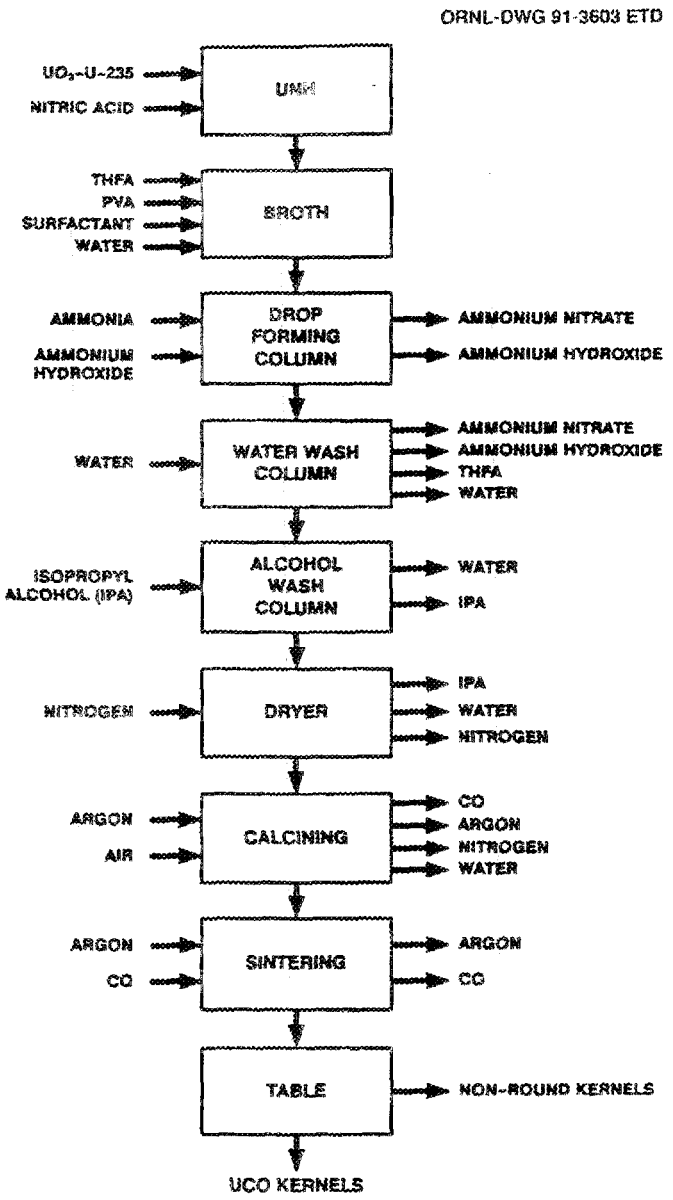

Figure 2.2-2 Flow sheet for manufacture of UCO kernels

This broth is pumped through a droplet generator where an electromagnetic driver axially vibrates several small-diameter needles to produce uniform spheres. This droplet generator is located above a precipitation/extraction column into which the droplets fall.

The broth droplets fall into an ammonia gas atmosphere where they react at the drop surface with anhydrous ammonia gas to form ammonium nitrate, which lowers the free water of the broth, causing precipitation of the PVA. As ammonia diffuses inward, a PVA gel lattice forms in the outer layer of the sphere/drop, forming a hardened shell over the drop. Complete gelation occurs when the droplets are immersed in aqueous ammonia where the reaction is completed. The internal gelation method is similar, except that urea is added to the broth so that ammonia is generated internally on contact with the hot organic liquid following droplet formation.

The kernels are then washed in water and isopropyl alcohol and dried at 100°C. During calcining, PVA is decomposed, ammonia and water are driven off, and uranium is reduced from UO_3 to UO_2. All these reactions are temperature-induced with temperatures extending up to 700°C.

During the final sintering process, the UO_2 is partially converted to UC_2, and the kernels are densified. Final sintering temperatures rise to 1850°C. Control of the sintering temperature, time at temperature, and CO/CO_2 composition of the gaseous environment is essential for producing a kernel of desired density and UO_2/UC_2 composition.

2.2.2 TRISO Coated Particles

The coating of the fuel kernels can be produced in either a continuous or an interrupted coating process. In the past, a single continuous coating operation was used to apply the buffer, IPyC, SiC, and OPyC coatings. There was a concern that interruption in the coating runs could cause the coating to have a layered structure with a variation in properties that might not be detected with routine quality-control procedures.

Revised coating continuity specifications require that each coating step be completed without interruption, except for the buffer layer and the IPyC coating under certain conditions (Scheffel and Tang 1989). The technical justification

for these permissible interruptions is the knowledge that structural integrity requirements are met by controlling the thickness and fraction in the critical region on the uninterrupted portion of the IPyC, SiC, OPyC, and protective layers to meet coating thickness requirements.

The deposition process and coating properties partially depend on the coater design. However, for any coater design, three process variables strongly influence the important PyC coating properties of porosity and density:

1. coating rate → porosity,
2. active coating gas ratio → porosity and density,
3. deposition temperature → density.

For example, the degree of interstitial porosity and surface porosity increases with coating rate and active coating gas ratio. Controlling the amount of surface-connected porosity is important because it influences the coating permeability and the bonding characteristics with the fuel compact matrix.

Early PyC coating development focused on high-temperature isotropic (HTI) coatings where the PyC layers were deposited from methane at temperatures in the range of 1800 to 2100°C. Currently, coatings are applied at substantially lower temperatures [low-temperature isotropic (LTI) coatings] from a variety of hydrocarbons. The coating process conditions are summarized in Table 2.2-2.

2.2.3 Buffer Coating

Kernel volume and buffer layer void volume (thickness and density) are important parameters influencing irradiation-induced stresses in the coating layers due to internal fission-gas pressure.

2.2.3.1 Attributes

The attributes of the buffer layer are summarized in Table 2.2-3. The purpose of the buffer layer is to

- provide void volume for gaseous fission products,
- accommodate fuel swelling, and
- attenuate fissile recoils.

2.2.3.2 Fabrication

The low-density, porous pyrocarbon buffer coating with a thickness of 100 μm is the first coating applied to the fuel kernels. It is applied by vapor deposition in a fluidized bed. The vapor is formed through the cracking of acetylene at 1200°C with argon being the fluidizing gas. The kernels are added to the coater at a temperature of 1000°C and heated in the bed before coating begins. The coating density is controlled by the bed temperature, coating gas entry rate, and the argon to acetylene ratio (Scheffel and Tang 1989).

Table 2.2-2 Coating process conditions

Coating	Levitation and diluent gas	Coating gas[a]	Minimum coating rate (μm/min)	Maximum coating rate (μm/min)	Active coating gas ratio
Buffer	Ar, He	C_2H_2	≈8 met requirements		
Seal	Ar, He, H_2	C_3H_6			
IPyC	Ar, He, H_2	C_2H_2/C_3H_6	≥1.0	≤4.0	≤0.25
SiC	H_2	CH_3SiCl_3	≤0.33 (mean)		
OPyC	He, Ar, N_2, H_2	C_2H_2/C_3H_6			≥0.25
PPyC	Ar, He	C_2H_2	≈8 met requirements		

[a]The active coating gas volume ratio is defined as [C/(C + L + D)] with
C = active gas flow rate to coating zone ($C_2H_2 + C_3H_6$),
L = levitation gas flow rate to coating zone (Ar or He or N_2),
D = diluent gas flow rate to coating zone (Ar or He or N_2 or H_2).

Source: W. J. Scheffel and I. M. Tang, *Technical Support Document for the MHTGR Fuel Production Specification*, GA Document 903728, Issue D, 1989.

Table 2.2-3 Attributes of the buffer layer

Important design parameters	Function	Consequences of specification violation
Density (max)	• Provide void volume for fission products • Low strength accommodates fuel swelling by yielding	• High density can cause early particle failure due to lack of void space for fission products • Excess strength can cause kernel damage due to failure to yield
Thickness (min)	• Provide void volume • Accommodate fuel swelling • Attenuate fissile recoils	• Missing or thinner than specified buffers can cause early particle failure because of high pressure • Missing buffer allows fission products to recoil into IPyC and accelerate transport to SiC

2.2.4 The Inner Pyrolytic Carbon Layer (IPyC)

2.2.4.1 Attributes

The attributes of the IPyC are summarized in Table 2.2-4. The purpose of the inner pyrolytic carbon layer (IPyC) is to provide impermeability to chlorine compounds during SiC layer deposition to protect fuel kernels from HCl attack and limit detrimental interaction between the fuel and carbide layer.

It should be noted that the thickness of the IPyC is not determined by considerations of fission-gas retention, but is determined solely by the requirement to provide a high-density, low-permeability coating to prevent chlorine from entering the buffer coating during the subsequent SiC deposition process. Such a coating thickness is also expected to meet the as-manufactured defective SiC specification.

2.2.4.2 Fabrication

The 50-μm-thick IPyC layer is a high-density coating over the buffer layer that is applied in the same fluidized bed as the buffer coating. Propylene is pyrolized to carbon and coats the buffer surfaces with a thin layer of pyrocarbon. While the cracking of the acetylene in the buffer coating deposition is an exothermic reaction, the application of the IPyC is an endothermic reaction. To minimize the temperature depression in the fluidized bed, propylene is mixed with acetylene to maintain a uniform bed temperature.

The carrier gas for the IPyC is either helium, argon, or hydrogen. It has been observed that pyrocarbon deposited from the large (commercial) coaters using H_2 as diluent is identical to coatings made in smaller coaters. However, coatings deposited in smaller coaters using no diluent gas generally had a higher permeability and anisotropy value at a given coating rate and contained soot inclusions (Scheffel and Tang 1986).

2.2.5 The Silicon Carbide Layer (SiC)

2.2.5.1 Attributes

The attributes of the SiC layer are summarized in Table 2.2-5. The purpose of the silicon carbide layer is to

- provide containment for solid and gaseous fission products,
- provide mechanical support for the particle, and
- provide structural rigidity and dimensional stability.

2.2.5.2 Fabrication

The 35-μm-thick SiC layer is the primary fission product diffusion barrier. The SiC layer is deposited by chemical vapor deposition in a fluidized bed. Hydrogen passes over methyltrichlorosilane (MTS) and reduces it to SiC, hydrogen, and HCl:

$$CH_3SiCl_3 + H_2 \rightarrow SiC + 3HCl + H_2 \ .$$

Table 2.2-4 Attributes of the inner pyrolytic carbon layer

Important design parameters	Function	Consequences of specification violation
Thickness	• Bar entry of HCl, released during SiC coating into kernel/buffer volume; HCl can corrode SiC and react with U; consequence of such reaction is dispersion of U within SiC coating; if excessive, results in corrosive damage to SiC by fission products; IPyC layer is effective sink for some highly mobile fission products	• To meet as-manufactured SiC defect fraction limits and required high-temperature performance, chlorine must be prohibited from entering buffer coating in subsequent SiC deposition process • SiC coating defects generated by reaction of HCl with heavy-metal kernel to form volatile metal chlorides that evaporate during SiC coating deposition inhibiting complete sealing of SiC coating layer
Density (min) and porosity (max)	• High-density, low-porosity IPyC is required to prevent chlorine-containing by-products of MTS[a] decomposition from getting into buffer, where it can react with fuel kernel and form volatile and highly mobile compounds, resulting in dispersion of fuel throughout buffer layer	• Same as above
$BAF_o \leq 1.12$ (Bacon Anisotropy Factor)	• High values of BAF_o factor indicate high crystallite anisotropy that is correlated with high density and low gas permeability; highly anisotropic PyC subject to radiation damage; specification is compromise that provides for kernel protection from HCl (main function of IPyC), yet maintains reasonable degree of radiation stability • Specification limits radial swelling of PyC after irradiation-induced failure rather than limiting failure itself	• Manufacturing studies show that when IPyC coating rate, active coating gas volume fraction, and density specifications are met, anisotropy factor is >1.085 BAF_o; no statistical significance for total coating failure observed for BAF_o ranging from 1.062 to 1.211; desire to minimize irradiation-induced dimensional changes led to specification of anisotropy measure and failure potential expected to increase for values outside of permissible range

[a]*MTS–Methyltrichlorosilane.*

The SiC vapor is deposited over the IPyC-coated kernels at temperatures in the range of 1550 to 1650°C. It has been observed that for coating temperatures below 1450°C, there is a tendency for circumferential banding in the SiC structure attributed to elemental Si and/or microporosity; at coating temperatures above 1700°C, there is a tendency for large columnar grains and excess microporosity (Price 1977). Over the whole range of deposition conditions, the predominant phase is β (cubic) SiC, which is the desired phase.

The use of a very low coating rate of ≤0.33 μm/min (that corresponds to the length of a coating run of just under 2 h) and a coating temperature around 1600°C provides assurance that the mean density of this layer is at least 3.18 g/cc, and that the thermal decomposition rate is below the value of free decomposition of SiC single crystals in the temperature range of 1400 to 1700°C (Krautwasser 1982).

Table 2.2-5 Attributes of silicon carbide layer

Important design parameter	Function	Consequences of specification violation
Thickness (min)	• Provide retention of metallic and gaseous fission products • Provide adequate structural stability during fuel compact fabrication	• Peak tensile stresses can be exceeded leading to particle failure • During compact fabrication, high contact pressures develop between particles in close-packed bed during fuel rod injection and SiC layers can crack
Density (min)	• High-density SiC used to increase strength and decrease diffusion constant for metallic fission products	• Use of low-strength SiC can lead to early particle failure • Use of low-strength SiC decreases the layer's efficiency in retaining metallic fission products • Low-density SiC layers occur when coatings are deposited below ~1400°C while coatings deposited above 1700°C may have excess microporosity and large columnar grains

2.2.6 The Outer Pyrolytic Carbon Layer (OPyC)

Both the IPyC and OPyC coatings are high-density coatings. However, while fission-gas retention was not a design consideration for the IPyC coating, it is an important consideration for the OPyC layer, which can remain intact even if the SiC layer fails. In BISO particle designs that consisted only of a buffer layer and the OPyC, the OPyC coating was the primary barrier to fission-gas release.

2.2.6.1 Attributes

The attributes of the OPyC layer are summarized in Table 2.2-6. The purpose of the outer pyrolytic carbon layer (OPyC) is to

- protect the SiC layer from external gas reactions,
- provide secondary barrier to gaseous fission product release,
- provide compressive prestressing of the SiC layer, and
- protect the SiC layer from damage during handling.

2.2.6.2 Fabrication

According to Scheffel and Tang (1989), the coating thickness requirement for the OPyC is based on empirical irradiation data and analytical model studies. To assure an even stress distribution in the SiC layer, thicknesses of >35 μm are required. To make this layer impermeable to gaseous fission products, a thickness of 40 μm was selected. The latter function comes from the requirement that gaseous fission products are retained in the event of SiC failure resulting from metallic fission product attack.

The deposition of this layer is similar to the IPyC coating application. To permit effective prestressing and improve the SiC layer function as the primary pressure boundary, it is important that the OPyC coating meets anisotropy and microporosity requirements.

2.2.7 The Outer Protective Layer (PPyC)

An outer protective coating layer is analogous to the matrix overcoat layer used in the German design. Its main purpose is to reduce SiC coating damage in the compact fabrication to meet the requirement on low initial defects.

2.2.7.1 Attributes

The attributes of the PPyC are summarized in Table 2.2-7. The purpose of the outer protective coating (PPyC) is to

- provide an interface layer between the coated particle and the compact matrix to avoid damage to the OPyC and SiC layers during compact formation,
- provide a bonding surface for the matrix, and
- prevent coating damage during handling operation.

Table 2.2-6 Attributes of outer pyrolytic carbon layer

Important design parameters	Function	Consequences of specification violation
Thickness (min)	• Thicknesses of >35 μm are necessary to ensure acceptable SiC stress distribution • Target mean thickness of 40 μm is necessary to ensure that OPyC impermeable to gaseous species • To reduce potential for irradiation-induced failure, total OPyC outer diameter must be <800 μm	• If OPyC layer cannot prestress SiC layer as expected according to design criterion, particle failure can occur under accident conditions • Thinner than specified OPyC does not perform its function as backup barrier to gaseous fission products in case of SiC layer failure • If OPyC layer exceeds specification and limit on particle size, potential for irradiation-induced failure increases
Density (min)	• High-density coating layer is required to ensure sufficient strength to provide compressive prestressing of the SiC layer	• Low-density OPyC layer does not have strength to prestress SiC layer and increases potential for failure under irradiation
BAF_0 (max) (Bacon Anisotropy Factor)	• A low value for crystallite anisotropy required to reduce difference between irradiation-induced strains in radial and circumferential direction of the pyrocarbon; experimental data showed that BAF_0 and OPyC layer failure are not well correlated and that microporosity also has to be considered to better correlate the BAF_0 value with OPyC layer failure	• If upper bound for the BAF_0 value is exceeded and large crystallite sizes appear, failure probability for OPyC increases
Microporosity (min/max)	• Upper limit on microporosity is necessary to restrict permeability • Lower microporosity specification limit is needed to ensure adequate radiation stability	• If microporosity is too high, OPyC is not efficient barrier to fission-gas release • If microporosity is too low, OPyC failure rate increases rapidly

Table 2.2-7 Attributes of outer protective coating

Important design parameters	Function	Consequences of specification violation
Thickness (min)	• Specified PPyC thickness is maximum permitting required HM loading of MHTGR fuel compact • Protect OPyC and SiC layers from damage during compact fabrication	• Deficient PPyC layers increase probability for particle damage during compact fabrication, thus increasing as-manufactured defect fraction
Density (max/min)	• Low-density graphite layer is required to avoid particle damage during compact formation and to avoid mechanical interaction with other PyC layers	• High-density PPyC layer could be of sufficient strength to interact with adjacent PyC layers and cause damage

2.2.7.2 Fabrication

A 40-μm-thick layer of amorphous carbon is applied, similar to the application of the buffer layer. The coating gas is acetylene (C_2H_2) to ensure that a low-strength protective coating is applied. It has been observed that the use of propylene as a coating gas results in coatings that are too strong and often shows crack propagation under irradiation.

2.2.8 Seal Coatings

Three thin seal coatings are applied consisting of anisotropic PyC. A seal coat deposited as a thin high-density PyC layer between the buffer layer and the IPyC permits a clean separation of the buffer from the IPyC for the measurement of the IPyC coating density.

The second seal coat deposited as a thin high-density PyC layer is between the OPyC and the PPyC for ease of characterization and to protect the OPyC from failure due to shrinkage and failure of the PPyC.

The third seal coat is applied as a thin high-density PyC on the exterior of the finished particle to reduce the friction and abrasion between particles so that they can flow freely in the metering, blending, and mold-loading operation needed for the fuel compact fabrication, as well as to facilitate handling of the particles during compact fabrication without dust formation.

The active coating gas for the seal coatings is propylene (C_3H_6), with argon or helium as diluent gas.

2.3 Compact Fabrication

The fuel particles are bonded into a fuel compact to

- prevent mechanical interaction between fuel particles and moderator graphite,
- maximize the thermal conductivity of the fuel, and
- provide a secondary barrier to metallic fission product release through adsorption mechanisms.

Fuel particles and graphite shim particles are blended to obtain the desired uranium loading. This blend is placed in a die. The compacts are formed by hot injection molding (at about 160°C) using a mixture of petroleum pitch, graphite flour, octadecanol, and polystyrene injected under pressure into the die. Once the compact has cooled, it is removed from the die, packed in Al_2O_3 powder to maintain compact dimensions, and carbonized at 800°C. During the carbonization, organic compounds are decomposed and volatized leaving a solid carbon compact.

After the carbonization is complete, the compacts are removed from the Al_2O_3 bed, cleaned, and placed in graphite trays where they are slowly heated to ~1600 to 1850°C for about 30 to 90 min. During this final heat treatment, residual hydrocarbons and impurities are volatized from the matrix. According to Price (1977), bare SiC begins to show measurable thermal decomposition at about 1600°C, at which point its Si pressure equals about 0.1 Pa. The predicted decomposition rate at this temperature is 10 μm in 10^7 s. Data of Kurata (1980) indicate that bare SiC suffers about 1% density reduction at 1940°C in 20 min. Degradation becomes severe at 2000°C. Therefore, selection of the compact carbonization conditions (time at temperature) is a sensitive compromise between the need to drive off volatiles and chemically stabilize the compact and to avoid damaging the SiC layer due to thermal decomposition.

Concerns about the fuel compact manufacture process regarding fuel reliability are the possibility for coating damage during the compact manufacture and the maintenance of radial tolerances to keep the gap between compact and graphite block small enough to avoid high fuel temperatures, but large enough to facilitate easy loading.

2.4 Manufacturing Defects

Manufacturing defects are, in the broadest sense, deviations from fuel specifications. Most commonly, manufacturing defects are missing, defective, or incomplete coating layers and heavy-metal contamination. For example, missing buffers can result from deficiencies in the coater design that permit uncoated particles to be trapped during buffer deposition and released in later coating steps.

Defective or incomplete coatings (such as the SiC layer) can be caused by coating bed instabilities and nonuniform coating conditions. During the compact fabrication, the possibility exists that uncontrolled pressure surges during the compacting of particles in the mold can lead to fractured SiC layers through particle-to-particle contact.

Because the elastic modulus of PyC is significantly less than that of SiC, fracture of the SiC layer might occur while the OPyC layer is still intact.

The contamination of the matrix with heavy metal can be caused by broken particles and contact with contaminated surfaces and equipment.

Among the many possible manufacturing defects, the most severe are missing buffers and missing or defective SiC layers. Missing buffers can cause early particle failure due to excessive stresses in the SiC layer. Missing or defective SiC layers permit a greater fraction of fission products to escape from the fuel particles even under normal operating conditions.

A further discussion of the range of potential manufacturing defects and their role in generating fuel particle failures in normal or accident conditions is provided in Sect. 3.

2.5 Status of Fabrication Technology for High-Quality Fuel

Large quantities of TRISO coated fuel have been produced for the FSV reactor. However, this fuel was produced to far less demanding fuel specifications than those for the MHTGR. Furthermore, this fuel never reached the target burnup in the FSV reactor, although test fuel did achieve full burnup.

Fuel fabricated recently for in-pile irradiation tests is often referred to as "high quality fuel." The design requirements for this newer fuel are more exacting compared with fuel manufactured for the FSV reactor: an as-manufactured SiC defect fraction of 5×10^{-5} is now required compared with 3×10^{-3} for FSV fuel, and a uranium contamination level of 10^{-5} is now required compared with 3×10^{-3} for the older fuel. The new fuel was fabricated for capsule HRB-21, which has recently completed its irradiation (March 1992), and for capsules NPR-1, 1a, and 2, which contain a very similar fuel for the NPR version of the MHTGR.

Despite the designation as high quality, the newer fuel is fundamentally similar to the older fuel; kernel compositions differ, but methods for coating the buffer, inner, and outer PyC layers and the SiC layer are identical. An important difference is the addition of the PPyC layer to the newer fuel. This is effective in reducing damage incurred during the compact fabrication step and may be credited with contributing to the observed improvement in the as-manufactured defect fraction. The performance of this fuel during the capsule irradiation is still under study; however, early indications are that failure rates, at least for the NPR capsules, are significantly higher than were predicted.

It should be mentioned that the fuel for capsule HRB-21 was manufactured using the full-size coating equipment to be used on a commercial scale. However, some portions of the UCO fabrication system may be less than full scale. While the QC techniques employed were generally prototypic of the full-size process,* manual scanning of radiographs still played an important role. In contrast, fuel for the NPR capsules was fabricated using laboratory-scale equipment. In addition, more extensive QC testing was performed on the NPR fuel than is currently planned for the commercial MHTGR.

2.6 Evaluation

MHTGR fuel fabrication involves a moderately complex series of steps resulting in a fuel that consists of seven separate components, excluding the three seal coatings and the graphite moderator block. All stages of the manufacturing process are at least equal to or more complex than corresponding steps for LWR fuel. While the all-ceramic product is highly suitable for the intended service, the complexities of the manufacturing process and of the fuel form present some potentially negative aspects.

For fuel with the intended low as-manufactured defect fraction, the majority of failures (i.e., loss of fission product containment) may result from the effects of manufacturing defects. Although the process steps will be automated to minimize variability, the complexity and length of the process offers opportunity for a wide range of potential defects. The nature of these potential defects and the manner in which they could lead to failure are discussed in Sect. 3.

*Personal communication from M. J. Kania, ORNL, to R. P. Wichner, ORNL, March 1992.

The precise cause of some of the manufacturing defects may be difficult to isolate and correct. Defective coatings of various types can result from occasional, unfortunate exposure histories of particles in the coater. Particles may become trapped or temporarily attached to surfaces and, as a result, miss exposure to a portion of a coating run. The frequency of such coating defects is a function of the coater design, as well as the mode of operation. Similarly, out-of-round kernels and particles may result from both the inherent features of the fabrication apparatus and its mode of operation.

A second category of defects may result from process control errors. Each step in kernel, coatings, and compact manufacture is controlled with respect to duration, temperature, pressure, and feed composition. Most of these controlled parameters are critical for obtaining a satisfactory product. Undoubtedly, careful design and control redundancy will minimize process control errors. In addition, the QA program will include documentation verifying the process control conditions. Nevertheless, the large number of critical manufacturing steps provides opportunities for process control errors.

Two types of manufacturing defects can result from the expected variability of properties. The behavioral models take into account that certain fractions of fuel, not to exceed specified limits, will exhibit some properties beyond desired limits. In addition, defective particles may result from unfortunate combinations of properties each within specifications limits (e.g., a somewhat large kernel combined with an SiC layer of below average thickness). Fuel failures that result from expected parameter variability can be reduced by tightening the allowable range of the fuel specifications around the mean, a process that usually involves evolutionary improvements and process experience.

An additional type of defect should be cited as a possibility. Containment of fission products depends upon adequately low diffusivities of the principal sealing boundaries, the SiC, and OPyC layers. However, diffusivities can vary between apparently identical SiC layers, often for quite subtle reasons.

It is not intended here to be overly negative, but merely to point out that the complexity of the manufacturing process provides opportunities for pitfalls between successful tests using bench-scale fuel and proper reactor performance of fuel from a commercial fabrication system.

3 Fuel Failure Mechanisms

3.1 Introduction

This section reviews the mechanisms by which a fuel particle may fail to perform its function of fission product retention. Attention is paid to the two principal fission product barriers, the SiC and the OPyC layers. Failure of the SiC layer causes loss of containment for fission metals; hence, this occurrence signifies fuel particle failure. While failure of the OPyC does not of itself indicate loss of function for the particle, it provides an additional barrier for fission gases and structural support for the SiC layer.

Because failures generally result from complex causes involving chemical and mechanical phenomena and because failures are difficult to observe directly in post-irradiation examinations, a model format has evolved that is based on statistical correlation of empirical data. Impetus for this trend was caused by the difficulty of earlier, mechanistic models to adequately describe fuel failure data. For example, data from Kovacs et al. (1983), as cited by Martin,* indicate that trends in observed pressure vessel failures often run counter to the predictions of models based on known mechanisms. In such cases, the root cause is attributed to unobserved manufacturing defects, and statistical correlation of the observed failure data offers a modeling alternative.

When applied to accident consequence estimation, the fuel behavior models generally lead to encouragingly low estimates. Moreover, the body of accident condition test data and reactor experience indicate their general validity regarding the overall fuel performance.

Nevertheless, a good understanding of potential fuel failure mechanisms is a great advantage, and perhaps a necessity, to provide a foundation for developing further confidence in the consequence estimates. It is seen in Sect. 6 (LWR Fuel Reliability Perspective) that an important factor in the continued improvement of LWR fuels has been the gradual unfolding of the failure mechanisms, which, in turn, has permitted progressive improvements in fuel design. Hence, recognition and understanding of failure modes can be an important factor in gaining confidence in HTGR fuel reliability.

*R. C. Martin, "Compilation of Interim Fuel Performance and Fission Product Transport Models and Data Base for Initial NP-MHTGR Design," ORNL/NPR-91-16 (to be published).

Because the fuel behavior models are mostly empirical, there is some question regarding their validity outside of the parameter range used for development, including the inevitable modifications of the fuel manufacturing process. In addition, a soundly based QC program rests directly on recognition of potential failure mechanisms. The QC plan needs to be prioritized toward measurement of those parameters that most significantly affect fuel failure.

3.2 Manufacturing Defects

3.2.1 Commonly Cited Manufacturing Defects

A large number of manufacturing defects are conceivable. These defects are conventionally grouped as follows for the purposes of fuel design (FDDM 1987):

1. missing or defective buffer layer,
2. missing or defective IPyC layer,
3. missing or defective SiC layer,
4. missing or defective OPyC layer, and
5. missing or defective PPyC layer.

In addition to these five defects, the following two heavy metal (HM) concerns are generally included in the list of manufacturing defects:

6. HM contamination, and
7. HM dispersion.

Two of these manufacturing defects, missing or defective SiC and HM contamination, may be considered as manufacturing failures (as opposed to defects) in the sense that the fission product containment function is lost by virtue of the defect. The remaining five defects contribute to fuel failure during normal use in various ways and constitute fuel weakness under accident conditions.

Note that exposed kernels are not explicitly included as a manufacturing defect. However, if defect types (2) through (4) occur simultaneously, the result would be an exposed kernel. In addition, HM contamination is considered in the same category as exposed kernels because the current QC procedure does not distinguish between the two.

A distinction is made between HM contamination and HM dispersion. The former refers to HM material outside the SiC layer and thus contributes at the outset to fission product release from fuel. HM dispersion refers to a condition

wherein an unacceptable level of HM has moved from the kernel throughout the interior of the particle within the SiC layer. If present in excess, such material has a high potential for damaging the SiC layer. HM dispersion is usually attributed to a defective IPyC layer that exposes the kernel to HCl gas generated during the SiC coating process.

3.2.2 Other Manufacturing Defects That May Affect Fuel Failure

In addition to the above-listed manufacturing defects, a variety of defects can occur that could lead to failure. Some of the more significant defects, together with the manner in which each may influence fuel failure, are identified below.

3.2.2.1 Kernel Fabrication Defects

The fission product retention function of intact fuel particles is relatively insensitive to variability in the as-manufactured kernel. The effects of shape variations on stress levels in the coating layers are blunted by the presence of the relatively thick buffer layer. However, the retention capability of particles with exposed kernels can be quite sensitive to certain features of the manufactured kernel. This is especially true of the fission gases, which are generally short-lived and, thus, sensitive to holdup time in the exposed kernel.

1. An important part of the fission product retention capability of fuel particles is provided by a dense kernel that prevents rapid evolution of fission gases. Because many of the important fission gases are short-lived (e.g., the 8.1-d ^{131}I), the transport delay provided by the kernel allows significant radioactive decay prior to release from the kernel. Kernel densities significantly below specification limits permit higher fission-gas release rates from exposed kernels than predicted by fuel transport models. Low kernel densities may result from excessive gas evolution rates during sintering or improper UC_2 formation conditions.

2. Excessive kernel size elevates coating stresses by reducing the available buffer layer volume (assuming constant outer diameter) and raising the fission-gas generation rate by virtue of the larger mass. Kernel size limits are set (Scheffel and Tang 1989) so that <1% of the kernels exceeds 400 μm, compared to the overall mean of 350 μm. This size distribution is stated to result in $<1 \times 10^{-6}$ failure fraction of particles with intact IPyC/SiC/OPyC layers of design thickness at the end of normal service, using the pressure vessel failure estimation procedure described by the Fuel Design Data Manual (FDDM) (1987).

3. Certain chemical impurities in the kernel are known to have a deleterious effect on the SiC layer. Iron, nickel, and chromium corrode SiC by forming more stable carbides or silicides. Impurity levels of <100 ppm are specified for each by FDDM (1987) to limit SiC corrosion.

4. Improper adjustment of UCO kernel stoichiometry results in less than optimal fuel performance. The selected composition is an optimized balance to take advantage of both the retentive power of UO_2 for certain metallic fission products and the chemical contribution of UC_2 for reduction of the oxygen pressure in the fuel particle.

The major constituent of the UCO kernel, UO_2, provides a retention capability for strontium and the rare earths. Several studies have shown that the rare earths may corrode the SiC layer if present in the reduced form [i.e., as either the element or the carbide (e.g., Grubmeier et al. 1977)]. An adequate level of UO_2 in the kernel creates sufficient oxygen pressure such that these metals are present in the less mobile oxidized form.

Uranium dicarbide in the UCO kernel acts as a sacrificial material, placing an upper limit on the oxygen pressure generated by UO_2 and the fission process. It does so by allowing formation of UO_2 and C by reaction of oxygen with UC_2, instead of forming CO and CO_2 by reaction of oxygen with C. Analyses by Lindemer and deNordwall (1974) indicate that the kernel migration coefficient for basically UO_2 kernels is markedly reduced as the oxygen pressure is reduced for temperatures in the normal operating condition (NOC) range (i.e., T < 1250°C).

Thus, an absence of carbon in the kernel would result in excessive pressure and kernel migration. At the other extreme, an excess of carbon in the kernel would result in excessive fission metal migration and possible harm to the SiC layer. Hence, the kernel is designed for an optimal composition of $UC_{0.3}O_{1.7}$.

3.2.2.2 As-Manufactured Coating Layer Defects (Other than those Cited in Sect. 3.2.1)

A large number of as-manufactured coating defects are possible as a result of incorrect settings of the coating temperature and active gas pressure, or otherwise improper coater operation (such as poor gas, particle distribution, or intermittent operation). In addition, particle transfers during

the coating operation may cause mechanical damage. The more significant possible defects are listed below.

1. **Inadequate Buffer-Layer Porosity.** Specifications call for a buffer-layer porosity of ~50% to limit the gas pressure developed in the particle due to burnup (Scheffel and Tang 1989). High porosity results from a high coating rate that, in turn, is regulated by the partial pressure of the active coating gas (acetylene for the buffer layer) and the coating temperature. High coating gas pressure and high temperature both tend to increase the porosity of the buffer layer.

2. **Excessive Permeability of the IPyC Layer.** The principal function of the IPyC is protection of the kernel from HCl formed during the SiC coating process. Therefore, IPyC coating conditions are selected to maximize density at the expense of irradiation stability. Excess IPyC porosity would allow some redistribution of uranium within the SiC layer, a defect that is termed HM dispersion. If present in excess of some undefined limit, HM dispersion has a high probability of failing the SiC layer during normal service. [FDDM (1987) cites an SiC failure probability of 50% at discharge burnup in cases of excessive HM dispersion.] High IPyC density is achieved by setting coating conditions for a low deposition rate (i.e., low active gas concentration and optimum coating temperature).

3. **Excessive Permeability of SiC to Metals.** The SiC layer can become excessively permeable to fission metals either by inclusion of free Si in the microstructure or by excessive porosity. According to Price (1977), free Si can appear when coating temperatures fall below ~1450°C and also by improper adjustment of the hydrogen to argon ratio in the coating gas. According to Scheffel and Tang (1989), excessive porosity can also develop when coating temperatures exceed ~1700°C.

4. **Low SiC Strength.** Low-density SiC deposits that contain free Si also possess low strength, in addition to high permeability for fission metals. Weak SiC layers are a result of deposition at temperatures below ~1450°C (Price 1977). Weakness may also result from an interrupted coating run (Scheffel and Tang 1989) that creates a spherically laminated structure. In addition, too high or too low coating temperatures (i.e., >1700 or <1400°C) also cause high susceptibility to thermal decomposition (Scheffel and Tang 1989).

5. **Excessive Gas Permeability of the OPyC.** The principal functions of the OPyC are to ensure low gas permeability and to protect the SiC layer. Both functions require maintenance of structural integrity during irradiation. Adequately low gas permeability is developed by placing an upper limit on the coating rate; that, in turn, is regulated by the partial pressure of the active coating gases. Excessive coating gas pressure results in excessive porosity. There is also a lower limit to the coating rate and active gas pressure, as noted in item 6 below.

6. **Inadequate Irradiation Stability of the OPyC.** Coating rates below specified limits, as controlled by the active gas pressure, result in an anisotropic crystal structure that performs poorly in normal service. In addition to anisotropy produced by low deposition rates, poor irradiation stability may also be caused by excessive crystallite size, which generally increases with deposition temperature. A crystallite size limitation is achieved by limiting the coating temperature to <1500°C (Scheffel and Tang 1989).

7. **Broken Particles Due to Compact Fabrication.** As noted in the previous section, compact fabrication entails high-pressure injection of a binder and graphite filler into a close-packed array of fuel and graphite particles contained in a cylindrical mold. Following injection, the green compacts are heated to 1850°C in incremental steps to drive off volatiles and to partially graphitize the binder. The process involves some risk of damage to fuel particles by a number of potential mechanisms: (a) mechanical interaction between adjacent particles may cause fracture to the OPyC and/or the SiC layers; (b) matrix/particle adhesion during graphitization, at which time a significant degree of shrinkage occurs, may damage the PPyC and/or OPyC layers; and (c) the final graphitization temperature of 1850°C involves some risk of thermal degradation to the SiC layer.

These risks are known and minimized by the selected process. The function of the protective PyC coating (PPyC) is to protect the OPyC during compact fabrication. Moreover, the duration of the curing at 1850°C is limited to minimize thermal degradation of the SiC. Nevertheless, the compact fabrication step entails at least the potential for particle damage.

8. **Faceted and Nonround Particles.** Faceting and the degree of nonsphericity of the coatings are important parameters with respect to the generation of stresses in the coatings. According to Scheffel and Tang (1989), particle faceting may occur as a result of irregularly shaped kernels or an improperly operated coating furnace. Generally, increased batch size and reduced levitation gas flow rate tend to increase faceting. Data shown by Scheffel and Tang indicate that large variations in apparent SiC strength occur

with faceted particles, with no clear trend with aspect ratio (defined as the ratio of maximum to minimum diameter) for aspect ratios of <1.15. In contrast, ellipsoidal particles show a gradual decline in SiC strength with aspect ratio.

Current specifications limit aspect ratios of fuel particles such that <10% of the particles exhibit aspect ratios >1.2 (Scheffel and Tang 1989), evidently for both faceted and spheroidal particles. Such stipulation limits SiC strength loss to 10% for 90% of the ellipsoidal fuel particles. However, much larger degrees of strength loss may be expected for faceted particles for this aspect ratio range, perhaps more than a factor of 2 (Scheffel and Tang 1989).

3.3 Fuel Failure Mechanisms in Normal Operation

3.3.1 Categories of Fuel Particles

The peak service conditions for the fuel assumed for design are 1250°C irradiation temperature, 8.0×10^{25} neutrons/m^2 fluence of neutrons in excess of 29 fJ, and 26% FIMA burnup (Scheffel and Tang 1989). The fuel lifetime in the core is 3 years (PSID 1986).

A range of particle types inevitably exists within the as-manufactured compact, each of which responds differently to the normal service conditions. For the purposes of discussion, it is useful to define three such categories of fuel particles. (These definitions may differ somewhat from the usual terminology.)

1. **Ideal Fuel Particles.** This type of particle possesses all the properties selected by the fuel designer, within an extremely small range about the mean. Assuming a correct design for the conditions of service, ideal particles will not fail under normal operating conditions (NOCs). However, this is a hypothetical category only, because no particle or group of particles can be shown to be ideal without destructive testing. The underlying reason is that some properties are not precisely predictable even under the most stringent fabrication conditions. For example, properties such as SiC tensile strength or diffusivity for metals appear to depend on subtle and incompletely understood fabrication parameters. Therefore, behavioral models are generally written in statistical terms, with the specified mean and standard deviation being selected to yield an acceptable level of failure for the known service conditions. Nevertheless, ideal fuel is a useful concept, both as a performance standard and as a long-range goal in fuel development.

2. **Standard Fuel Particles.** This category is defined as a group of particles that are within the range of all specifications, i.e., the particles pass the prescribed QA/QC procedures. Standard fuel particles experience some degree of failure under NOCs for basically two reasons: (a) some fraction of the fuel possesses adverse features within the tails of the property distribution curve and would therefore be predicted to fail by the statistically based fuel performance models, and (b) failures may also be caused by combinations of adverse properties, each of which is nevertheless well within specified tolerances (e.g., a somewhat large kernel occurring in conjunction with a somewhat thin or weak SiC layer may combine to cause failure, whereas individually a deterministic behavioral model would not predict failure). Note that as defined here, this category excludes obvious manufacturing defects cited in Sect. 3.2.1. In practice, however, fuel particle batches that pass QA/QC procedures will contain some particles with such manufacturing defects because of the statistical nature of QC methods.

3. **As-Manufactured Defective Fuel Particles.** These are particles that contain some manufacturing defect(s) of the type cited in Sect. 3.2.1 but are allowed at low concentration in an accepted production batch. Some of these defects cause a high probability of failure under NOCs. Others (defective SiC and HM contamination) represent as-manufactured failures because the containment function is already partially lost.

3.3.2 Normal Service Failure Mechanisms

1. **Pressure Vessel Failure.** This pertains to the bursting of the SiC layer due to the generation of excessive internal pressure. The source of the pressure is the generation of noble fission gases and iodine and the fission process that has a net effect of releasing oxygen from UO_2, which reacts with fission products and UC_2 to form refractory oxides, the excess converting principally to CO. Mechanistic pressure vessel models generally predict no failures under NOCs for particles that may be considered as approximately ideal. Statistical models (FDDM 1987) currently predict an extremely low degree of failure by this mechanism when applied to standard particles. However, the chance for pressure vessel failure increases with certain types of manufacturing defects, notably, (a) missing buffer or inadequate void space in buffer layer; (b) missing or defective OPyC, which provides protection and

stabilization to the SiC layer; and (c) out-of-round or faceted particles that exhibit stress peaking.

2. **Corrosion of the SiC Layer.** This is often cited as a potential fuel failure mechanism; however, the most recent authoritative study (Lauf et. al. 1984) downplays its significance. SiC corrosion may occur when the reduced form of chemically active fission metals (i.e., metal carbides or free metals) contacts the SiC layer. In particular, Sr, La, and other rare earths tend to form more stable carbides than SiC does; hence, these metals are incompatible with SiC. However, kernel stoichiometries in which UO_2 is the major species exhibit sufficiently high oxygen pressure to ensure that such active metals exist entirely as oxides, in which form they do not attack SiC. According to Homan (1977), kernel compositions containing as little as 32% UO_2 suffice to convert Sr and the rare earths to the oxide form, compared to the reference composition of 85% UO_2. Therefore, SiC corrosion by means of this mechanism is unlikely, except for particle defects in which the UC_2 concentration limit is grossly exceeded.

Scheffel and Tang (1989) state that excessive impurity levels of Fe, Ni, and Cr, incorporated with the kernel during manufacture, may also corrosively damage SiC. As a result, contamination limits of 100 ppm have been set for each such impurity.

SiC corrosion has also been attributed to attack by Pd. However, the study by Lauf et al. (1984) concluded that while noble metals such as Pd may pass through SiC (by means of a poorly understood mechanism), such passage does not damage the SiC layer. (This conclusion, however, needs to be confirmed. At present Pd attack on SiC is still considered to be a significant failure mechanism for normal reactor temperature conditions.)

At least three other mechanisms for corrosive attack on SiC have been cited. Grubmeier et al. (1977) have shown that SiC may be chemically attacked by HCl formed from the coating gas during SiC deposition. In addition, the FDDM (1987) cites HM dispersion as a likely cause for SiC corrosion. These two mechanisms may be closely related in that HM dispersion is caused by the presence of a damaged IPyC layer that permits contact of HCl with the kernel. Thus, the root cause of both these corrosion mechanisms is likely the presence of a damaged IPyC layer. Finally, kernel compositions that contain substandard levels of the UC_2 would permit significant service life with only the UO_2 remaining in the kernel. Such a situation would elevate the oxygen potential of the atmosphere near the kernel and cause oxidative attack on the SiC layer.

In sum, SiC corrosion as a possible failure mechanism is not likely to occur in ideal particles, but may be enhanced by four types of manufacturing defects: (a) a grossly incorrect kernel composition of more than 68% UC_2, compared with a nominal level of 15%; (b) a defective IPyC layer that permits HCl penetration to the kernel during coating; (c) excessive Fe, Cr, and Ni impurity levels in the kernel; and (d) an incorrect kernel composition in which the UC_2 phase is significantly <15%.

3. **Kernel Migration.** This may be considered as a specific type of corrosive failure of the SiC due to the migration of the kernel. The mechanism for the migration is essentially a carbon transport cycle on an extremely small scale. [See Wagner-Loffler (1977) and Lindemer and deNordwall (1974).] Although many details are complex, the process basically involves carbon oxidation to CO on the hot side of the kernel and transport via the gas phase to the relatively cooler side. The oxygen released due to carbon deposition finds its way back to the hot side either by diffusion through the kernel or by gas transport as CO_2. The net effect is movement of the kernel relative to the coating layers into the direction of increasing temperature. Factors which tend to increase the kernel migration rate are (a) the magnitude of the temperature gradient, (b) the temperature level, and (c) the oxygen pressure within the IPyC. Of these, only the last item may be considered as controllable by fuel particle design and fabrication.

Because recent, modular HTGR versions have reduced the maximum fuel temperature and temperature gradient, kernel migration is currently not considered to be a significant contributor to fuel failure. However, the current approach for estimating the kernel migration distance (FDDM 1987) uses a statististical method that yields a mean migration distance and a range about the mean. As such, even ideal fuel particles would be predicted to experience some small but finite level of kernel migration failure. Standard fuel particles, which exhibit an acceptable range of property parameters but no manufacturing defects, are likewise designed to yield insignificantly low-failure levels due to kernel migration.

The manufacturing defects that would significantly contribute to fuel failures by kernel migration are as follows: (a) a low concentration of UC_2 in the kernel relative to the

selected design level of 15% would allow higher oxygen pressures within the IPyC at end of life; and (b) an excessively large kernel would tend to increase the internal gas pressure, and if accompanied by correspondingly thinner coatings, would also enhance the failure probability.

4. **Irradiation Damage of the OPyC.** The OPyC layer is the part of the fuel particle that undergoes the most pronounced property changes as a result of fast neutron irradiation (Harmon and Scott 1977). Coating conditions for the OPyC are selected to yield an optimum set of properties with respect to strength, gas impermeability, and irradiation stability, as required for the overall function of the OPyC. Although failure of the OPyC does not of itself result in loss of fission product retention capability, provided the SiC layer is intact, it does cause a loss of SiC protection and, hence, an increased probability of subsequent SiC failure. Irradiation stability for the NOC design conditions is enhanced by a judicious selection of coating conditions that minimize the crystallite anisotropy and cause a deposit density in the range 1.85 to 1.95 mg/m^3. The principal means for assuring adequately low anisotropy is selection of a sufficiently high coating rate.

5. **Diffusive Failure.** Although not usually thought of as failure, fuel particles may lose containment function by means of diffusion through the intact coating layers. Even particles ideal in every respect lose significant fractions of Ag above ~1300 K in a neutron irradiation field (Groos et al. 1977). The same experimental data also indicate that Cs loss from ideal particles in a neutron flux may also begin to be at least measurable at about the same temperature. Thus, an MHTGR fueled entirely with ideal fuel would still exhibit measurable Ag and Cs contamination of the primary system.

The fabrication defect cited above (i.e., inclusion of free Si in the SiC layer as a result of an improperly low setting of the deposition temperature) enhances diffusive loss of fission metals under NOCs.

3.4 Fuel Failure Mechanisms Under Accident Conditions

1. **Thermal Decomposition of SiC.** Exposure of SiC to excessive temperatures tends to shift the chemical equilibrium toward the individual elements Si and C. According to Price (1977), such decomposition is generally considered to at least begin to achieve significant levels at ~1600°C, at which point unirradiated and exposed SiC develops an Si vapor pressure of ~0.1 Pa. A recent evaluation reported by Martin (1991) concludes that thermal decomposition is the principal failure mode of SiC at 1600°C and above. Physical removal of Si by vaporization is not required for loss of function. Decomposition with the Si retained in place, as may occur with fully contained SiC within intact IPyC and OPyC coatings, still results in loss of capability for containing fission metals. It is unclear whether the retention capability reappears on cooldown, which favors reforming SiC, albeit in a different crystal structure.

Empirical formulae given in FDDM (1987), based on a Weibull statistics format, provide an estimate for the SiC failure fraction due to thermal decomposition. Evidently, these formulae have recently been revised [see the review by Martin (1991)]. The revised formulae indicate a fairly strong dependence of failure fraction on integrated fission density and, to a lesser extent, on fast neutron fluence. From a fundamental point of view, it is not at all clear why these two parameters should effect thermal decomposition of SiC.

2. **Enhanced Diffusive Loss of Fission Metals and Gases.** Even with no structural alteration that may be construed as damage, diffusivities of fission products within the coating barriers increase with temperature fairly rapidly. For example, data summarized by Moormann and Verfondern (1986) indicate that the diffusivities of Ag and Sr in SiC each increase by a factor of ~30 between 1250°C, the upper limit temperature for NOCs, and 1600°C. Similar large increases in diffusivity are shown for the fission gases in PyC layers. (This rapid rise in noble gas release must be caused by something other than an inherent rise in diffusivity, because gas diffusivities increase only as the 1.5 power of temperature that would result in only 36% increase over the stated range.)

It is important to recognize enhanced release from fuel due to diffusivity increase because it is a completely reversible "failure," provided it is not accompanied or caused by an irreversible microstructural change.

3. **Fuel Hydrolysis in Steam Ingress Accidents.** The introduction of steam into the primary system creates numerous effects, most prominently, chemical reactions with exposed fuel kernels. Though such reactions are generally called "hydrolysis," that term applies strictly to the reaction of steam with UC_2 to form UO_2, plus various hydrocarbon gases and H_2. While chemical data predict the

effect of steam on UO_2 to be much milder than with UC_2, fuel capsule data indicate an approximately equal response to steam ingress of UCO and UO_2 kernels [Myers (1991)]. At low steam pressures, Myers found that the degree of stored fission gas promptly released (<1 h) varied as the square of the steam pressure, reaching ~3% at 200 Pa. Since steam ingress events could cause steam pressures of up to 10^6 Pa in the primary system, the measured trend strongly indicates that 100% stored fission-gas release from defective fuel particles may be expected within 1 h of the exposure. Richards et al. (1990) report agreement with that trend up to ~10^3 Pa steam pressure. However, they contend that a steam saturation effect occurs within the fuel, limiting stored fission gas release to ~30%.

4. **Effects of Steam on Fuel Particles.** In addition to the hydrolysis of exposed fuel, steam ingress can cause other deleterious effects on fuel particles: (a) some oxidation of the OPyC occurs due to the reaction of steam with carbon; however, this is generally considered to be a small effect for cases with proper safety system response to a steam generator failure. (b) Particles with defected OPyC may experience damage to the SiC layer due to a hydrolysis reaction with steam. (c) Fuel particles adjacent to hydrolyzed kernels experience collateral damage by means of an unknown mechanism. The most recent examples of this effect are illustrated by photomicrographs presented in the HRB 17/18 capsule report (Ketterer and Myers 1987). Particles adjacent to hydrolyzed kernels are shown with severely corroded OPyC layers.*

5. **Pressure Vessel Failure.** Accident conditions may cause a rise in the internal pressure of a fuel particle due to a temperature increase that, when combined with the expected loss of strength with temperature of SiC, can cause pressure vessel failure of the coatings. Certain types of manufacturing defects or normal fabrication variations can enhance the probability of pressure vessel failure during accidents.

The following types of fabrication variations, even occurring within specified QC limits, can enhance the degree of pressure vessel failure experienced under accident conditions: (a) high buffer layer density, (b) excess kernel size, (c) thin SiC layer, (d) weak SiC due to nonoptimum coating conditions, and (e) nonspherical or faceted coating layers.

*Reviewers were divided as to whether this was a real effect or an artifact of the metallographic process. Because the phenomenon also appears in early hydrolysis experiments in an identical way, the authors believe it to be a real effect.

3.5 Conclusions Regarding Fuel Failure Mechanisms

Evidence indicates that a properly designed fuel particle, fabricated to within tight variations about the selected mean for all attributes (i.e., an "ideal" fuel particle), will not fail under either normal or postulated accident conditions. Failures that do occur result from either manufacturing defects, several of which are cited in this section, or unavoidable coincidences of manufacturing variability. Thus, given a proper design, fuel failures during service would tend to be reduced by both the reduction in the number of manufacturing defects and property variability.

It is apparent that numerous fuel particle failure modes are possible, many of which are mechanically and chemically complex. As a result, failure mechanisms are not fully understood in many instances.

Currently, fuel behavior models are expressed in statistical terms and based mostly on empirical evidence. When applied to accident conditions, they generally yield extremely low site boundary exposures. These encouraging results carry some force because they are based mainly on in-pile tests and out-of-pile heatup data.

However, incomplete understanding of fuel failure mechanisms has its negative aspects. Most importantly, statistical and empirical evidence alone may not be fully convincing that all important factors have been considered. Experiments can be complex and open to interpretation, and reactor designs change with time, rendering the experience obsolete for current concepts. Hence, the complexity and lack of full understanding of the failure mechanisms must be viewed as a drawback.

In addition, it appears advisable to prioritize QC procedures with respect to the importance of the particular defect to fuel failure. Doing so requires a recognition of the mechanistic connection between the defect and the resulting failure mode. (QC tests are discussed in Sect. 5.)

Of the various manufacturing defects cited in this section, three may be noted as being potentially important with respect to fuel reliability. These are (1) fuel particle damage during compact manufacture, (2) HM dispersion, and

(3) fuel particle faceting.* The first two defects result from processing errors that should be prevented by the process control system and proven so by accompanying QA documentation. However, should they occur through some system flaw, it may be difficult, using current QC procedures, to reliably infer their adequately low frequency (see Sect. 5.).

The third defect, particle faceting, is not due to a processing error, but may result from subtle operational or design variations of a coater. Principal means for assuring its low frequency in the product is the tabling operation (see Sect. 2). However, information is not available regarding the reliability of the tabling operation for rejection of faceted particles. The planned QC procedure for detection of nonspherical particles, the aspect ratio test (see Sect. 5), is not appropriate for detection of faceting.*

These three manufacturing defects, should they occur, each have a high probability of causing premature failure of the fuel particle during normal operation, or more extensive failures under accident environments.

Hence, these three types of defects potentially exhibit the attributes of weak fuel. The concept of weak fuel, initially expressed as an intuitive conservatism on the part of the NRC, does have a mechanistic component. Adoption of QA/QC procedures that convincingly eliminate these three types of manufacturing defects would contribute toward reducing the currently imposed weak fuel restrictions.

*Reviewers indicated that defective SiC with excessive permeability may be added as a fourth significant manufacturing defect.

*A reviewer indicated that X-ray radiography can detect faceted particles. Radiography is included as a QC method; however, it is currently used only for monitoring coating thickness and kernel diameter [see Sect. 5 and Bresnik (1991)].

4 Fuel Design Requirements

4.1 Definitions and Development

Fuel design requirements define the behavior of the fuel required to meet the top-level performance goals of the reactor. The most recent documentation, presented by Tang (1989), appears to be consistent with a more extensive description provided in a prior document (DOE, 1987). The following top-level goals that ultimately define the fuel design requirements are stated in the PSID (1986):

Goal 1. Maintain Plant Operation. This encompasses all phases of normal operation including shutdown, routine maintenance, refueling, and startup.

Goal 2. Maintain Plant Protection. This is an investment protection goal that limits plant unavailability to <10%/year due to unscheduled events and loss of investment to a probability of $<10^{-5}$/year.

Goal 3. Maintain Control of Radionuclide Release (i.e., to the environment). This goal is to limit releases during accidents so the dose limits stated by the EPA Protective Action Guidelines (PAGs) are not exceeded at the Exclusion Area Boundary (EAB). Thus, meeting this goal precludes the need for public evacuation planning.

Goal 4. Maintain Emergency Preparedness. An example of the logic for deriving the fuel design requirements from the top-level goals is illustrated in Fig 4.1-1, which is an adaptation of a similar figure shown by Tang (1989). The figure also illustrates the relationship between the so-called Core Performance Criteria, often cited along with the Fuel Design Criteria, as well as the Fuel Product Specifications derived from the design requirements. Figure 4.1-1 applies to the requirements that satisfy the aspects of Goals 1 and 3 relating to radioactive release to the environment. Different, but similar, logic diagrams are required for satisfying other aspects of the top-level goals.

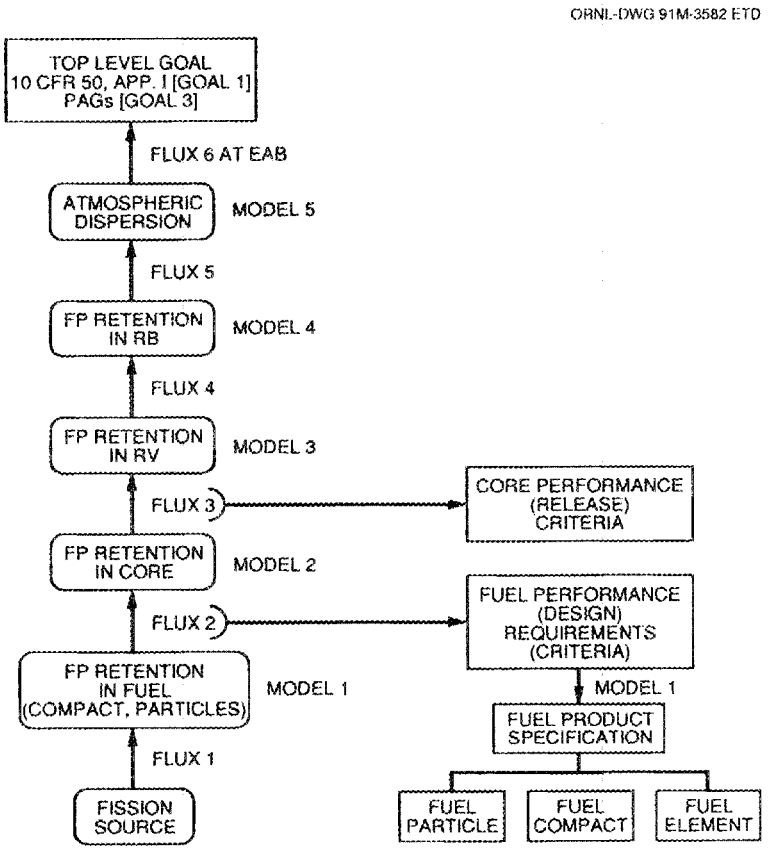

Figure 4.1-1 Determination and definitions of fuel criteria

The arrows shown in Fig. 4.1-1 signify the direction of radioactivity flow from the fission source to the atmosphere. The magnitude of the flow along the pathway from the source to the EAB is estimated by a series of models that describe retentions by the various barriers and atmospheric dispersion. However, the calculation proceeds predominantly in the reverse direction, from the given goal backward to the source. Defining the fuel criteria is a process of selecting the retentions by the principal fission product barriers required to meet the top-level goals, given the fission source and a conservative estimate of atmospheric dispersion.

The process can involve a good deal of trial and error or iteration. Note also that alterations of either the models for the various transport barriers, selection of accident scenario, or just about any feature of the reactor concept can, in principle, lead to modifications of the fuel requirements. However, programmatic and lead time considerations for fuel development call for as much stability in the fuel requirements as possible. Therefore, model or concept modifications are likely to be accommodated first by design alterations that do not require fuel alteration.

Core Performance and Fuel Design Criteria are often cited together. As Fig. 4.1-1 shows, the difference between the two relates to retention of radioactivity by fuel element graphite and the graphite associated with moderator elements through the core. Fuel Product Specification refers to the design details of the as-manufactured fuel element, including dimensions of the kernel and coating layers, properties of all parts of the fuel element, and impurity levels (as required to meet the Fuel Design Criteria).

4.2 Core Performance and Fuel Design Criteria

According to Tang (1989), top-level Goal 3, relating to radioactive release to the atmosphere caused by accidents, is the most restrictive requirement for defining core performance and fuel design criteria. Second in importance (according to Tang) is Goal 1, in particular the stated desire to limit occupational exposures to <10% of the 10 CFR 20 requirements. Tang cites unpublished estimates that indicate this occupational exposure limit may be satisfied when primary circuit plateout of radionuclides causes doses of <10 mR/h during scheduled maintenance activities.

Core performance criteria that allegedly satisfy the aspect of Goal 1 relating to releases from the core during normal operation are presented in Table 4.2-1. Tables 4.2-2 and 4.2-3 cite the core performance requirements relative to Goal 3 for long- and short-term accident events, respectively (Tang 1989).

Table 4.2.1 Maximum allowable releases from fuel element during normal operation averaged corewide (Goal 1 or 3 requirement)

	Allowable fractional release	
Nuclide	**≥50% confidence**	**≥95% confidence**
^{3}H	<[TBD]	<[TBD]
^{88}Kr	$<7.5 \times 10^{-7}$	$<3 \times 10^{-6}$
^{133}Xe	$<1.5 \times 10^{-6}$	$<6 \times 10^{-6}$
^{131}I	$<1.9 \times 10^{-6}$	$<7.4 \times 10^{-6}$
^{90}Sr	$<5 \times 10^{-8}$	$<5 \times 10^{-7}$
^{110m}Ag	$<5 \times 10^{-4}$	$<5 \times 10^{-3}$
^{137}Cs	$<7 \times 10^{-6}$	$<7 \times 10^{-5}$
^{134}Cs	$<7 \times 10^{-6}$	$<7 \times 10^{-5}$

Source: I. U. Tang, *MHTGR Fuel Product Specification*, DOE-HTGR-88140, 1989.

Table 4.2-2 Maximum allowable releases from fuel element during long-term transients averaged corewide (Goal 3 requirement)

Nuclide	PAG (user) limits P ≥ 50%	10 CFR 100 (Reg.) limits P ≥ [50%]
^{88}Kr	<[TBD]	<[TBD]
^{133}Xe	$<1.1 \times 10^{-4}$	$<2.1 \times 10^{-3}$
^{131}I	$<7.1 \times 10^{-5}$	$<2.1 \times 10^{-3}$
^{90}Sr	$<5.7 \times 10^{-4}$	$<1.8 \times 10^{-3}$
^{110m}Ag	<[TBD]	<[TBD]
^{137}Cs	<[TBD]	<[TBD]

Source: I. U. Tang, *MHTGR Fuel Product Specification*, DOE-HTGR-88140, 1989.

Table 4.2-3 Maximum allowable releases from fuel element during short-term transients averaged corewide (Goal 3 requirement)

	PAG (user) limits		10 CFR 100 (Reg.) limits	
Nuclide	P ≥ 50%	P ≥ 15%	P ≥ 50%	P ≥ 95%
^{88}Kr	<[TBD]	$<9 \times 10^{-6}$	<[TBD]	$<2.1 \times 10^{-4}$
^{131}I	<[TBD]	$<2.2 \times 10^{-5}$	<[TBD]	$<6.6 \times 10^{-4}$

Source: I. U. Tang, *MHTGR Fuel Product Specification*, DOE-HTGR-88140, 1989.

A variety of situations may be assumed as a basis for developing the criteria shown in the three tables—precisely which ones assumed were not stated. For example, NOC releases from the core (Table 4.2-1) may be limited by either 10 CFR 50 considerations on routine releases or by occupational dose considerations defined in 10 CFR 20. Both of these would relate to the Goal 1 objective. Alternatively, NOC core releases may be limited by accident release considerations within the context of Goal 3. For example, dry depressurization consequences relate directly to the ex-fuel radioactivity that develops over the course of normal operation. In addition, the particular long- and short-term transients assumed for generating the criteria shown in Tables 4.2-2 and 4.2-3 are not described.

In addition to these fuel element criteria, upper limits on fuel particle manufacturing defects are given in Table 4.2-4, reproduced from Scheffel and Tang (1989). The statistical bases for these limits vary for different defects, as noted in the footnotes to the table taken directly from the reference. Figure 4.2-1 taken from Bresnick (1991) defines the various types of fuel populations used to formulate the sampling plan. All of the cited defect levels are based on QC tests to be performed on samples of loose particles, except for defective SiC, which is based on the burn-leach test procedure. (See Sect. 5 for a summary of QC procedures.)

Table 4.2-4 Maximum allowable manufacturing defects of fuel particles in fuel element

Manufacturing defect category	95% confidence level for defects (fraction)	Allowable specification limit at 95% confidence level (fraction)
Missing or incomplete buffer	$\leq 5.0 \times 10^{-5}$ [a]	$\leq 2.0 \times 10^{-4}$ [b]
Missing or defective inner PyC	$\leq 4.0 \times 10^{-5}$ [c]	$\leq 1 \times 10^{-4}$ [d]
Missing or incomplete SiC	$\leq 5.0 \times 10^{-5}$ [c,e]	$\leq 1.0 \times 10^{-4}$ [d,e]
Missing or incomplete OPyC	$\leq 1.0 \times 10^{-4}$ [a]	$\leq 1.0 \times 10^{-3}$ [b]
Missing or incomplete protective coating	$\leq 1.0 \times 10^{-3}$ [a]	$\leq 1.0 \times 10^{-2}$ [b]

[a]Segment mean of particle composites. (Mean value of composite defect fractions in a segment.)
[b]95% confidence that ≤5% of the particle composite means in a segment exceeds the specified limit.
[c]The specification limit is on the mean fuel compact property, applied to the segment and not at the compact lot level.
[d]95% confidence that ≤5% of the compact lot mean measurements in a core segment exceeds the limit. In addition, the number of compact lots in the segment exceeding the limits must contain ≤5% of the total compacts in the segments.
[e]Based on burn-leach quality control technique.
Source: W. J. Scheffel and I. U. Tang, *Technical Support Document for the MHTGR Fuel Production Specification*, GA Document 903728, Issue D, 1989.

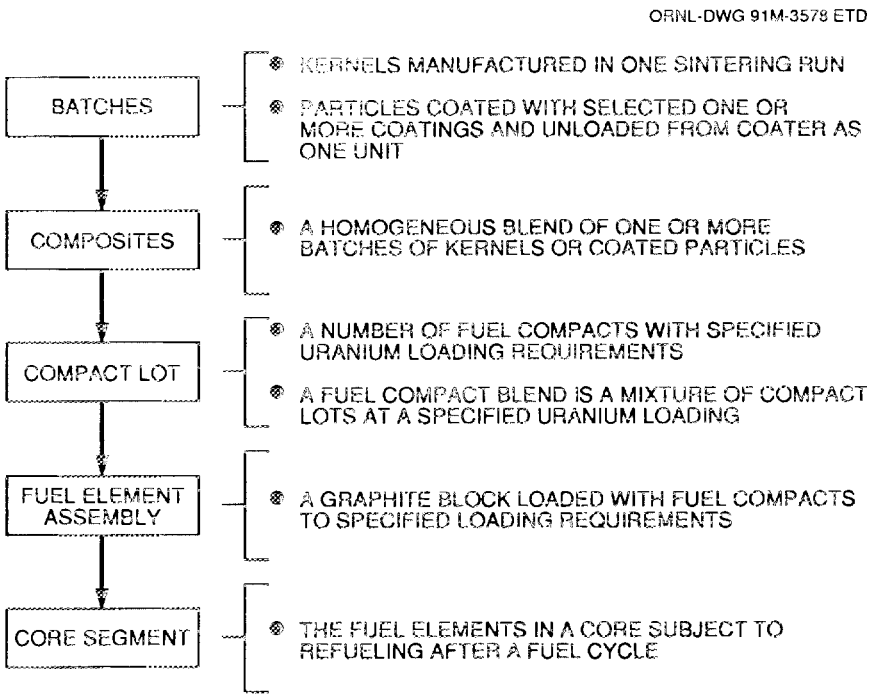

Figure 4.2-1 Fuel product specification units

The first column of specifications in Table 4.2-4 cites upper limits of the average value for each defect type based on an acquired sample, termed the "segment." That is, the specification cites that the segment mean for missing buffers should be $<5.0 \times 10^{-5}$, with 95% confidence. The second specification for each defect type is a limitation of the distribution of defects in the composites and lots. For example, the specification cites that <5% of the particle composites should contain more than 2.0×10^{-4} fraction missing buffers, again with 95% confidence.*

Notably absent from this list is the specification for maximum allowable HM contamination, cited by other documents as 1×10^{-5} fraction, presumably also based on the mean of samples from a set of composites of loose particles equal to a core segment. It is generally agreed that uranium contamination is the major source of fission gas release from fuel.

Table 4.2-5, taken from information presented in the preapplication draft SER (Williams et al. 1989) from an informal source, lists expected values of various types of fuel particle defects both in the as-manufactured condition and at the end of normal service. Tables 4.2-4 and 4.2-5 are consistent, except that the former does not include the degree of uranium contamination as a defect. These values should perhaps be considered as informal and reasonable fuel product goals projected by the potential manufacturer. The types of fuel failures in this format that release fission gases are expected to increase during service from 1×10^{-5} to 6×10^{-5} fraction at end of life. Table 4.1-4 shows the cause: the 5.0×10^{-5} fraction of particles with missing buffers is projected to fail in service in a way that exposes the kernel.

Table 4.2-5 also shows where fuel defects that release fission metals from the fuel particle are expected to increase from the as-manufactured level of 6×10^{-5} fraction to 12×10^{-5} at the end of life. The as-manufactured level is caused by a combination of uranium contamination and the expected existence of 5×10^{-5} fraction of defective SiC layers in "standard" fuel. The reasons for the expected increase with service life are the 5×10^{-5} particles with missing buffers plus an anticipated service failure fraction of the SiC layer of 1×10^{-5}.

*We are indebted to O. M. Stansfield for this lucid explanation.

Table 4.2-5 As-manufactured and EOL fuel particle failure fractions for release of fission gases and metals, projected for MHTGR

	As-manufactured	End of normal service life
Fission-gas release	1×10^{-5}	6×10^{-5}
Exposed kernels	(0)	(5×10^{-5})
Contamination	(1×10^{-5})	(1×10^{-5})
Fission-metal release	6×10^{-5}	12×10^{-5}
Exposed kernels	(0)	(5×10^{-5})
Contamination	(1×10^{-5})	(1×10^{-5})
Defective SiC	(5×10^{-5})	(6×10^{-5})

Source: P. M. Williams et al., "Draft Preapplication SER for the MHTGR," NUREG-1338, 1989.

4.3 Evaluation of Fuel Design Requirements

Appendix A outlines an order-of-magnitude comparison of Goals 1 and 3 requirements with the fuel design requirements listed in Tables 4.2-1 to 4.2-3.

4.3.1 Goal 3 Requirement (Maintain Control of Radioactive Release)

According to Table 4.2-3, the Goal 3 requirement for short-term accidental discharges will be met with 95% confidence by criterion restricting ^{131}I release from the core to 2.2×10^{-5} fraction of the inventory. The objective is to limit EAB doses to sufficiently low levels that preclude the need for protective action planning. This level is given by EPA (1975), which states that anticipated thyroid doses to the general population exceeding the range 5 to 25 rem would require protective action planning. The lower limit applies if there are "no major local constraints in providing protection at that level." Therefore, the quantitative Goal 3 limit of 5 rem is in accord with the EPA guideline.

The design requirement of 2.2×10^{-5} fractional release of ^{131}I for a short-term event is tested in Appendix A.1. As indicated there, the specified release fraction would result in the insertion of 257 Ci of ^{131}I into the reactor building (RB) in a depressurization event, assuming no holdup in the primary vessel. This is a conservative assumption, but not unreasonable for a wet depressurization event. A building leakage rate of 100%/d is shown to result in a release to the atmosphere of approximately 22.3 Ci of ^{131}I during the initial 2 h of the event, assuming the iodine remains in the gas phase.

The resulting dose at the site boundary, using an EAB radius of 475 m (PSID 1986), a breathing rate recommended by Reg. Guide 1.4 (1974), an atmospheric dispersion appropriate for ground release, and a dose conversion factor cited by Dunning et al. (1981), leads to a dose estimate of 20.1 rem at the site boundary due to ^{131}I (see Appendix A.1). If the ^{133}I design requirement is similar to ^{131}I, the total dose to the thyroid due to breathing for a short-term event is estimated to be 31.1 rem. This exceeds the Goal 3 requirement by about a factor of 6.

Thus, for the stated design requirement to be consistent with Top-Level Goal 3, it needs to be shown that the conservatisms assumed in the Appendix A.1 estimate, when more accurately evaluated, would lead to more than a factor of 6 reduction in the dose estimate.*

4.3.2 Goal 1 Requirement

Satisfaction of Top-Level Goal 1 (Maintain Plant Operation) involves several facets, one of which relates to allowable worker exposure levels during performance of

*Condensation of steam in the RB may be an effective attenuation mechanism for a wet depressurization event.

routine maintenance operations. As a device for meeting this aspect of Goal 1, Tang (1989) reports that Goal 1 will be satisfied if such exposure levels are limited to <10% of the limit set by 10 CFR 20. At the current level of design, according to Tang (1989), it is believed that this will be accomplished if "the gamma radiation fields around the primary circuit due to fission product plateout were limited to <10 mrad/h."

The exposure rate to workers performing contact maintenance on primary system parts is roughly estimated in Appendix A.2. It is assumed that the exposure is due solely to ^{137}Cs released from the fuel at the fractional rate of 7×10^{-5}, as cited in the fuel design criteria given in Table 4.2-1. (Note, this is the criterion for satisfying Goal 3. No equivalent criterion is given for Goal 1 because Goal 3 is held to be limiting.) It is further assumed that ^{137}Cs plates uniformly along primary system surfaces.

The precise geometry of the exposure is a critical feature of the maintenance-dose estimate. The estimate in Appendix A.2 assumes that a dose is received by direct contact of tissue with the exterior of a pipe contaminated on the interior surface. Contributing to the radiation field are all photons emanating from ^{137}Cs plated directly beneath the tissue from both the near and far surface of the pipe.

This rough model leads to a radiation field of 720 mrad/h adjacent to the contaminated pipe near the end of reactor life (at 35 years of operation), which is about 70 times the desired limit of 10 mrad/h. Because additional contributions to the radiation field from ^{134}Cs, ^{136}Cs, and ^{110}Ag may be expected, it is felt that there may be some question regarding the consistency between meeting Goal 1 and the pertinent fuel design requirements.*

*A teleconference was arranged by NRC between the authors and General Atomics (GA) personnel; also included were Bechtel analysts performing maintenance dose estimates under subcontract to GA. The purpose was to discuss the results presented in this section. This discussion concluded the following: (1) The <10-mrad/h criterion for satisfying the top-level maintenance dose requirement was based on a preliminary evaluation. (2) This criterion was used to specify the 50% confidence fission product release levels for routine operation. (3) More recently, Bechtel analysts have concluded that the fission product release criteria for routine operation, evidently based on the early rule of thumb, nevertheless satisfy the requirements of Top Level Goal 1 with respect to routine maintenance doses. The Bechtel analysis includes time studies of maintenance operations, dose estimation for the population of maintenance workers, and 3-D codes for estimating photon transport.

4.3.3 Comparison of Fuel Element and Fuel Particle Requirements

Tables 4.2-1 through 4.2-3 cite fractional release limits from the fuel element averaged over the core and service life of the element, as required to satisfy the top-level goals (Tang 1989). In addition, product criteria are cited that limit fuel particle defect fractions (e.g.,Tables 4.2-4 and 4.2-5). Consistency between these two types of specifications may be tested as follows.

Table 4.2-1 indicates an expected fractional release of $<1.9 \times 10^{-6}$ during normal operation is required. In comparison, Table 4.2-5 cites an expected defect fraction of the type that releases fission gases to be 3.5×10^{-5}, averaging the as-manufactured and end-of-life values in the table. Because the duration of the holdup of fission gases in defective particles appears to be about 1 month (Wichner 1991), and because all of the important fission gases have relatively short half-lives, radioactive decay significantly reduces release of fission gases from defective fuel. An evaluation presented by Wichner (1991) indicates that the defect fraction cited in Table 4.2-5 results in an ^{131}I fractional release of 3.37×10^{-6}, with the predominant share due to uranium contamination. Because very little iodine holdup is expected in the fuel element graphite, the expected release fraction from the cited particle defect fraction exceeds the specified allowable fuel element release by about a factor of 2.

The expected failure fraction for releasing fission metals (e.g., ^{137}Cs) is given in Table 4.2-5 as 9×10^{-5}, averaging the as-manufactured and end-of life values. In contrast to fission gases, there is little holdup decay for generally long-lived fission metals. Therefore, at temperature below which diffusive release from intact particles becomes significant (~1000°C), fractional release rates are approximately the sum of the SiC defect fraction and the uranium contamination level (i.e., the fractional release rate of fission metals indicated by Table 4.1-5 is 9×10^{-5}). In comparison, the mean release rate of ^{137}Cs from the fuel element for satisfying top-level Goal 3 is specified in Table 4.2-1 as 7×10^{-6}, about a factor of 10 lower.

This discrepancy is somewhat relieved by recognizing that there is a strong tendency for cesium sorption in the fuel element graphite. However, fission metal holdup by sorption in graphite thereby becomes a transport step of equal significance to holdup by the particle coatings.

4.4 Summary of Fuel Design Requirements Evaluation

An order of magnitude estimate indicates that the cited fuel specifications are consistent with meeting top-level Goal 3 (Control of Radionuclide Release). However, the comparison is fairly close, and a presumption of even a small degree of "weak" fuel may require high vessel and building retention factors for Goal 3 to be met.

The cited maximum allowable release fractions from the fuel element for normal operation appear to significantly exceed the level required for satisfying the aspect of Goal 1 pertaining to routine maintenance doses. The discrepancy may be on the order of a factor of 1000 during the latter years of reactor operation, unless the equipment is decontaminated, at least for cesium, prior to performing the maintenance.

Cited fuel particle defect objectives may permit releases of fission gases and fission metals that exceed the stated core performance criteria. The difference is about a factor of 2 for the ^{131}I and a factor of 10 for ^{137}Cs. The estimated ^{137}Cs release from the fuel element would be reduced by accounting for holdup in graphite. Doing so would bring the defect fraction objective and the release criterion closer together.

5 QA/QC Methods

The fission product retention capability of the MHTGR fuel depends strongly on the as-manufactured attributes of the coated particle fuel. Key attributes are the as-manufactured, heavy-metal contamination, dispersion, and the fraction of particles with coating defects that can lead to in-service failure (see Chap. 4 for details).

The heavy-metal contamination consists of uranium located outside the SiC coating layer either in the fuel particles or the fuel rod. When this uranium undergoes fission, its fission products can easily migrate into the coolant. The heavy-metal dispersion consists of uranium that moved outside the fuel kernel as a result of a defective IPyC layer that did not protect the fuel kernel from chlorine attack during SiC coating.

Coating defects are missing coatings or out-of-spec coatings that can lead to a failure of the fission product retention capability of the coated particle fuel (Chap. 3).

Quality assurance and quality control measures are employed to guarantee that fuel of a given design is manufactured with the required degree of precision. The QA/QC methods discussed here deal with as-manufactured fuel and do not address whether the fuel is properly designed.

5.1 Past Practice

The FSV initial core required about 20,000 kg of HEU $(U,Th)C_2$ and ThC_2 TRISO-coated particles that were assembled into about 1500 hexagonal prismatic fuel elements. Subsequently, three reload segments with 250 fuel elements each were manufactured. Presently available techniques and instruments ensured good quality fuel for FSV. However, the MHTGR has an oxide-based fuel, as compared to the carbide fuel in FSV, with substantially lower defect and contamination requirements. According to the fuel technology development plan (Techplan, 1987), present techniques fall short in several areas, particularly the measurement of the heavy metal contamination of the matrix and determination of the fraction of exposed kernels in the compact. Furthermore, more reliable methods are required than the burn-leach technique to determine SiC layer defects.

Techplan (1987) characterizes current deficiencies of the burn-leach process as follows:

> The primary limitation of existing techniques is that the nitric acid liquid leach methods do not remove the contamination and exposed oxide kernels with sufficient speed and completeness to make the techniques commercially viable. Measurement of contamination levels on the order of 1×10^{-5} fraction is near the limit of detectability in carbide fuel systems, and when oxide fuel is present the results often show more variation and uncertainty. The limitations arise in part from the fact that for the extremely low concentrations the chemical activity of the heavy metal in the leach solution rapidly approaches that in the matrix and leaching action stops. In addition, the oxide fuel form is much less readily attacked by nitric acid than the carbide form.
>
> Particles with a missing buffer layer are detected by X-radiography and manual scanning of the radiograph to detect individual defective particles. In order to make statements regarding the presence of defects at $<5.0 \times 10^{-5}$ fraction at least 40,000 particles must be individually examined. This is 40 times more than required for prior HTGR designs. The time and associated cost of using current techniques to characterize missing buffer layers would be excessive. The application of automated computerized techniques to interpret radiographs of coated particles and detect defective particles may be a viable alternative to current manual methods.

5.2 Proposed Practice

The proposed practice for MHTGR fuel quality assurance is described in the fuel manufacturing QA plan (Miller et al. 1988), and more recently by Bresnick (1991). This QA Plan consists of three elements:

1. fuel production quality control,
2. administrative controls, and
3 record control.

Each element of the proposed QA Plan will be summarized. In addition to these elements, Process Control is also expected to be a part of the overall QA system. Processing conditions along the manufacturing route are expected to be included in the traveling records accompanying each batch of fuel.

5.2.1 Fuel Quality Control

The MHTGR core will contain about 9.2×10^9 UCO TRISO and 2.5×10^9 ThO_2 particles that are produced in coating batches of about 20 million particles of either UCO or ThO_2 kernels. Typical production rates for a 4×350 MW(t) MHTGR would be

8.1 elements per day,
25,500 fuel compacts per day,
5.7 fissile fuel batches per day, and
2 fertile fuel batches per day.

Table 5.2-1 shows typical steady-state MHTGR fuel production quantities.

Table 5.2-1 Typical steady-state MHTGR fuel production quantities

MHTGR core component	Approximate quantity
Number of fertile ThO_2 particles/kg heavy metal	1.5×10^6
Number of fissile UCO particles/kg heavy metal	4.05×10^6
Number of fertile particles/compact	1200
Number of fissile particles/compact	4500
Number of fuel compacts/regular fuel element	3126
Number of fuel compacts/lot	40,000
Fertile fuel batches/composite	13
Number of fissile batches/composite	4
Number of fertile particles/core	2.5×10^9
Number of fissile particles/core	9.2×10^9
Number of fuel elements/core	660
Number of core segments/core	2

Source: C. M. Miller et al., "MHTGR Fuel Manufacturing QA Plan," DOE-HTGR-88091, Rev. 0, 1988.

Both destructive and nondestructive quality control methods are proposed to determine the attributes of the fuel particles/compacts. The available quality control methods are summarized in Table 5.2-2.

Because of the large number of particles involved and the need for destructive testing, a statistically based sampling program is planned to characterize the particle/compact quality to ensure that they conform with specified limits on properties and defect levels.

The proposed sampling plan covers the raw materials used in the particle and compact fabrication, the fuel particles, and compacts.

Raw material sampling plan: Table 5.2-3 shows the proposed sampling plan for raw materials. The actual sample size will be determined by Fuel Quality Control in accordance with the MHTGR specification requirements.

Fuel particle production sampling plan: Table 5.2-4 shows the sampling plan for fuel kernels and TRISO particles. The sampling is done at the composite level (a composite consists of a homogeneous mixture of 4 batches of fuel, and a fuel batch consists of 20 million particles). The composite sampling process depends on the attribute that needs to be controlled. According to Miller et al. (1988), the sampling plan is structured to operate under the following acceptance criteria:

1. Sample each composite according to Table [5.2-4] for variable properties at a 50% confidence level to meet the segment or the composite requirements. If the property meets this acceptance criterion, the property is accepted and the batches making up the composite are physically blended.

   Alternately, if the composite batch fails this acceptance criteria, the individual batches making up the composite are sampled and the property measured to determine which batches should be rejected to increase the composite quality enough to be accepted.

2. Sample each composite for attribute properties, i.e., defective buffer, IPyC, OPyC, and PPyC layers, to determine if zero defects

Table 5.2-2 Available quality control techniques

Technique	Property	Component	Destructive
1. Emission spectrography	Impurities	Kernel	Yes
2. Atomic absorption	Impurities	Kernel	Yes
3. Spectrophotometry	Impurities	Kernel	Yes
4. Burn/gravimetry	Carbon, wt %	Kernel	Yes
5. Mass spectrometry	U isotopics	Kernel	Yes
6. Wet chemistry	Total U wt %	Kernel	Yes
	U loading	Fired compact	Yes
	Th loading	Firec compact	Yes
7. Gas chromatography	Oxygen, wt %	Kernel	Yes
8. Mercury pycnometry	Density	Kernel	Yes
9. Mercury intrusion	Microporosity	OPyC	Yes
10. Gradient column	Density	IPyC	Yes
		SiC	Yes
11. Bulk density	Density	OPyC	Yes
		PPyC	Yes
12. Methylene iodide intrusion/X-ray	Porosity	IPyC	Yes
13. Radiography	Diameter thickness	Kernel	No
		Buffer	No
		IPyC	No
		SiC	No
		OpyC	No
		PPyC	No
	Faceting	Particle	No
	Missing/incomplete buffer	Buffer	No
	Missing/incomplete OPyC	OPyC	No
	Particle shape	Shim	No
14. Particle-size analyzer	Diameter	Kernel	No
15. Metallography	Porosity	OPyC	Yes
	Macroporosity	Fired compact	Yes
16. Seibersdorf unit	Anisotropy	IPyC	No
		OPyC	No
17. X-ray diffraction	Filler crystallite	Matrix	Yes
18. Coulter count,	Filler particle size	Matrix	No
Sartorius sedimentation balance, Tyler screen	Particle-size distribution	Shim	No
19. Gamma spectroscopy	Fuel homogeneity	Green compact	No
20. Burn-leach	Defective SiC	Fired compact	Yes
	HM contamination	Fired compact	Yes
	Defective IPyC	Fired compact	Yes
21. Burn/gas analysis	Sulfur content outside SiC	Particle	Yes
22. Burn/colorimetry	Iron impurities	Fuel particle	Yes
23. Gas or liquid leach	HM contamination	Fired compact	Yes

Source: C. M. Miller et al., "MHTGR Fuel Manufacturing QA Plan," DOE-HTGR-88091, Rev. 0, 1988.

Table 5.2-3 Proposed raw materials sampling plan

Material name	Pop. size	Sample size
Uranium oxide	150 kg	250 g
Thorium oxide	1 lot	100 g
Argon, nitrogen, hydrogen	Material certification	
Propylene	Material certification	
Acetylene	Material certification	
Methytrichlorosilane	0.21 m^3	100 ml
Calcinated alumina powder	1000 lb	50 g
Carbon cement	10 gal	800 ml
Carbon cement primer	10 qt	50 g
Anhydrous hydrogen chloride	Material certification	
Methylchloroform	55 gal	1000 ml
Petroleum pitch	550 gal	200 g
Petroleum pitch (low sulfur)	550 gal	200 g
Manufactured graphite flour	500 lb	
Octadecanol	500 lb	
Polystyrene	500 lb	
Shim	Product analysis	
Alcohol	Material identification	

Source: C. M. Miller et al., "MHTGR Fuel Manufacturing QA Plan," DOE-HTGR-88091, Rev. 0, 1988.

are observed in the minimum particle amounts listed in Table [5.2-4]. If the composite meets this acceptance criterion, the property is accepted and the data are pooled with previous measurements on defective particle fractions for the segment.

Alternately, if a defective particle is observed in the minimum sample, the measurement data is pooled and evaluated with respect to prior accepted composites for the segment. If the pooled data passes the core segment specification requirements, then the marginal (previous failed) composite is accepted.

Fuel compact production sampling plan: The fuel compact production sampling plan is applied to a lot level of production, with 40,000 fuel compacts constituting a lot. The lot is divided into 5 sublots of 8000 compacts each, with the first 8000 compacts produced in the first sublot, the next 8000 compacts produced in the second sublot, etc. The fuel compact sampling plan showing the minimum number of properties to be sampled is shown in Table 5.2-5. According to Miller et al. (1988), the sampling plan is based on the following acceptance criteria:

Sample each sublot at a 50% confidence level to the compact lot or core segment requirements. If the property meets this acceptance criterion, the property is accepted and the data is pooled with previous measurements on this property.

Alternately, if the sublot fails the acceptance criteria, the measurement data is pooled and evaluated with respect to previously accepted sublots or lots. If the pooled data passes the lot and/or core segment acceptance criteria, then the marginal (previously failed) sublot is accepted.

Samples are to be taken from sequential increments of the lot (consisting of 40,000 fuel compacts), with each increment representing ~20% of the compacts in a lot.

The sampling strategy is a two-stage process. Products are tested and are found acceptable if they meet acceptance criteria. Those products that at this preliminary stage are found marginally unacceptable are placed on a "hold" status and then pooled and evaluated with previously accepted lots/sublots/composites/segments.

5.2.2 Administrative Controls

According to Miller et al. (1988), a Quality Assurance Program Document (QAPD) is expected to establish quality assurance requirements that will be implemented. The QAPD is a controlled document that invokes the Quality Assurance manual (QAM) for use on the MHTGR program and establishes the authority of quality assurance activities.

Table 5.2-4 Proposed MHTGR particle production sampling plan

Specification requirement		Composite process sampling		Acceptance criteria
Category	Property	Number of particles/kernels	Weight (g)	
Kernels	Chemistry		≥10	*a*
	Impurities			
	Density			
	Diameter	≥100		
TRISO	Buffer thickness	≥50		*a*
	Buffer density		≥10	*a*
	IPyC thickness	≥50		*a*
	IPyC density		≥10	*a*
	IPyC anisotropy	≥10		*a*
	SiC thickness	≥50		*a*
	SiC density		≥10	*a*
	OPyC thickness	≥50		*a*
	OPyC density		≥10	*a*
	OPyC anisotropy	≥50		*a*
	OPyC microporosity		≥10	*a*
	OPyC (oriented porosity)	≥50		*a*
	PPyC thickness	≥50		*a*
	PPyC density		≥10	*a*
	Faceting	≥30		*a*
	Defective buffer	$\geq 10^4$		*b*
	IPyC porosity	$\geq 10^4$		*b*
	Defective OPyC	$\geq 10^3$		*b*

[a]Sampling for variable properties at the 50% confidence level of specified composite specification limits.
[b]Sampling for attribute properties at composite level based on observing zero defects in stated minimum particle population.
Source: C. M. Miller et al., "MHTGR Fuel Manufacturing QA Plan," DOE-HTGR-88091, Rev. 0, 1988.

Table 5.2-5 Proposed MHTGR fuel compact production sampling plan

Specification requirements		Lot sample size (compacts)	Acceptance criteria
Category	Property		
Green compact	Matrix filler content	≥10	*a*
	Fuel homogeneity	≥10	*a*
Fired compact	Uranium loading	≥10	*a*
	Thorium loading	≥10	*a*
	Diameter	*b*	*b*
	Length	≥10	
	Stack height	*b*	*b*
	Coke content	≥10	*a*
	Macroporosity	≥10	*a*
	Mean heavy metal contamination fraction	≥300	*a*
	Mean defective SiC plus heavy metal contamination	≥300	*a*
	Mean defective SiC	≥60	*a*
	Mean defective IPyC	≥60	*a*
	Mean impurities burnable, nonburnable, hydrogen, chlorine, and sulfur	≥60	*a*
	Iron content and transition metal impurities	≥10	*a*

[a]Sampling for variable properties at the 50% confidence level of specified composite specification limits.
[b]100% sampling.
Source: C. M. Miller et al., "MHTGR Fuel Manufacturing QA Plan," DOE-HTGR-88091, Rev. 0, 1988.

The proposed organization for the MHTGR Fuels QA program is shown in Fig. 5.2-1. It shows that fuel fabrication and fuel quality control are performed by different organizations whose managers report to the director of nuclear fuel fabrication. He reports to the senior vice-president. At the same level but in a different organization is the quality assurance organization whose director also reports to the senior vice-president.

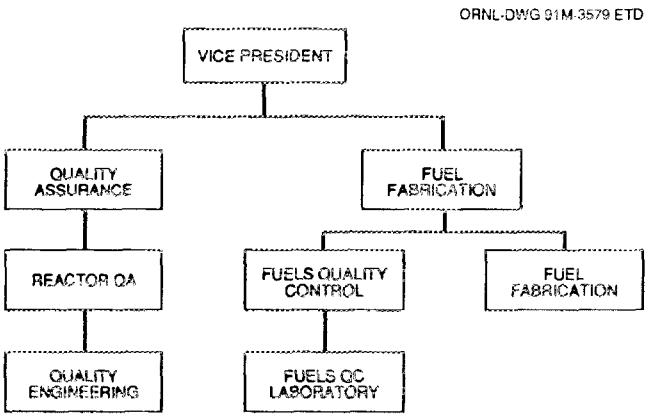

Figure 5.2-1 Organization for fuels QA program

This organization provides for the required independence of quality control from quality assurance but brings fuel fabrication and fuel quality control under the same management.

5.2.3 Records Control

It is proposed in Miller et al. (1988) that all records shall be collected, indexed, and stored in an orderly and legible form. The types of records required and the storage responsibilities are shown in Table 5.2-6.

5.3 Sample Size Considerations

Many factors involving details of the manufacturing process, desired level of quality, level of manufacturing capability, cost and availability of QC methods, process maturity, and selected confidence levels contribute to the selection of an optimum QC sampling strategy. This complexity is indicated by preliminary discussions of the sampling plan provided in the QA plan report (Miller et al. 1988) and the fuel production specification report (Scheffel

Table 5.2-6 QA record retention responsibilities

Record types	Record form	Storage responsibility	Transmittal to storage responsibility
Quality Assurance Program Document	Microfilm	Quality systems	Quality systems
Quality Assurance Manual	Microfilm	Quality systems	Quality systems
Program/Resource Procedures Manual	Microfilm	Records management	Planning and cost estimating
Design documents	Aperture cards Microfiche	Records management	Configuration management
Receiving/Source Inspection Plans (completed) including their associated data packages	Microfilm	Quality systems	Cognizant QE
Nonconformance reports (completed)	Microfilm	Quality systems	Cognizant QE
Fuel Operating Procedure	Microfilm	Quality systems	Fuel fabrication
Product/Process Run Sheets	Microfilm	Quality systems	Fuel fabrication
Fuel Quality Department Instructions	Microfilm	Quality systems	Fuel quality control
Product Release Records	Microfilm	Quality systems	Fuel quality control
Product Analysis Results	Microfilm	Quality systems	Fuel quality control
Raw Materials Records	Microfilm	Quality systems	Fuel quality control

Source: C. M. Miller et al., "MHTGR Fuel Manufacturing QA Plan," DOE-HTGR-88091, Rev. 0, 1988.

and Tang 1989). A recent report indicating the status of the sampling plan is provided by Bresnick (1991). The principal intention here is to illustrate the difficulty in inferring an extremely low defect fraction with high reliability.

5.3.1 Required Sample Size

Assume a sample of N_s items drawn from a large population, where each item may be labeled as defective or not by some measured criterion. The best situation regarding defects in the population occurs when zero defects are detected in the sample. If q is the unknown defect fraction of the population, the probability P_o of drawing no defects is given by

$$P_o = (1 - q)^{N_s} . \qquad (5.3\text{-}1)$$

If P_o is set at 0.05 (for the 95% confidence value) and the defect fraction is assumed to be 10^{-5}, Eq. (5.3-1) may be solved for sample size required to yield a 0.05 probability of containing no defects. Smaller sample sizes would exhibit higher probability for containing no defects. In other words, that particular sample of N_s items would indicate that the defect rate was no greater than 10^{-5} with 95% probability. For 10^{-5} defect fraction and 95% confidence, Eq. (5.3-1) indicates that a minimum sample size of 3×10^5 is required.

The relationship between defect fraction, required sample size, and confidence level is shown more generally in Fig. 5.3-1. As an example of this figure, if 10^5 items are drawn with no defects, a defect rate of 3×10^{-5} or less is inferred with 95% probability. The true defect fraction may be any value lower than this. However, larger samples would be required to infer lower defect fractions with 95% confidence.

However, this represents the most optimistic result. Characteristics of the Bernoulli probability distribution, of which Eq. (5.3-1) is a special case, indicate that on the average, two defects would be drawn with a standard deviation of 1.7.* Thus, drawing 1, 2, or 3 defects would be more likely in this case than drawing none. Thus more

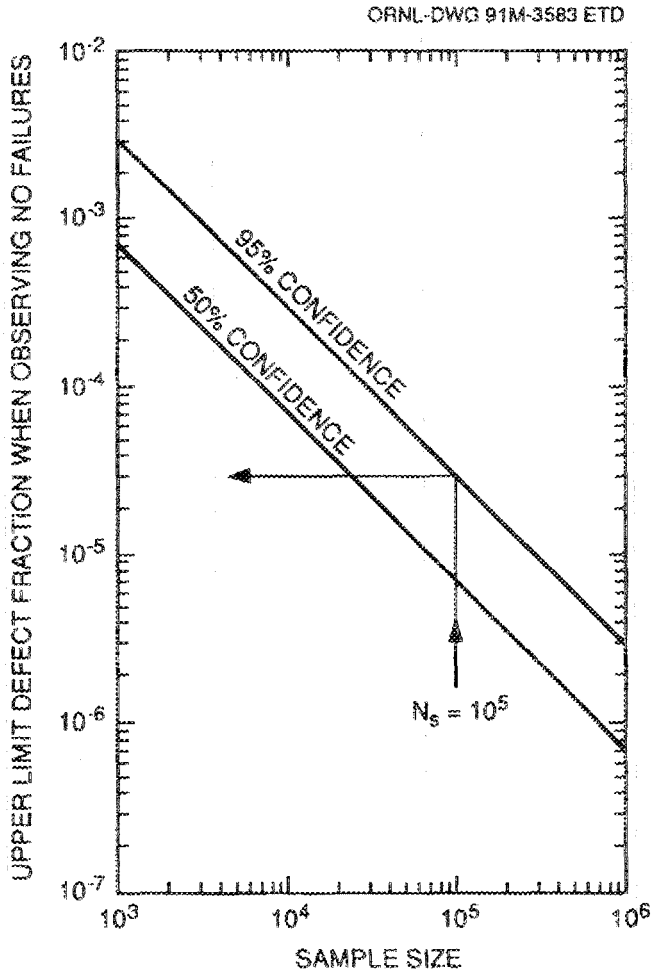

Figure 5.3-1 Relation between sample size and detectable defect fraction

usually, sample sizes far in excess of 10^5 would be required to infer a 3×10^{-5} defect rate with 95% confidence.

Bresnick (1991) asserts that rejections due to QC inspections may be reduced and the overall process efficiency increased when the production capability for quality significantly exceeds the specification. This is illustrated by assuming a production capability of 10^{-6} defect fraction and the same product specification of 3×10^{-5}. In this case, a sample size of 10^5 has a high liklihood of containing zero defects. (The mean value of defects in the sample would be $10^5 \times 10^{-6}$, or 0.1.)* Thus, Fig. 5.3-1 would apply and indicate that the 10^5 sample size with no defects infers a defect fraction of 3×10^{-5} or less with 95% confidence.

*According to the Bernoulli distribution, the average number of defects in a sample size of N_s is $N_s q$, where q is the defect fraction; the standard deviation is given by $[N_s(1-q)q]^{0.5}$.

5.3.2 Factors Influencing Sample Size

The facility for performing a particular QC test unavoidably tends to influence the sample size. For example, if a production line includes automated metrology, it would actually cost less to perform such metrology at a 100% rate than by acquiring samples. In contrast, there would be a natural tendency for carefully justifying the sample size of costly and destructive QC tests.

An important factor influencing sample size is the maturity of the process. Established manufacturing processes mainly require assurance of continued process and product stability. Such situations may call for smaller samples than indicated by statistical inference theory. In contrast, new processes with no track record may prudently perform QC tests on sample sizes in excess of the formal requirements.

Discussions with QA managers for LWR fuel vendors (Sect. 6) indicated that sample sizes for QC tests performed along the production line are determined in priority order. That is, QC tests on properties deemed most significant for product reliability are performed at the highest sampling rate. As seen in Sect. 6, several such properties are deemed sufficiently important to warrant 100% sampling. Of course, in such cases it is quite fortunate to have available a nondestructive test.

5.4 Evaluation

The QA/QC program, outlined in preliminary documents, indicates that the administrative plan for the program conforms to the general outline required for fabrication of nuclear fuel. QC tests performed at key points along the fabrication line indicate the degree to which the product conforms to the design specifications at various stages of completion. QC test results, with process control data and verification of raw material standards, constitute the record of the production unit (the batch) that is transferred to the QA department. The QA staff, administratively separated from both the QC activity and fabrication, may release the product after establishing from the record that the product conforms to the design specifications.

Some departure from usual practice is planned as a cost-savings measure. It is proposed to combine batches of loose particles, some of which may be outside of specifications, into composites so the composite as a whole conforms to the specifications. If instituted, this feature may run counter to the general trend of maximizing fuel quality, as has been adopted by LWR fuel vendors (see Sect. 6).

The role of QA/QC activities in development of fuel quality should be noted. Fuel quality is taken here to mean both conformance to design specifications by the fabrication process and performance in service according to expectations predicted by the behavioral models. QA/QC activities relate only to the former (i.e., assurance that the as-manufactured product conforms to specifications). Overall fuel quality, in the sense used here, requires a complementary set of activities, including establishment of design requirements, proper fuel design, fabrication process design and control, QA/QC, surveillance or other fuel testing, evaluation of failure modes, and possible consideration of improved fuel design. This is a more limited role for QA/QC than indicated in some of the reference documents.

The currently available tests, from which the QC program will be formulated, are listed in Table 5.2-2. The majority of the tests are destructive and would be performed on selected samples. A potentially troublesome feature is the availability of only destructive tests for the finished product, the fuel compact. As noted in Sect. 2, compact fabrication constitutes a significant threat to the integrity of the fuel particles. Hence, QC testing of the finished compacts is a critical area. The acknowledged uncertainties regarding the principal QC procedure available for the compact, the burn-leach test, exacerbates this problem. The burn-leach procedure is the only available test for the integrity of the SiC layer.

It is also noted that there is no QC test being considered that is a direct measure of proper functioning of the principal containment barriers, the SiC and OPyC layers. Instead, proper function is inferred from density and thickness measurements together with process control data. The latter indicates that the barriers behave properly when formed at the specified conditions. However, the lack of a specific test for proper function is a disadvantage.

This issue of proper sample size is complex and remains to be optimized. Some of the factors influencing sample size are process maturity, importance of the measurement relative to performance, cost, and availability of test. It is noted that attribute measures to infer low defect rate with high confidence require a large sample size.

6 LWR Fuel Reliability Perspective

This section presents a review of the manufacture of LWR fuel with the objective of gaining some insight that may apply to the MHTGR. While LWR and MHTGR fuels are quite different, several failure modes are at least analogous. In addition there is a common desire for the achievement of high fuel reliability, specifically minimizing both as-manufactured defects and those that develop in-service. At the current time, LWR vendors have achieved a defect fraction for discharged fuel roughly equivalent to the MHTGR objective for as-manufactured fuel. Thus evolutionary improvements in LWR fuel manufacture have been highly successful.

The continually improving reliability of LWR fuel has resulted principally from the efforts of the manufacturers, with strong support from utilities, the Institute for Nuclear Power Operations (INPO), and the utility organization, EPRI. The DOE has provided support in some areas, for example, funding for tests leading to improved high-burnup performance. In addition, the NRC requirements for surveillance of discharged fuel and its continued interest, as exemplified by its annual summary of LWR fuel performance, has undoubtedly contributed a positive effect.

6.1 LWR vs MHTGR Fuel Parameters

Fuel elements for LWRs consist of sintered UO_2 pellets contained within a sealed tube of Zircaloy cladding. Pellet sizes vary somewhat between vendors but are roughly 1 cm in diameter by 1 cm in length. As such, they are approximately the same diameter as MHTGR fuel compacts, whose function is, however, quite different. MHTGR compacts contain about 6000 fuel particles, each composed of several layers of "cladding" that form the initial seal for fuel and fission products. While LWR pellets also provide some degree of fission product containment, none is relied upon; the initial containment function is being provided solely by the Zircaloy cladding. Table 6.1-1 lists some typical parameters comparing LWR and MHTGR fuel.

As the table shows, the number of fuel element assemblies and fuel pellets in LWRs and MHTGRs are roughly comparable on a per MW(t) basis, taking the fuel column of the MHTGR to be the equivalent of the LWR assembly. On the other hand, there are far fewer fuel elements in the MHTGR per MW(t), the MHTGR fuel element (i.e., the fuel block) being a far larger structure. Also, there is no equivalent of the MHTGR fuel particle in the LWR. The function of the fuel particle coatings that provide the initial container for fuel and fission products is served in the LWR by the fuel element cladding.

Table 6.1-1 Comparison of LWR and MHTGR fuel element parameters (typical values)

	PWR	BWR	MHTGR
Core power [MW(t)]	3000	3000	350
Assemblies in core	200	600	66[a]
Fuel elements in core	40,000	40,000	660[b]
Fuel pellets in core	1.6×10^7	1.6×10^7	2×10^6[c]
Fuel particles in core	NA	NA	10^{10}
Enrichment, %	2.6–4.0	1.9–2.8	20
Burnup,[d] %	4.7–5.5	3.5–5.5	26

[a]Fuel columns.
[b]Graphite fuel blocks.
[c]Fuel compacts.
[d]Fraction initial metal atoms.

6.2 Development of Improved LWR Fuel Reliability

6.2.1 LWR Fuel Failure Modes

Over the years, postirradiation examinations have revealed a series of mechanisms causing failures of LWR fuel rods, failure being defined as a breach of the cladding. A summary of these mechanisms, compiled by El-Adham (1988) and supplemented with information from Franklin et al. (1985), is presented in Table 6.2-1. While LWR fuel is quite different from that of an MHTGR, several failure mechanisms are at least similar. If we identify the SiC coating with the cladding, which has a roughly comparable function, we note that the pellet-cladding interaction (PCI) failure mechanism has its MHTGR counterpart in the corrosive failure of SiC by rare-earth fission products. In addition, hydriding failure has an analogy with corrosion of the SiC layer due to impurities in the kernel (e.g., transition metals and chlorine), and breakage due to mishandling of fuel rods is roughly comparable to particle breakage due to pressure during compact fabrication. Fabrication of both types of fuel are also subject to mishandling errors. LWR vendors have developed computerized logging procedures that identify each fuel pin and fuel pellet contents, tracking them back to the raw-material sources. An equivalent system would be applied to MHTGR fuel elements.

Table 6.2-1 LWR fuel failure mechanism

Phenomenon	Cause	Correction
Hydriding	Excess moisture in as-manufactured pellet	Reduced specs on moisture in fuel
Cladding collapse	Fuel densification leaving unsupported cladding	More stable pellet (i.e., higher firing temperature) and helium pressurization
Fretting	Vibration of fuel rods against space grids	Improved assembly design
Pellet/cladding interaction (PCI)	Stress Corrosion Cracking (SCC) of cladding due to contact with pellet; secondarily, power ramps and iodine release from the pellet	(1) SCC-resistant cladding, (2) modified plant operation, and (3) annular fuel pellet
Cladding corrosion	Induced by CuO corrosion product in BWRs	Maintenance of low Cu concentration in water
Cladding perforation	(1) Debris-induced failure and (2) localized erosion (baffle-jetting)	(1) Avoid debris in coolant, (2) assembly inlet filters, and (3) modified assembly design
Breakage	Improper fuel handling	

6.2.2 Evolution of Improved LWR Fuel Performance

The steps by which LWR fuel reliability improved over the years have not been clearly documented in any single authoritative source. The view presented here has been pieced together from information presented in the Fuel Performance Annual reports published by the NRC (e.g., Bailey and Wu 1990), an EPRI special report on LWR core materials (Franklin et al. 1985), and a review article by El-Adham (1988). Possibly the most important source for developing the record of the mechanism by which LWR fuel improved was gained from personal discussions with QA managers of the fuel vendors (see Acknowledgments).

The Initial Era, 1960–1975. The fuel designs of this era were based largely on test reactor data acquired under AEC programs. The cladding material for pressurized-water reactors (PWRs) was initially stainless steel. Zircaloy was introduced in 1968 for neutron economy (Bobe 1976). Both stainless steel and Zircaloy were used for boiling-water reactor (BWR) cladding. Essentially all of the failure mechanisms were recognized at this time, including hydriding, which was a unique additional failure mechanism that came with the introduction of Zircaloy. Though fuel failure data were acquired, it was not systematized or systematically analyzed. Bobe (1976) indicates that the fuel defect fraction on discharge was approximately 0.01 during this time frame.

This relatively high defect rate was considered to be a success at that time. Since statutory requirements were met, the cost of improved fuel reliability needed to be justified in terms of operating cost savings. However, due to a fairly short experience, the full impact of high fuel defect rates was not fully recognized. A modern estimate of the true cost of LWR fuel failures, based on mid-1980 defect rates (which were a factor of 100 better) indicates the operating cost penalty to be approximately $4 million per plant per year due to fuel failure fractions on the order of 10^{-4}.* Factors relating defective fuel to elevated operating costs are (1) loss of capacity factor due to unplanned shutdowns, (2) loss of efficiency, (3) increased inspection costs, (4) fuel assembly reconstitution costs, (5) increased maintenance costs, and (6) added storage and disposal costs.

*Personal communication from M. M. Glotzer, Nuclear Fuel Manufacturing, to R. P. Wichner, ORNL, March 14, 1991.

Motivation for Improved Fuel Reliability. The initial impetus for improved fuel reliability was chiefly competition between the five fuel vendors. The higher operating costs associated with lower reliability would tend to favor vendors with a superior product. In addition, the warranty on the sale, which provides monetary penalties for losses incurred due to poor fuel performance, contributes an economic incentive.

During the 1980s, a marked attitude change occurred with respect to LWR fuel reliability; it was no longer a matter of a simple cost balance, but became a goal in itself. The current goal of INPO, whose authority vendor representatives appear to respect, is zero as-manufactured fuel defects and zero defects incurred in normal service.

Method for Development of Improved Reliability. The principal steps by which LWR fuel reliability was improved have been (1) location and identification of the defective fuel rod by poolside examination using radioactive sipping, ultrasonic testing, or eddy current methods; (2) hot cell dissection of the defect zone; (3) analysis of the defect by various means; (4) elucidation of the root cause; and (5) fuel design change to eliminate the cause of the defect. Thus far, design, materials, or fabrication modifications have been readily found that eliminate or reduce the development of the particular defect. For example, once the cause of the hydriding defect was recognized, process modifications that reduced the hydrogenous impurity level in the pellet eliminated the defect. Possibly the most complex failure mode has been PCI. Early evaluations based on empirical tests developed a reactor control strategy that limited the range of power ramping of individual fuel rods. This served to reduce PCI, but at a significant operational penalty. More recent hot cell tests have now identified the cause to be SCC induced by iodine when the pellet comes into forced contact with the cladding. An interior cladding barrier has been developed (consisting of zirconium) resistant to PCIs which promises to completely eliminate this type of defect.

The progressive elimination of defect causes has evolved to the point where the current principal defect mechanism of LWR fuel is debris-induced perforation of the cladding. The effectiveness of the fuel improvement activities is illustrated in Fig. 6.2-1, taken from a QA brochure of an LWR fuel vendor. The Fuel Reliability Index (FRI), which is a normalized concentration of ^{131}I in the coolant, is seen to have dropped by an order of magnitude over the most recent 7-year period for this vendor. Note that an FRI of $<5 \times 10^{-4}$ is stated as representing a condition where there is a high probability of zero defects on fuel discharge.

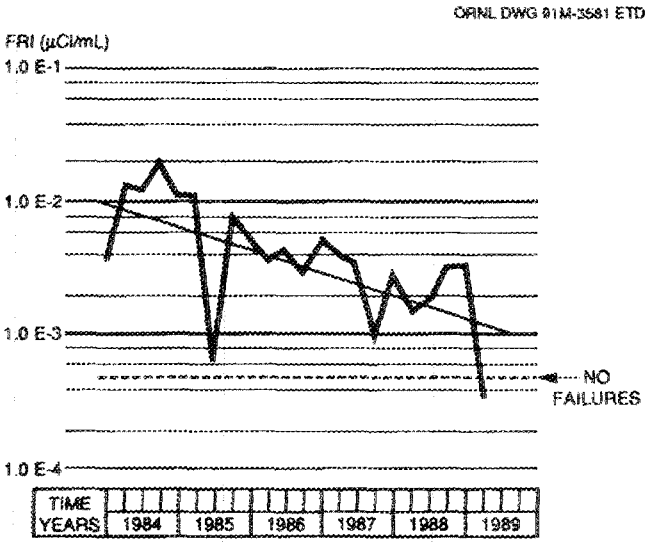

Figure 6.2-1 Fuel reliability index (FRI) for an LWR vendor

6.3 QA/QC Procedures for LWR Fuel

Figure 6.3-1 illustrates a typical organization chart for LWR fuel manufacture showing the relationship of QA and QC activities to production and engineering. The total separation of the QA director from the production organization is generally mandated (e.g., by 10 CFR 50, Appendix B) in order to free him from production pressures. The high level within the organization is also a requirement that provides the QA director with an authority equal to the authority of the other associated directors. As shown by the figure, QA activities are primarily administrative in nature. The main purpose is verification and approval of process parameters and QC data provided in documentation developed by the operations and QC departments. In contrast, QC activities are highly technical and are better performed within production organizations, but they are generally completely separated from the operations department.

The fuel production facility contains engineering activities that include product and process design. Both the fuel design and the details of the process have a history of continual evolutionary development. The primary driver for modifications in fuel design has been information

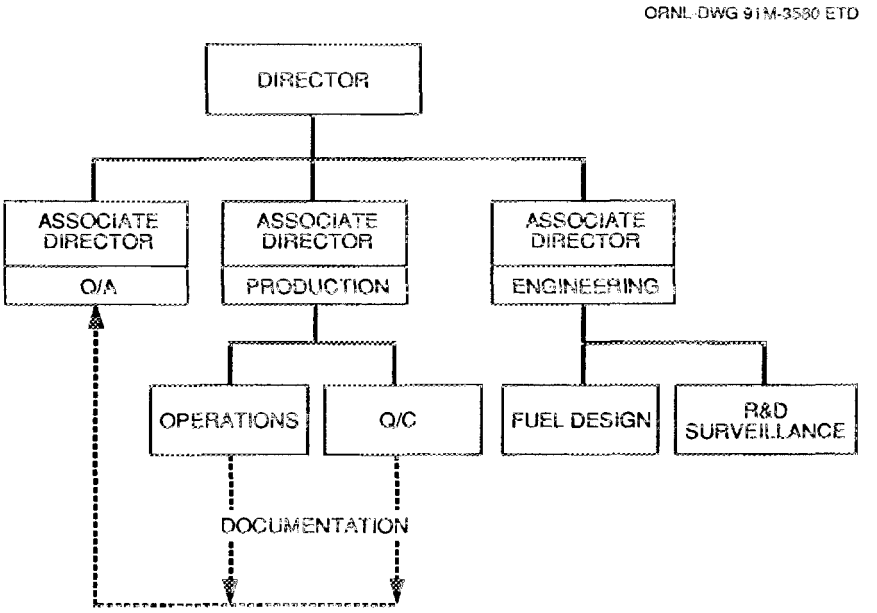

Figure 6.3-1 Typical relationship of QA and QC activities in LWR fuel manufacture

developed by surveillance programs on discharged fuel, especially examinations of failed fuel elements.

A typical set of QC tests performed on LWR fuel is listed in Table 6.3-1, as compiled from discussions with several QA managers for LWR vendors. The principal point in this table is that each fabricated fuel element is tested for function by means of the helium leak test; that is, there is a 100% sampling rate for this critical QC test. It is a major advantage for LWR fuels to have available an inexpensive test of the completed product for proper function.

Other critical features of the fuel pin are also nondestructively tested at a 100% sampling rate (e.g., fuel pellet locations, radial gap, and end cap welds). In contrast, the fuel assembly is tested only for its mechanical tightness to ensure its resistance to fretting corrosion; no further tests are required for the assembly because the process of assembling the fuel bundle is deemed to contain no threat to the integrity of the fuel element.

Destructive chemical analyses and crystallographic tests are performed on the fuel pellet before insertion into the fuel pin at the sampling rates indicated in the table. For lot sizes of about 2 million, these rates correspond to tests on 1 pellet per lot (for porosity and grain size) up to perhaps 100 pellets per lot for density and metrology.

The sampling plan for the QC testing program is based on the principle that the most critical items are tested to the highest level of confidence. Thus, 100% of the fuel pins are tested for function. The less critical features of the fuel pellet are tested at much lower sampling rates. Furthermore, the small sample sizes for the destructive pellet tests are indicative of a mature production facility. In such cases, much lower sampling rates are selected primarily to ensure stability of process parameters rather than proof of product quality to a high level of confidence.

6.4 LWR Perspective Relative to MHTGR Fuel

Examination of the mature LWR fuel industry leads to several observations that may apply to prospective commercial MHTGR fuel manufacture.

1. There appears to be unanimous approval of the change in LWR fuel reliability philosophy that occurred in the early 1980s. The objective (possibly unattainable) is now

Table 6.3-1 QC tests on LWR fuel[a]

Component	Test	Sample size[b] (%)	Comment
Fuel pellet	Isotopic content Stoichiometry Impurity level Boron	2×10^{-4}	Destructive chemical analyses
	Porosity Density Pore size Grain size	5×10^{-5} 2×10^{-3} 5×10^{-5}	Destructive crystallographic analysis
	Diameter Length End shape	3×10^{-3} to 100 3×10^{-3}	Metrology, nondestructive
Zircaloy tubing	Corrosion rate Composition Metallography Tensile strength Burst strength dimensions		Performed by tubing sampler or fuel vendor
Fuel element	Ultrasonic, weld test Ultrasonic, wall Helium leak test X-ray, radial gap, and pellet locations Dimensions Weld	100 100 100	Nondestructive
Fuel assembly	Vibration response		Nondestructive

[a]Compiled from conversations with several QA managers.
[b]Tests and sample sizes will differ from vendor to vendor.

zero fuel element defects on discharge. The principal motivator for the change appears to have been INPO. Also, intense competition between five fuel vendors has been a significant factor in improved fuel reliability.

2. The principal means by which improved fuel reliability evolved has been the identification of failure mechanisms by dissection and analysis of the failed fuel element, followed by design and/or material changes that circumvent the cause of failure. A necessary adjunct has been an industry-wide data system cataloguing fuel failure statistics initiated in the mid-1970s.

3. A specific fuel reliability goal is not a direct objective of the selected QC procedures. The purpose of QA and QC activities is more limited, namely, to ensure that the product conforms to the designers' specifications. Fuel reliability in service is attained by proper design and care that the design is accurately fabricated by means of QC and process control procedures.

4. The key element in the LWR fuel QC methodology is the 100%, nondestructive testing of the completed fuel pin for function by leak testing. All fuel vendors perform this product test. The rationale is that the final test for proper function must be performed after the last process step that threatens the integrity of the fission product barrier. The equivalent MHTGR test would entail nondestructive examination of individual particles in each fuel compact for function. The current lack of such an equivalent test may be a major disadvantage in MHTGR fuel manufacture relative to LWRs.

7 Summary and Conclusions

7.1 Summary

1. The objective of this study is to review issues bearing on MHTGR fuel reliability, principally to assess the advisability of retaining the "weak fuel" penalty. This penalty has been adopted by NRC on an interim basis for MHTGR concepts with no conventionally sealed containment. Conditions conducive to reducing or eliminating this burden are defined (see Conclusions). Weak fuel is a conservative concept whereby the fuel is assumed to respond less favorably to environmental conditions than predicted by fuel behavior models. Usage to date has entailed presuming apparently satisfactory behavior under normal operation but assuming an added degree of fuel damage during accidents beyond model predictions. The main reason for adopting the weak fuel penalty is the increased dependence of satisfactory accident consequence results on fuel reliability in the absence of a sealed containment vessel.

2. Fuel reliability is defined as fuel behavior under normal and accident conditions that is in accord with model predictions. Fuel reliability depends on (a) proper fuel design to satisfy performance requirements, (b) fabrication and process control techniques that accurately produce the design, (c) well-constructed QA and QC procedures, and (d) behavior of the product in service that is in accord with expectations. Hence, evaluation of fuel reliability must cover these areas.

3. There are factors other than absence of a sealed containment and the associated added reliance on the fuel particle that suggest adoption of a weak fuel penalty at this time: (a) The MHGTR fuel is of a relatively new design that uses UCO kernels and a somewhat modified set of coatings. (b) As a result, a comprehensive data base for this fuel under normal and accident conditions does not currently exist (while the data base for other fuel types is highly supportive, it is not an adequate substitute). (c) A sufficient capability for relating the range of possible manufacturing defects to failure rates does not currently exist; such capability is necessary for confident application of the empirical fuel behavior models to the reference fuel. (d) QC and fabrication process control methods, both of which bear directly on fuel reliability, are currently still under development.

4. The fuel manufacturing process is outlined in Sect. 2. This is a fairly complex process, beginning with the fabrication of a 350-μm-diam, LEU UCO kernel composed of 15% UC_2 with the balance UO_2. Seven coating layers are applied to the kernel in a levitating bed apparatus. Coating characteristics are regulated by the composition and feed rate of the levitating gas, temperature, and duration of the process. Coating process parameters strongly affect the microstructure, irradiation stability, thickness, uniformity, and diffusivity of the coatings. Physical conditions in the coater need to be carefully selected to preclude formation of various types of coating defects. Note that the compact fabrication step, in which ~6000 fuel particles are incorporated into a carbonaceous compact by high-pressure injection of an oil and filler into a mold followed by curing, involves a potential threat to the integrity of the fuel particles.

5. Section 3 provides a brief overview of fuel failure mechanisms grouped as (a) manufacturing defects that may lead to failure, (b) failures under normal operating conditions, and (c) failures under accident conditions. Several types of manufacturing defects can cause general weakening of the fuel particle. Most of these are detectable only by means of destructive sampling methods. In particular, damage to fuel particles caused by the compact fabrication process is noted as being potentially troublesome due to a lack of a satisfactory QC method for SiC defect detection.

6. A quasi-mechanistic basis for the possibility of weak fuel is outlined in Sect. 3. It is reasoned that weak fuel may occur as a result of a manufacturing defect type that has a high probability for causing failure, and for which there is only a weak defense against appearance in the product. The weak defense may consist of (a) a costly and difficult QC procedure, (b) inadequate sample size, or (c) the possibility of unnoticed processing errors.

7. Three types of manufacturing defects that may fit the above description and thus lead to weak fuel are cited in Sect. 3: (a) fuel damage during compact fabrication, which involves significant threat to the fuel particle; (b) defective IPyC layer, which may result in excessive HM dispersion and corrosive failure of the SiC layer; and (c) faceted particles, which may lead to failure due to excessive stress concentration. An imperfect SiC layer, which exhibits higher than expected diffusivity to fission products, may be the fourth type of manufacturing defect contributing to weak fuel.

8. Fuel design requirements are reviewed in Sect. 4. They define the behavioral properties of the fuel required to meet the top-level reactor goals. As such, they are the targets for the fuel developer and fabricator. An order of magnitude evaluation of the consistency between the fuel design requirements and top-level Goal 3 is outlined in Appendix A.1. The result shows that top-level Goal 3 (Maintain Control of Radionuclide Release) can be met by the fuel design requirements when a significant degree of iodine trapping by primary systems and RB surfaces (about 80%) can be demonstrated for all depressurization accident sequences. Imposition of a weak fuel penalty will require proof of higher degrees of iodine trapping for satisfaction of Top Level Goal 3.

9. Fuel design requirements for normal operation are also influenced by Top-Level Goal 1 (Maintain Plant Operation), one aspect of which deals with doses to employees involved in maintenance operations. As a preliminary device, designers selected 10 mrad/h as the maximum allowable radiation field in the vicinity of maintainable equipment. This approach would limit routine maintenance doses to <10% of 10.CFR.20 limits, which was deemed to be in compliance with the top level goal. However, an approximate calculation (Appendix A.2) shows that the resulting fuel design criteria would likely result in significantly higher radiation field than the 10-mrad/h rule of thumb in the latter years of operation due to the accumulation of long-lived metallic fission products. Reactor designers, nevertheless, assert that the selected fuel design critieria do, in fact, lead to compliance with the <10% of 10.CFR.20 limitation when times required for maintenance operations are more fully analyzed and doses are distributed over the maintenance employee population.

10. Preliminary QA/QC plans for the manufacturing process are described in Sect. 5. Past practice employed for Fort St. Vrain fuel provides the basis for the proposed QA/QC methods. Most of the QC techniques have been developed for fuel with an initial defect fraction in the range of 10^{-3}; these now need to be adapted to a much lower initial defect fraction of $\sim 5 \times 10^{-5}$. A program for development of improved QC methods is currently in progress within the DOE fuel development program.

11. Note that the available QC procedure for detecting flawed SiC layers, the so-called burn-leach method, may entail a significant degree of uncertainty as applied to both loose particles and the finished compact. Additionally, an apparent deficiency in QC capability is the lack of tests, other than the burn-leach procedure, for proper function of the fuel as a sufficient fission product barrier.

12. Sample sizes required for QC tests constitute a complex issue. Statistical inference of an extremely low defect rate with high confidence requires large sample size. Roughly, a 10^5 sample size is required for inference of a 10^{-5} defect rate with 95% confidence. Because the available tests are generally destructive, such proof of quality by means of destructive sampling can be prohibitively expensive, especially for the finished compact. Required sample sizes diminish as the process matures; ultimately, only proof of product stability is required in a fully mature process.

13. A review of the LWR fuel quality situation, including discussions with several QA managers for LWR fuel vendors, is outlined in Sect. 6. The motivation was to gain insights from a successful, mature fuel fabrication industry that may be relevant to the MHTGR. The success of the industry is indicated by a steady increase in fuel quality so that defect rates for discharged LWR fuel are currently in the vicinity of the targeted as-manufactured MHTGR rates.

14. Several characteristics of the LWR fuel fabrication industry may be worthy of consideration for the MHTGR: (a) The LWR fuel industry as a whole has a target of zero defects on discharge. While this may never be achieved, it provides an incentive for continued improvement. The economic and institutional forces that created this ambitious goal may likewise apply to MHTGR. (b) At least some LWR fuel fabricators carefully prioritize QC procedures with respect to importance for fuel quality. The most significant QC tests are performed at a 100% rate. (c) A great advantage for LWR fabricators is that the final product, the fuel pin, can be tested nondestructively for function. This test is performed at a 100% rate by all fabricators. (d) There is a closed loop of activities including material selection, fuel design, fabrication process controls, QA/QC, in-reactor surveillance, examination of discharged fuel, and identification of defect causes. The last activity feeds back to the first, leading to improved product design.

7.2 Conclusions

1. The following conditions are judged to be conducive for the reduction or elimination of the weak fuel penalty for MHTGRs with no sealed containment:

a. results of a testing program of convincing scope on the reference fuel produced using prototypical methods, demonstrating performance accordance to model predictions for both normal operation and accident conditions;
b. a good comprehension of fuel failure mechanisms to provide an unambiguous interpretation of capsule test and HTGR operational data;
c. identification of the range of possible fuel manufacturing defects and their mechanistic relation to fuel failures; and
d. adoption of a carefully considered QC program based on identification and rejection of the most significant manufacturing defects.

2. Because the conditions given above do not currently exist, it may be prudent to maintain some type of a weak fuel penalty for concepts with no sealed containment.

3. Manufacturing defects that result in a high probability for fuel failure and for which there is a fairly weak defense against appearance in the product provide a mechanistic basis for the weak fuel concept. Such weak defense could be a result of a difficult or expensive QC procedure, inadequate sample size, or vulnerability to a single-process control error. Several types of such defects are noted that, as a result, may be considered as a mechanistic basis for the concept. These defects are (a) particle defects caused by the compact fabrication process, (b) faceted particles, and (c) excessive HM dispersion or HCl contamination. Undetected SiC defects may be a fourth type of manufacturing defect contributing to weak fuel.

4. The unique problem of establishing compact quality needs to be emphasized. Compact fabrication entails a potentially significant threat to fuel particle integrity. Therefore, product testing following compact fabrication is critical. At the same time, the large number of particles in the compact (about 6000) render extensive destructive sampling methods prohibitive. In addition, there may be some uncertainty regarding the accuracy of the current compact testing method, the burn/leach method.

5. Fabrication process control and QA/QC methods alone, while extremely important, can not ensure fuel reliability. At most, they ensure that the product conforms to the intended design. Fuel reliability additionally requires that the design provide the fuel behavior consistent with the design requirements. In this regard, it may be profitable to note the highly successful situation in the LWR fuel fabrication industry. LWR fuel manufacture involves a closed loop of activities including (a) design and materials, (b) fabrication, (c) QA/QC, (d) reactor surveillance, (e) failure analysis, and then back to step (a) for an improved design. A similar arrangement would benefit MHTGR fuel fabrication.

6. The current QA/QC plan lacks a clear prioritization of control activities. Such a prioritization is essential and needs to be based on the relative importance of particular measurements with respect to achievement of the performance requirements. In addition, there needs to be a close correlation between the QC plan and potential failures resulting from manufacturing defects.

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*Available for purchase from National Technical Information Service, Springfield, VA 22161.

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Appendix A

Comparison of Fuel Design Requirements and Top-Level Reactor Goals

A.1 Goal 3, Short-Term Accidental Discharges

A.1.1 Assumptions

1. The principal contributors to the dose at the EAB are the nuclides ^{131}I and ^{133}I via breathing.

2. The maximum fraction of the iodine inventory in the core specified for rapid release under accident conditions, as cited in fuel specifications (Tang 1989), is discharged rapidly to the reactor building (RB) gas space. (This is a conservative, but fairly realistic, assumption for a wet depressurization event.)

3. The iodine in the RB gas space remains in the gas phase.

4. The RB gas leakage rate is 100% of its volume per day.

5. The dose is incurred at the EAB by a stationary individual directly downwind for a 2-h period.

A.1.2 Dose Model

The above assumptions lead to the following expression for the activity of iodine in the RB gas space:

$$A_i(t) = A_{0i} \exp\left[-(\lambda_i + Q/V)t\right] \quad , \qquad (A.1)$$

where

A_{0i} = initial activity of nuclide-i in the RB gas space, Ci;
$A_i(t)$ = activity of nuclide-i in the RB at time t, Ci;
λ_i = decay constant of nuclide-i, s^{-1};
Q/V = fractional leakage rate from the RB, s^{-1}.

The initial activity in the RB gas A_{0i} is the product of the core inventory of nuclide-i, as given in PSID (1986), and the specification for fractional release due to a rapid event (Tang 1989).

The release rate to the atmosphsere Ci/s is given by $QA_i(t)/V$, where $A_i(t)$ is defined by Eq. (A.1). The total release to the atomosphere, $R_i(t')$, up to time t', is obtained from the difference, $A_{0i}-A_i(t')$;

$$R_i(t') = A_{0i}\left\{1 - \exp\left[-(\lambda_i + Q/V)t'\right]\right\} \quad . \qquad (A.2)$$

The dose at the EAB to the thyroid due to breathing is approximated by

$$\text{Dose (rem)} = \sum_{i=1}^{2} R_i(t')\chi Q_B (DCFB)_i \quad , \qquad (A.3)$$

where

χ = atmospheric dispersion factor, s/m^3;
Q_B = breathing rate, m^3/s;
$DCFB_i$ = dose conversion factor to the thyroid, rem/Ci.

A.1.3 Parameter Values

Parameter values required for the estimate are provided in Table A.1 of Sect. A.1.4. Dose conversion factors were obtained from Dunning et al. (1981). Core inventories of ^{131}I and ^{133}I were obtained from PSID (1986). The values of the breathing rate and the atmospheric dispersion were taken from Reg. Guide 1.4 (1974). The breathing rate is the value recommended for the initial 8-h period. The selected dispersion factor is the recommended value for the initial 8-h period for ground release and transport to a site boundary at a distance of 600 m.

A.1.4 Estimated Dose at the EAB

Results of the estimated dose are presented in Table A.1. As noted, the estimated dose according to these conservative assumptions is 31.1 Ci, which exceeds the 5-rem objective by a factor of 6. It appears that a significant degree of attenuation in the RB would be required to bring levels down to the desired goal. In a wet depressurization accident, attenuation of iodine will be provided by condensation of steam in the RB. In a dry depressurization event, attenuation is provided by sorption of iodine on surfaces.

A.2 Goal 1, Routine Maintenance Doses (See footnote on p. 28)

A.2.1 Assumptions

1. The maintenance dose results principally from ^{137}Cs. Contributions from ^{134}Cs, 136Cs, and ^{110m}Ag are neglected.
2. The source of the ^{137}Cs activity in the primary system is fuel with defective SiC layers; diffusive release is neglected.

Table A.1 Estimated site boundary dose due to rapid release of iodine from fuel

Nuclide	Decay constant (1/s)	Core inventory (Ci)	Initial inventory (Ci)	Release to air to time, t′ (Ci)	Dose factor thyroid, breath (rem/Ci)	Accumulated dose at EAB to t′ (rem)
^{131}I	9.98E-07	1.17E+07	2.57E+02	2.23E+01	1.00E+06	2.01E+01
^{133}I	9.21E-06	2.10E+07	4.62E+02	6.42E+01	1.90E+05	1.10E+01
					Dose at EAB to thyroid, 2 h	3.11E+01

Note:

Breathing rate	3.47E-04 m^3/s
Dispersion	2.60E-03 s/m^3
Q/V	1.16E-05 1/s
Duration (t′)	7200 s (2 h)
Release fraction	2.20E-05 (specification)

3. Cesium that leaks from the fuel deposits uniformly on the metallic surfaces of the primary system.
4. A simple, planar exposure geometry is assumed, as illlustrated in the figure in Sect A.2.4. Tissue is assumed to be exposed by close proximity to two planes of deposited ^{137}Cs. The dose is assumed to result only from the photons emanating from the two deposit planes directly adjacent to the tissue.

A.2.2 Primary System Inventory of ^{137}Cs

The release rate of ^{137}Cs from fuel, R (mol/s), is given by

$$R = (R/BH) \cdot fr \cdot y \ , \qquad (A.4)$$

where

R/B = the release to birthrate ratio of the fuel, which in accord with assumption 2 is the fraction of SiC defects, 7×10^{-5} (see Table 4.1-1, at 95% confidence);
fr = the fission rate, 1.81×10^{-5} mol/s for 350 Mw(t);
Y = ^{137}Cs yields, 0.0618 atoms/fission.

The mass balance of ^{137}Cs in the ex-fuel primary system is given by

$$A\frac{dS}{dt} = R - \lambda \bullet A \bullet S(t) \ , \qquad (A.5)$$

where

S = the plateout concentration of ^{137}Cs, mol/m^2,
A = primary circuit surface area, 4020 m^2,
λ = decay constant, 7.28×10^{-10}/s.

Solving Eq. (A.5) for S yields

$$S = \frac{R}{A\lambda}\left[1 - \exp(-\lambda \bullet t_R)\right] \ , \qquad (A.6)$$

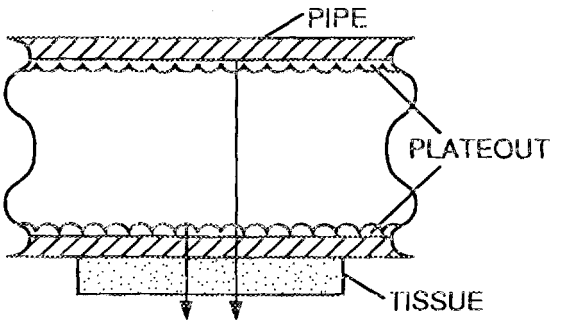
where t_R is assumed duration of reactor operation, 1.1×10^9 s (35 y).

These parameter values, assumptions, and equations yield the following release rate and plateout concentration:

$$R = 7.83 \times 10^{-11} \text{ mol/s},$$
$$S(35\text{ y}) = 1.48 \times 10^{-5} \text{ mol/m}^2.$$

A.2.4 Estimated Maintenance Dose Rate

The following contact geometry between the photon source and the tissue is assumed.



The photon flux, Γ ($1/cm^2$ s), based on the above sketch is given by

$$\Gamma = S \cdot 10^{-4} \cdot Av \cdot \lambda \cdot Eff \quad , \qquad (A.7)$$

where

Av = Avagadro's number, 6.023×10^{23} atoms/mol,
Eff = photon efficiency for ^{137}Cs, 0.9 photons/disintegration.*

The following photon flux is obtained from Eq. (A.7) and the cited parameter values:

$$\Gamma = 5.83 \times 10^{5} \ \ cm^{-2}s^{-1} \ .$$

The dose rate to the tissue, D (rad/h), is estimated from the following:

$$D = K \cdot (\mu / \rho) \cdot E\gamma \cdot \Gamma \quad , \qquad (A.8)$$

where

K = a conversion factor, $= 5.77 \times 10^{-5}$ rad g s/h MeV,
μ/ρ = photon energy absorption factor, 0.032 cm^2/g,†
$E\gamma$ = photon energy, 0.662 MeV.*

The above values substituted into Eq. (A.8) yield the following estimated maintenance dose rate:

$$D = 0.72 \text{ rad/h} \ ,$$

which is equivalent to 0.72 rem/h, assuming a relative biological effectiveness (RBE) of unity for exposure to gammas.

*Kocher (1981); see reference list.

†E. P. Blizard "Nuclear Radiation Shielding," Unpublished Oak Ridge National Laboratory Report prepared for the *Nuclear Reactor Handbook*, McGraw-Hill Book Co., 1956

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11. ABSTRACT (200 words or less)

Modular High-Temperature Gas-Cooled Reactor (MHTGR) concepts that house the reactor vessel in a tight but unsealed reactor building place heightened importance on the reliability of the fuel particle coatings as fission product barriers. Though accident consequence analyses continue to show favorable results, the increased dependence on one type of barrier, in addition to a number of other factors, has caused the Nuclear Regulatory Commission (NRC) to consider conservative assumptions regarding fuel behavior. For this purpose, the concept termed "weak fuel" has been proposed on an interim basis. "Weak fuel" is a penalty imposed on consequence analyses whereby the fuel is assumed to respond less favorably to environmental conditions than predicted by behavioral models. The rationale for adopting this penalty, as well as conditions that would permit its reduction or elimination, are examined in this report. The evaluation includes an examination of possible fuel-manufacturing defects, quality-control procedures for defect detection, and the mechanisms by which fuel defects may lead to failure.

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