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Letter Report

Addendum to Thermal/Hydraulic Calculations for Phase IV of the LWR MOX Irradiation Average-Power Test : Extension to 52 GWd/MT Burnup

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***Addendum to Thermal/Hydraulic Calculations for Phase IV of the LWR MOX Irradiation Average-Power Test : Extension to 52 GWd/MT Burnup*, ORNL/MD/LTR-191-AD**

The enclosed report is a supporting document for the Advanced Test Reactor (ATR) average-power test irradiation sponsored by the Fissile Materials Disposition Program. The results discussed in this addendum are the products of a set of conservative analyses performed to establish upper bounding estimates for fuel pellet swelling and the fuel pin/capsule gas plenum temperatures for the test specimens to be irradiated during Phase IV (irradiation extension to 52 GWd/MT burnup). A second purpose of these analyses is to demonstrate conclusively that the components of the test assembly conform to the operational design limits for the Departure From Nucleate Boiling Ratio (DNBR) and for coolant approach to boiling as established by the ATR Technical Specification Requirements (TSRs).

This is a Level-2 document as defined in the *Fissile Materials Disposition Program Light-Water Reactor Mixed-Oxide Fuel Irradiation Test Project Plan*, Revision 2, ORNL/MD/LTR-78, dated May 2000.

Sincerely,

Stephen A. Hodge, Manager
MOX Irradiation Test Project

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Enclosure: As Stated

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ACRONYMS

Acronym	Definition
APT	Average-Power Test
ATR	Advanced Test Reactor
BOL	Beginning of life
BWR	Boiling water reactor
CARTS	Capsule Assembly Response - Thermal and Swelling developed at ORNL
CFD	Computational fluid dynamics
csa	Cross-sectional area
DNBR	Departure from nucleate boiling ratio
DOE	U.S. Department of Energy
ESCORE	Fuel performance code developed by the Electric Power Research Institute
FFFAP	Flashing Fluid Flow Analysis Program developed by ORNL
FIR	Flow instability ratio
FLUENT	Commercial computational fluid dynamics code developed by Fluent, Inc.
FMDP	Fissile Materials Disposition Program
FRAPCON	Fuel performance code developed for the U.S. NRC
HEATING	General purpose conduction heat transfer program developed by ORNL
HPT	High-power test
ID	Inner diameter
INEEL	Idaho National Engineering and Environmental Laboratory
LANL	Los Alamos National Laboratory
LEU	Low enriched uranium
LHGR	Linear heat generation rate
LWR	Light Water Reactor
MATPRO	A library of material properties for LWR structural components developed for the U.S. NRC
MCNP	Monte Carlo N-Particle Neutronics code
MOX	Mixed uranium-plutonium oxide
MPRA	MPR Associates
NRC	U.S. Nuclear Regulatory Commission
OD	Outer diameter
ORNL	Oak Ridge National Laboratory
PCS	Primary coolant system
PIE	Postirradiation examination
PWR	Pressurized Water Reactor

Acronym	Definition
RELAP	A steady-state and transient fluid analysis code developed for the U.S. NRC
rms	Root mean square
SW	Southwest
TS	Technical Specifications

Addendum to Thermal/Hydraulic Calculations for Phase IV of the LWR MOX Irradiation Average-Power Test : Extension to 52 GWd/MT Burnup

1. INTRODUCTION

The Light Water Reactor (LWR) Mixed Oxide (MOX) Fuel Irradiation Test Project utilizes a small I-hole (I-23 or -24) in the reflector of the Advanced Test Reactor (ATR) at the Idaho National Engineering and Environmental Laboratory (INEEL) to irradiate up to nine fuel pins (simultaneously) containing various fuel types as described in the Fissile Materials Disposition Program LWR MOX Fuel Irradiation Test Project Plan (Ref. 1).

During Phases I, II, and III of this project, the MOX fuel was irradiated to burnup levels as high as 30 GWd/MT. For these phases of the Average-Power Test (APT), the test capsules were exposed to linear heat generation rates (LHGRs) of 6–10 kW/ft, a range corresponding to the pellet centerline temperatures taken as a core average for the various commercial reactor designs. To achieve the proper thermal neutron flux such that the LHGR did not exceed 10 kW/ft, an Inconel thermal neutron shield was incorporated into the basket assembly for Phase I. Because of fuel burnup, the thermal neutron shield was removed for Phases II and III and an all-aluminum basket assembly was used during these periods of irradiation.

In Phase IV it is desired to extend the burnup to approximately 50 GWd/MT while maintaining the LHGR in the range of 2 to 8 kW/ft (Ref. 2). Neutronic analyses (Ref. 3) have shown that the all-aluminum basket assembly is adequate for Phase IV; however, for burnups greater than ~36 GWd/MT it is necessary to move the basket assembly from the I-24 position to the I-23 position in order to maintain the LHGR above the lower limit of the 2-kW/ft range.

A primary consideration in extending the burnup for some of the APT capsules beyond 30 GWd/MT is the small initial diametral gap (2.0 to 3.5 mils) between the pellet and the Zircaloy clad. For comparison, U.S. pressurized water reactors (PWRs) employ diametral gaps in the range from 6.5 to 8.4 mils. With the two lead capsules removed for Postirradiation Examination (PIE) at a burnup of approximately 30 GWd/MT (that is, after completion of Phase III), five capsules remained for additional irradiation (Phase IV). Two additional capsules (4 and 13) were withdrawn from the ATR at approximately 40 GWd/MT burnup for PIE (at the end of Phase IV-Part 1). The concern in further irradiation is not pellet centerline temperature, but rather possible capsule deformation due to pellet swelling and thermal expansion.

The original safety analyses for the APT (References 4–6) were conservatively based upon an assumed continuous irradiation at a constant rate of 12 kW/ft. For the extension beyond 30 GWd/MT, the safety analyses (Ref.7) were based upon the capsule internal configuration established by the actual (as-run) LHGRs during Phases I, II, and III. At the end of Phase III, the LHGRs (Ref. 3) ranged from 4.9 to 5.6 kW/ft. By ~36 GWd/MT burnup, the LHGRs in I-24 had decreased to a range of 3.3 to 4.5 kW/ft. In order to increase the LHGR and speed up the MOX fuel burnup rate after ~36 GWd/MT, the MOX test assembly was moved to the southwest (SW) small I-23 position (with a SW lobe power of 23 MW). The predicted (Ref. 3) initial LHGRs in the I-23 position ranged from 4.1 to 6.0 kW/ft. Further irradiation, due to depletion of ^{239}Pu, results in lower LHGRs. Since the same basket (with aluminum shield) is employed throughout the Phase-IV irradiation, LHGRs exceeding 8 kW/ft are unrealistic.

As specified in the design, functional, and operational requirements (Ref. 2) for Phase IV of the APT, the thermal responses of the fuel pin/capsule assemblies (Ref. 7) were evaluated at an LHGR of 9 kW/ft, 112.5% of the specified maximum heating rate of 8 kW/ft, and with assumption of a surface heat transfer coefficient at least 20% below the calculated best-estimate value.

The safety analysis (Ref.7) for Phase IV of the APT applies to fuel burnups equal to or less than 50 GWd/MT. Based on as-run data through Cycle 129B and the current ATR schedule for the remaining cycles of Phase IV, burnups GWd/MT) at completion of Cycle 132A (October 2003) are expected to be 48.9 GWd/MT for Capsule 5 and 49.5 (average) for Capsules 6 and 12. Since the goal of the irradiation is to reach 50 GWd/MT, it is tentatively planned to include Cycle 132C. The added burnup will be about 1.3 GWd/MT for each of the three remaining capsules; the final burnups thus would range from 50.2 to 50.8 GWd/MT, values that slightly exceed the highest burnup assumed in the safety basis for the Phase IV irradiation.

It is the purpose of this addendum to the Phase IV safety basis to extend the thermal/hydraulic calculations to a burnup of 52 GWd/MT. The maximum predicted LHGR for the remaining capsules in Cycle 132C is ~3.7 kW/ft; to provide a conservative margin, these thermal/hydraulic calculations will be evaluated at an LHGR of 5 kW/ft (135 % of the maximum expected heating rate of 3.7 kW/ft).

Reference 2 also specifies that during ATR operation in the pressurized mode at a lobe power of 60 MW (SW I-hole requirements), that the following thermal/hydraulic criteria shall be met:

- the departure from nucleate boiling ratio (DNBR) shall always be greater than two,
- the rise in bulk primary coolant temperature along the experiment hot track shall be less than half the value that would cause flow instability,
- all criteria shall be met with two or three primary coolant pumps in operation (normal operation); and for abnormal conditions (to be evaluated for a flow coastdown from a lobe power of 60 MW).

The thermal/hydraulic calculations addressing these issues are discussed in Chapter 2 of this addendum.

The thermal/hydraulic analyses presented in Chapter 2 of Ref. 7 employed an average LHGR of 9 kW/ft in the fuel pins to predict the fluid conditions to be used in the thermal analyses of the fuel pin and capsule assembly given in Chapters 3 and 4 of that report. The thermal analyses presented in Chapter 3 of Ref. 7 supplied the three-dimensional temperature field required for the stainless steel capsule stress/strain analyses (Reference 8). Chapter 3 of this addendum discusses the implications of the irradiation extension to 52 GWd/MT burnup on the capsule stress/strain analyses in Ref. 8 and the predicted fuel response to the increased irradiation.

Also, since the extended burnup produces additional fission product gases (krypton and xenon), it is necessary to evaluate the increase in fission gas pressure within the fuel pin (Reference 9); the thermal analyses in Chapter 4 of Ref. 7 of the fuel pin and capsule gas plena supported the Reference-9 calculations. Chapter 4 of this addendum discusses the implications of the irradiation extension to 52 GWd/MT burnup on the fission gas pressure analyses in Ref. 9.

2. THERMAL/HYDRAULIC ANALYSES

The hydraulic response of the APT MOX irradiation test assembly for flows within and around the capsule basket was evaluated (Ref.7) for three conditions for the Phase-IV irradiation:

- at normal ATR operation (with two or three primary coolant pumps) with an LHGR of 9 kW/ft (Section 2.3 of Ref.7),
- at an ATR lobe power of 60 MW (normal pressurized operation) with two or three primary coolant pumps functioning (Section 2.4 of Ref.7),
- for a coastdown (initiated by loss of off-site power) from lobe power of 60 MW with two-pump operation (Section 2.5 of Ref.7).

These analyses were intended to provide a conservative estimate of the response of the assembly, especially with respect to the evaluation of the DNB and flow instability ratios. As shown in Sections 2.4 and 2.5 of Ref.7 for normal operating conditions and abnormal (coastdown) conditions respectively, all surfaces of the test assembly meet the Technical Specifications (TS) criteria for DNBR (the minimum computed value being 5.60) and for FIR (the minimum computed value being 3.71).

For the normal operation analyses performed for 9 kW/ft (Section 2.3 of Ref.7), the minimum calculated DNBR is 20.16.

These thermal/hydraulic evaluations were performed with the FFFAP code (Ref.10), originally developed at ORNL and experimentally validated using geometries (nozzles, orifices, annuli, and long tubes) very similar to those found in the MOX test assembly. The APT assemblies have been flow tested at ORNL, validating the performance predictions of the FFFAP code. In Section 2.2 of Ref.7, it was assumed that the Model-1 assembly flow characteristics (surface roughnesses and orifice loss form coefficient) were applicable for the hydraulic analyses. These hydraulic calculations proved to be conservative in that there is more flow in the Model-2 assembly (than in the Model-1 assembly) for a given core pressure drop.

In all cases, the computed DNBRs and FIRs exceeded 2.0.

As shown by Chang (Ref. 11), there is azimuthal variation in the power generation within the fuel pellet. This azimuthal dependence in the power generation translates into an azimuthal variance in the computed capsule surface temperature and heat flow into the coolant; thus the DNBR varies azimuthally around the capsule. This azimuthal variability in the DNBR calculation was addressed in the multidimensional thermal calculations discussed in Chapter 3 of Ref.7. At worst, the surface heat flux varies by ~3% due to the azimuthal variance in the power generation.

For the cases presented in Sections 3.4.2–3.4.4 of Ref.7, the maximum variance in the surface flux at the fuel pin midplane is 82.5 W/cm^2 to 87 W/cm^2. The DNBR and FIR analyses in Chapter 2 of Ref.7 conservatively used the 20 GWd/MT axial peaking factors ; therefore, at the position of minimum calculated DNBR (the corresponding FFFAP node is the bottom half of the last MOX pellet in the bottom MOX capsule), the mean surface heat flux used is 89.45 W/cm^2. This is greater than the maximum surface flux in the 3-D simulations; therefore, no adjustment of the calculated DNBRs is needed.

The thermal/hydraulic calculations performed in Chapter 2 of Reference 7 at an LHGR of 9 kW/ft involve significantly higher capsule surface temperatures and therefore bound the conditions to be encountered during the period of extended burnup from 50 to 52 GWd/MT at 5 kW/ft.

3. THERMAL ANALYSES OF THE APT MOX FUEL CAPSULE

The primary objectives of the thermal analyses of the APT MOX fuel capsule for Phase IV are the following:

- to provide the three-dimensional temperature field within the stainless steel capsule wall (the primary containment for the MOX irradiation experiment), which is an input in the stress analyses performed by Luttrell and Yahr (Reference 8);
- to predict capsule deformation (if any) due to fuel pellet swelling and structural thermal expansion.

The proposed ATR MOX high-power irradiation test (HPT) safety analyses (Ref. 12) required consideration of possible fuel centerline melting; that is, the analyses had to demonstrate that the fuel centerline temperature at all times was less than the MOX melting temperature. That analyses assumed an LHGR of 16 kW/ft and the thermal calculations included all known uncertainties (dimensions, physical properties, models, structural eccentricities, burnup effects, etc.). The HPT analyses clearly showed that even under the worst combination of uncertainties, the fuel centerline temperature remained below the MOX melting temperature. The analyses for the APT Phase-IV extension (Ref. 7) assumed an LHGR of 9 kW/ft (per Ref. 2) and conservatively estimated a maximum centerline temperature of 1115°C during all of the Phase-IV irradiation. This is more than 1500°C below the melting temperature of MOX at a burnup of 50 GWd/MT (~2653°C). Centerline melting during Phase IV is not a concern.

A primary consideration when the burnup for some of the APT capsules was extended beyond 30 GWd/MT is the small initial diametral gap (2.0 to 3.5 mils) between the pellet and the Zircaloy clad. For comparison, U.S. PWRs employ diametral gaps in the range from 6.5 to 8.4 mils. Since pellet-to-clad contact was predicted to have already occurred during previous irradiation cycles (beginning in Phase II), the concern in further irradiation is not pellet centerline temperature, but rather possible capsule deformation due to pellet swelling and thermal expansion.

The codes employed in these analyses were the experiment-specific Capsule Assembly Response - Thermal and Swelling (CARTS, Section 3.3 of Ref. 12) and HEATING codes (References 13 and 14). CARTS is the primary tool in the thermal/strain analysis. The HEATING 3-D model of the fuel pin and capsule generates the capsule wall temperature field needed as input for the thermal stress analyses (Ref. 8).

The APT capsule dimensions, structural material properties and fluid boundary conditions required for the current thermal analyses (supporting the irradiation extension to 52 GWd/MT burnup) are identical to those discussed in Sections 3.1 and 3.2 of the original Phase IV calculations (Ref. 7). The one-dimensional CARTS results are detailed in Section 3.1. The HEATING 3-D models and results are presented in Section 3.2.

3.1 CARTS Analyses

A general description of the CARTS code is given in Section 3.1.1. The results of the CARTS analyses, with respect to the burnup extension to 52 GWd/MT, will be discussed in Section 3.1.2.

3.1.1 Description of the CARTS Code

In order to predict the response of the capsule assemblies in the MOX irradiation experiments in the ATR, including the effects of fission gas release and fuel swelling during irradiation, ORNL has developed the Capsule Assembly Response (Thermal and Swelling) [CARTS] code.

The capsule assembly as represented by CARTS is one-dimensional in the radial direction. The model initially addresses the following configuration in the radial direction (from the centerline, respectively): MOX fuel, gas gap, Zircaloy cladding, gas gap, and 304L stainless steel capsule wall.

In essence, CARTS determines the coupled thermal/mechanical solution at each time step (i.e., advancement in burnup). At each increment in burnup, given an initial radial geometry (radial component interfaces from the previous time step) and the appropriate boundary conditions, CARTS first solves for the steady-state thermal solution, then determines the radial dimensional changes according to the computed temperature profile. CARTS then iterates until both the thermal and mechanical solutions have converged. The fuel burnup is then advanced and the solution process repeated until the specified total accumulated fuel burnup has been reached.

In addition to thermal expansion, the MOX fuel also undergoes dimensional changes due to irradiation. Initially, there is densification so that the pellet-to-clad gap increases. Subsequently, with increased burnup, the fuel begins to swell so that the gaps begin to shrink. Depending on the initial radial dimensions, the power generation within the capsule components, the boundary conditions, and the extent of burnup, the gas gaps at some point may be computed to close completely; this dynamism is included in the CARTS model.

The primary objectives of CARTS are to determine the temperature distribution within the capsule assembly, the extent of the gas gap closures, and the strain in the Zircaloy and stainless steel walls as functions of the fuel pin pressurization, the thermal expansion, and the fuel swelling and densification.

3.1.2 CARTS Code Analyses for the APT Phase-IV Extension to 52 GWd/MT

For test fuel burnups beyond 30 GWd/MT, the safety analyses are based upon the capsule internal configuration established by the actual (as-run) LHGRs during Phases I, II, and III. At the end of Phase III, the LHGRs (Ref. 3) range from 4.9 to 5.6 kW/ft. At ~36 GWd/MT burnup, the predicted LHGRs in I-24 decrease to a range of 3.3 to 4.5 kW/ft. In order to increase the LHGR and speed up the MOX fuel burnup rate after ~36 GWd/MT, the MOX test assembly was moved to the SW small I-23 position (with a SW lobe power of 23 MW). The predicted (Ref. 3) initial LHGRs in the I-23 position range from 4.1 to 6.0 kW/ft. Further irradiation, due to depletion of ^{239}Pu, occurs at lower LHGRs. Since the same basket (with aluminum shield) is employed during the Phase-IV irradiation, LHGRs exceeding 8 kW/ft are unrealistic.

As specified in the design, functional, and operational requirements (Ref. 2) for Phase IV of the APT, the thermal response of the fuel pin/capsule assemblies was evaluated at an LHGR of 9 kW/ft (Ref. 7), which is 112.5% of the specified maximum heating rate of 8 kW/ft. For the irradiation extension from 50 to 52 GWd/MT burnup, a LHGR of 5 kW/ft (135% of the maximum expected heating rate of 3.7 kW/ft) is assumed. Furthermore, the surface heat transfer coefficient employed for this calculation is required to be at least 20% below the calculated best-estimate value.

Of the five remaining capsules (numbers 4, 5, 6, 12, and 13) irradiated in Phase IV, Capsules 4 and 13 achieved the highest LHGRs during Phases I, II and III; thus the extent of irradiation changes (i.e., swelling) to the fuel has been greatest for Capsules 4 and 13. The irradiation histories for Capsules 4 and 13 (through the end of Phase III) are conservatively used for the CARTS analyses to represent all of the capsules to be irradiated during Phase IV.

As noted earlier, the calculated fuel centerline temperatures in Phase IV are approximately 1500°C below the MOX melting temperature at 50-GWd/MT burnup; fuel melting is not an issue. Rather, due to the small initial gas gaps, fuel swelling and the resulting impact on the Zircaloy clad and capsule stainless steel wall are the important concerns. Therefore, the CARTS analyses have primarily been focused on the swelling and densification models (either ESCORE [Ref.15] or FRAPCON [Ref.16]) and the code input parameters (degree of fuel densification, fuel thermal conductivity model) that most affect the fuel behavioral models. For these CARTS analyses, the following definitions of "best estimate" and "conservative" apply (the same as were used in Reference 7):

"best-estimate" cases:

- boundary conditions from FFFAP with no reduction in surface heat transfer coefficient
- ESCORE fuel swelling model
- MATPRO (Ref. 17) fuel thermal conductivity correlation
- fuel densification of 0.5%

"conservative" cases:

- boundary conditions from FFFAP with 20% reduction in surface heat transfer coefficient
- FRAPCON-3 fuel swelling model
- FRAPCON-3 fuel thermal conductivity correlation
- fuel densification of 0.0%.

The as-built capsule dimensions (with minimum initial gas gaps) produce the highest predicted strains in the Zircaloy and stainless steel clads and are used for both the best-estimate and the conservative cases.

The CARTS simulation results for the "best-estimate" case through 50 GWd/MT are illustrated in Figure 3.1 (reproduced from Ref.7). The LHGR is assumed to remain constant at 9 kW/ft throughout Phase IV. The pellet-to-clad gap closes early in Phase II at ~8.4 GWd/MT burnup and—except for two brief low-power ATR cycles in Phases II and III—remains closed through the end of Phase IV. At 50 GWd/MT, 9 kW/ft LHGR, and normal ATR operating conditions, the predicted mechanical strain on the Zircaloy clad is 0.61%.

The CARTS simulation results for the "best-estimate" case through 52 GWd/MT are illustrated in Figure 3.2. Through 50 GWd/MT burnup the response is identical to that illustrated in Figure 3.1; the response should be the same since the version of the CARTS code and the input files (except for the irradiation from 50 to 52 GWd/MT) are the same as were used in the Reference 7 calculations. With the drop in heating rate at 50 GWd/MT from 9 kW/ft to a more realistic but still conservative 5 kW/ft, the mean fuel temperature drops 183°C (from 466°C to 283°C). The pellet-to-clad gap remains closed but the imposed mechanical strain on the Zircaloy clad drops from 0.61% to 0.47% (~0.50% at 52 GWd/MT). The mean temperature in the clad drops from ~210°C to ~157°C; and the mean capsule wall temperature drops from ~110°C to ~88°C.

In all phases of the ATR irradiation, the Zircaloy-to-capsule gap remains open; there is no mechanical strain transmitted from the fuel pin onto the stainless steel capsule. The maximum fuel centerline temperature during Phase IV is ~904°C (at the beginning of Phase IV) and the centerline temperature steadily declines as the contact pressure between the fuel and clad increases, and, thus, the gap conductance increases.

In the "conservative" CARTS simulation (Figure 3.3, reproduced from Ref. 7, and Figure 3.4, through 52 GWd/MT) the pellet-to-clad gap closes at the beginning of Phase II and remains closed for the duration of the irradiation (and after the fuel has cooled at hot-cell conditions). The resulting mechanical strain on the Zircaloy clad is 1.16% at 50 GWd/MT in the ATR, drops to 0.90% when the LHGR drops from 9 to 5 kW/ft and subsequently increases to 0.94% at 52 GWd/MT. A displacement of 0.67% remains as a residual strain at hot-cell conditions.

The Zircaloy-to-capsule gap is predicted to close at ~33.3 GWd/MT burnup and remains closed through 52 GWd/MT; at hot-cell conditions this gap is predicted to be closed (slight mechanical strain of 0.03%). The maximum mechanical strain on the stainless steel wall reaches 0.38% (total strain including thermal is 0.53%) at 50 GWd/MT. When the LHGR subsequently drops to 5 kW/ft, the strain drops to 0.18% and then increases to 0.22% at 52 GWd/MT.

The fuel centerline temperature at the beginning of Phase IV for the "conservative" case is 1077°C; it drops initially and then slowly increases (due to burnup degradation effects as represented in the FRAPCON model for the fuel thermal conductivity) to ~1098°C at 50 GWd/MT. After 50 GWd/MT with the lower LHGR, the centerline fuel temperature drops from 1098°C to ~599°C (the mean fuel temperature drops from 639°C to 363°C). The mean temperature in the clad drops from ~191°C to ~135°C; and the mean capsule wall temperature drops from ~116°C to ~92°C.

The fuel/clad/capsule conditions at the 52 GWd/MT burnup are more benign than at a burnup of 50 GWd/MT. Conservative (higher than actual) LHGRs are assumed at both burnups.

The hot dimensions in the "conservative" case were used in the HEATING three-dimensional simulations at 30-, 40-, and 50-GWd/MT burnup (Section 3.4 of Ref. 7), and for the FLUENT calculations at 50 GWd/MT discussed in Chapter 4 of Ref. 7.

A summary of the HEATING calculations from Reference 7 is given in Section 3.2; however, from the previous discussion, the HEATING calculations in Ref. 7 were performed for more conservative conditions (higher temperatures and mechanical strains) than are predicted to occur in the fuel/clad/capsule during the irradiation extension from 50 to 52 GWd/MT.

3.2 HEATING Thermal Analyses of the APT MOX Fuel Capsule

The code employed for the three-dimensional thermal analyses of the MOX fuel capsule is HEATING (Reference 13), which was originally developed at ORNL (late 1950s) and has been extensively upgraded over the past 35 years. HEATING is a general purpose conduction heat transfer program that can solve steady-state and/or transient heat conduction problems in one-, two-, or three-dimensional Cartesian, cylindrical, or spherical coordinates. A model may include multiple materials with temperature dependent properties, and heat generation (if needed) may be time-, position-, or temperature-dependent. Also a full range of boundary condition specifications (time, position, type) can be used in the HEATING models. HEATING has been extensively verified and validated (Reference 14). HEATING has been used in the original safety analyses supporting the APT (Ref. 4), to support the HPT analyses (Ref. 12), and to support the APT Phase IV analyses (Ref. 7).

HEATING was employed to model the full length APT MOX fuel capsule for the "conservative" case 1-D CARTS simulations at burnups of 30, 40 and 50 GWd/MT, as described in Section 3.3.3 of Ref. 7.

3.2.1 Summary of the HEATING Analyses for the Conservative Case

A summary of the temperatures of interest for the 1-D CARTS and 3-D HEATING analyses of the "conservative" case is given in the following Table 3.1.

Table 3.1 Summary of conservative HEATING results

Model	Midplane MOX Pellet Centerline Temperature °C			Midplane Mean Capsule Surface Temperature °C		
	30 GWd	40 GWd	50 GWd	30 GWd	40 GWd	50 GWd
1-D CARTS	1076.3	1088.6	1097.6	90.2	90.8	90.7
1-D HEATING	1073.1	1079.9	1088.1	90.5	90.5	90.5
360° 3-D HEATING	1077.2	1087.3	1091.9	90.8	91.0	91.1

In general, there is little difference in the thermal results for the nine calculations (three code models and three burnup stages). The fluid boundary conditions are the same; the power generation within the fuel is the same (i.e., 9 kW/ft) although the spatial generation is different (per Chang's analyses, Ref. 11). For example, the 3-D axial peaking factors at the fuel midplane are 1.0017, 1.0034, and 1.0, respectively, for the 30-, 40-, and 50-GWd/MT burnups, and for the 1-D cases, the peaking factor is 1.0. With the boundary conditions (power generation and fluid conditions) being essentially the same, there should be no significant differences in the results and there are none.

The major difference observed in Table 3.1 is the increase in the centerline fuel temperature from 30- to 50-GWd/MT burnup, which is due to the FRAPCON-3 burnup degradation factor in the fuel thermal conductivity model. However, all maximum fuel centerline calculated temperatures are significantly below the MOX solidus temperature (approximately 1500°C below the melt temperature).

For the Phase-IV "conservative" case, forced concentricity of all the capsule elements is attained at ~33.3 GWd/MT due to fuel swelling (the pellet-to-Zircaloy clad gap closes during Phase I and the Zircaloy-to-capsule clad gap closes at ~33.3 GWd/MT). Eccentricities do not alter these results because they do not occur.

At worst, the surface heat flux varies by ~3% due to the azimuthal variance in the power generation.

The 360° 3-D HEATING simulations of the full MOX capsule at 9 kW/ft LHGR and 30-, 40-, and 50-GWd/MT burnups give conservative estimates of the structural Zircaloy and stainless steel temperatures. The 3-D temperatures calculated by HEATING for the Zircaloy and stainless steel were employed in the structural analyses of the capsule design performed by ORNL's Luttrell and Yahr (Reference 8). These structural temperatures and imposed mechanical strains employed in Luttrell and Yahr's calculations are conservative, especially with respect to the irradiation extension to a burnup of 52 GWd/MT, as discussed in Section 3.1.2 of this addendum. There is no need to redo Luttrell and Yahr's calculations for the 50-to-52 GWd/MT irradiation extension; the calculations at the 50 GWd/MT burnup and a fuel pin power of 9 kW/ft bound the operation from 50-to-52 GWd/MT at the conservatively assumed fuel pin power of 5 kW/ft during that period.

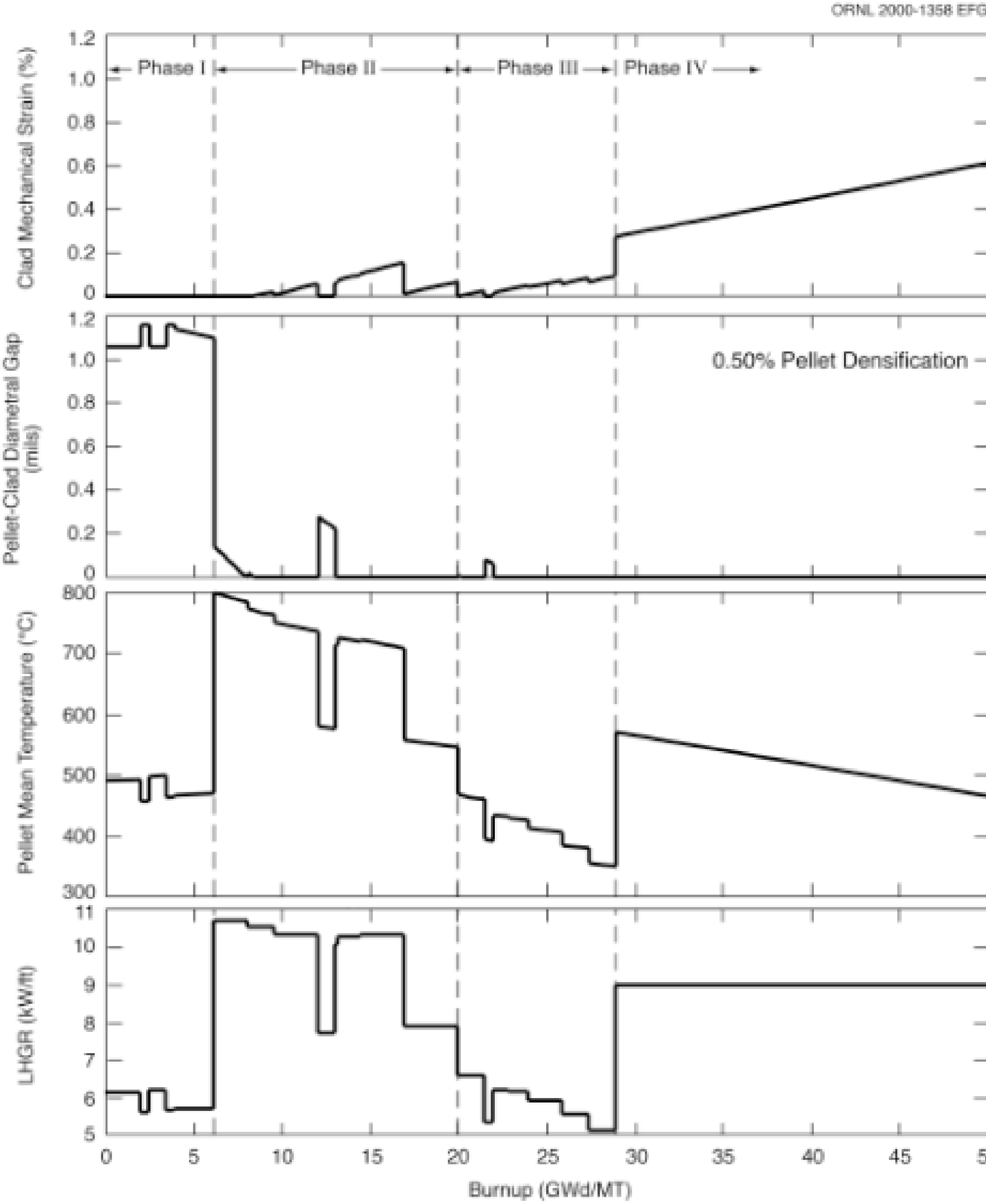

Fig. 3.1. CARTS best-estimate predictions based upon minimum initial gas gaps and 0.5% densification. The as-run LHGRs are those for Capsules 4 and 13. (From Ref. 7)

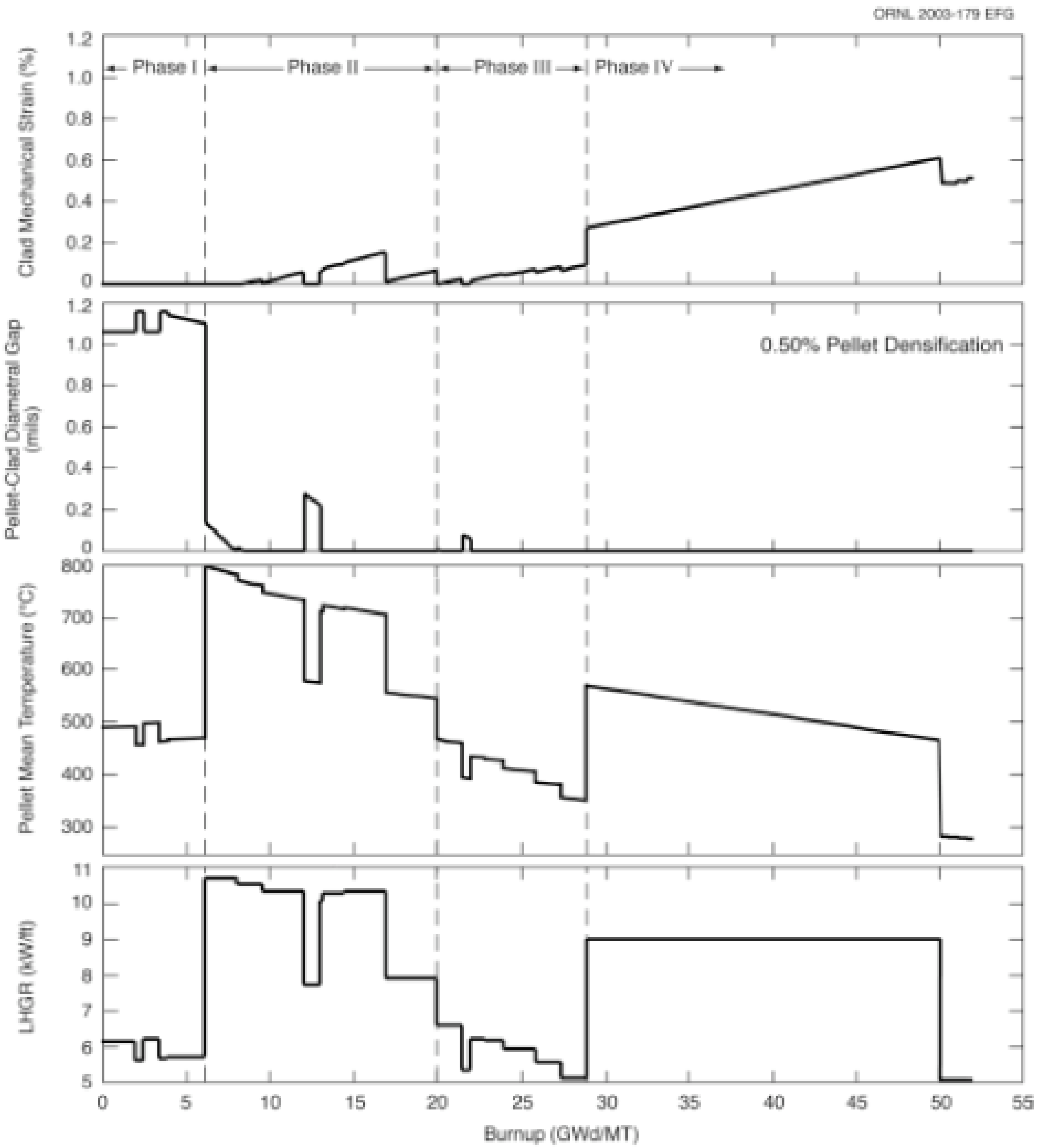

Fig. 3.2. CARTS best-estimate predictions through 52 GWd/MT burnup based upon minimum initial gas gaps and 0.5% densification. The as-run LHGRs are those for Capsules 4 and 13.

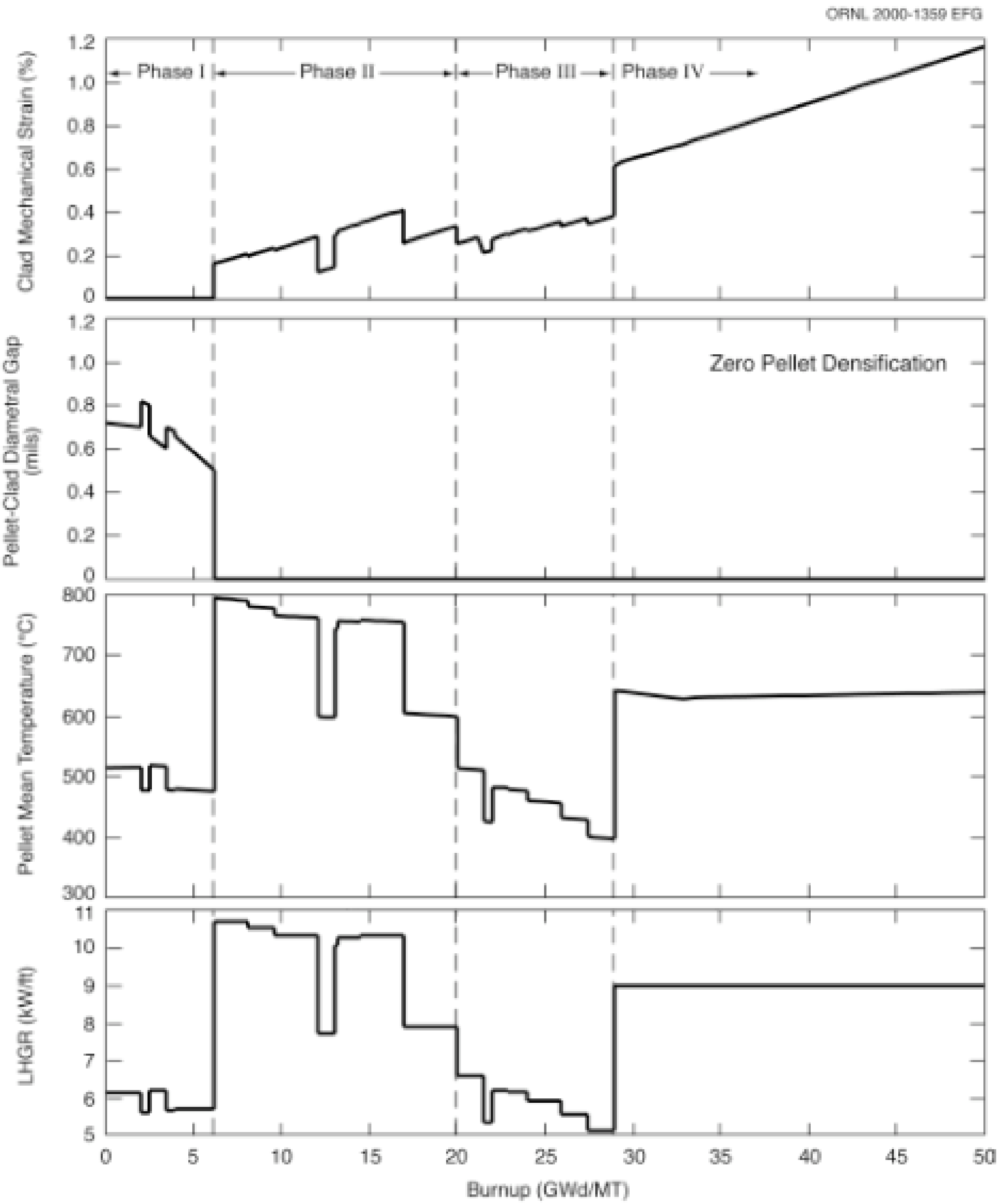

Fig. 3.3. CARTS conservative predictions based upon minimum initial gas gaps and 0.0% densification. The as-run LHGRs are those for Capsules 4 and 13. (From Ref. 7)

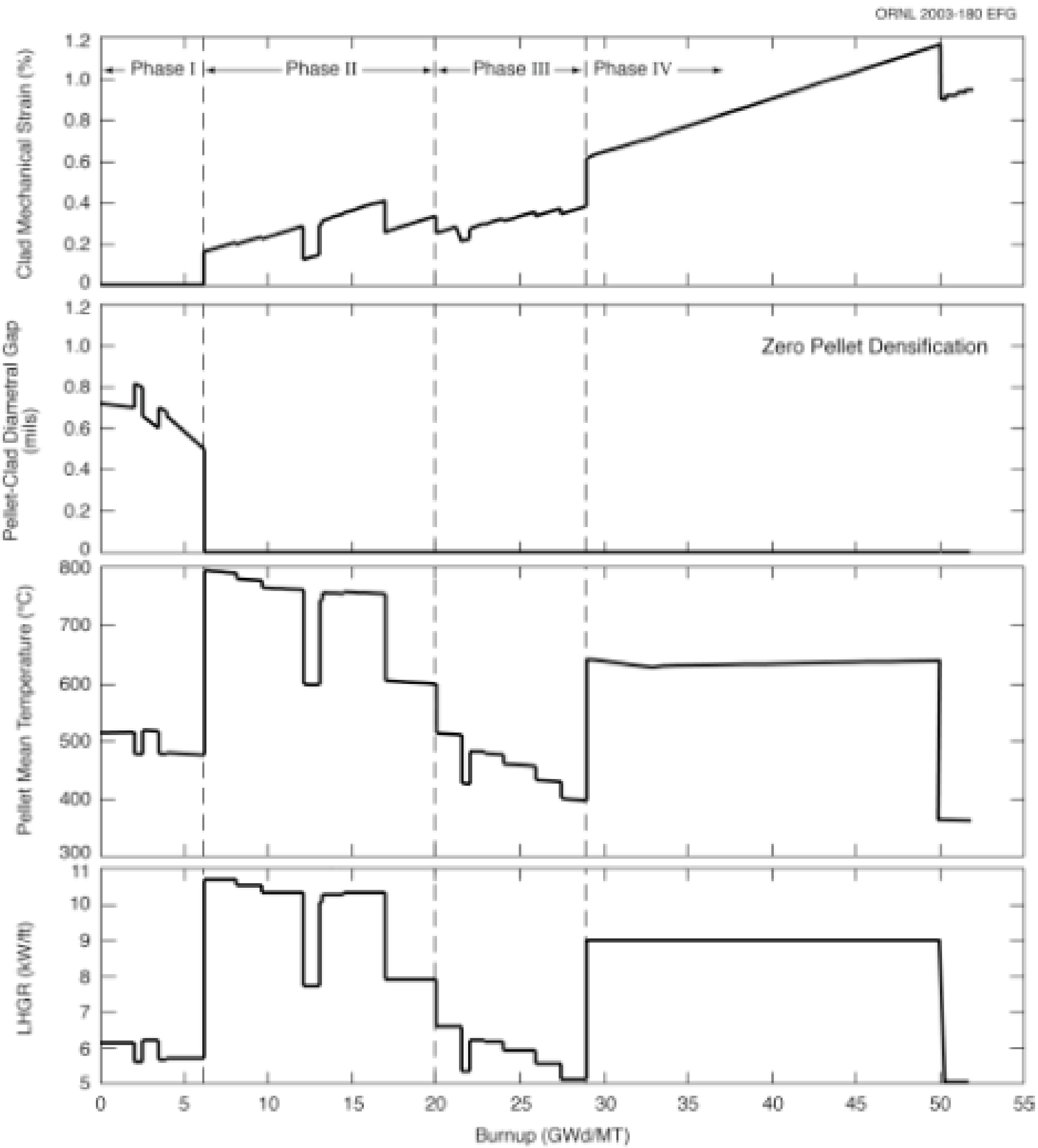

Fig. 3.4. CARTS conservative predictions through 52 GWd/MT burnup based upon minimum initial gas gaps and 0.0% densification. The as-run LHGRs are those for Capsules 4 and 13.

4. THERMAL/HYDRAULIC ANALYSES OF THE FUEL PIN GAS PLENUM

Hodge's analyses presented in the white paper (Reference 9) entitled

Fission Gas Release and Pellet Swelling Within the Capsule Assembly During Phase IV of the APT

were specifically supported by the thermal/hydraulic analyses of the fuel pin gas plenum discussed in Chapter 4 of Reference 7.

Models and simulations used to conduct the thermal/hydraulic analyses of the fuel pin gas plenum were based on the FLUENT computational fluid dynamics (CFD) code (Ref. 18).

The basis for the FLUENT simulations is consistent with the "conservative' approach described in Chapter 3, which was also used for the HEATING calculations. The basic assumptions are the following:

- power generation within the fuel equivalent to 9 kW/ft,
- boundary conditions from FFFAP with <u>20%</u> reduction in surface heat transfer coefficient,
- FRAPCON-3 fuel swelling model,
- FRAPCON-3 fuel thermal conductivity correlation,
- fuel densification of 0.0%.

Three FLUENT simulations were performed at a 50-GWd/MT burnup differing only in the amount of fission gas assumed to be released from the fuel (5, 11, and 100 percent).

The thermal/hydraulic analyses of the fuel pin gas plenum provided the representative gas temperatures needed to support Hodge's analyses (Ref. 9). The specific objective of these FLUENT simulations is to conservatively estimate the mean fuel pin plenum gas temperature to be used in Hodge's calculation of fuel pin internal pressure.

The highest calculated fuel pin plenum mean gas temperature was 136.4°C. For the capsule upper plenum, the highest calculated mean temperature is 63.7°C.

For Hodge's calculations as described in Reference 9, the mean gas temperature in the fuel pin plenum was conservatively assumed to be 160°C, and the mean gas temperature in the capsule upper plenum was conservatively assumed to be 64.0°C.

For the irradiation extension from 50 to 52 GWd/MT burnup, a power generation in the fuel of 5 kW/ft is conservatively assumed. As discussed in Section 3.1 of Chapter 3, at 50 GWd/MT and a LHGR of 9 kW/ft, CARTS predicts the fuel centerline temperature to be ~1098°C. The fuel is in direct contact with the gas in the fuel pin plenum, and the high fuel temperature is the forcing function for heating the plenum gas. However, at 52 GWd/MT burnup and a LHGR of 5 kW/ft, the CARTS calculated fuel centerline temperature is only ~599°C. Therefore, less heat will be transferred to the plenum gas and the fuel pin plenum mean gas temperature will be less than 136.4°C (maximum calculated in Chapter 4 of Reference 7). In addition, Hodge conservatively assumed 160°C for his analyses.

The analyses in References 7 and 9 are conservative and bounding for the irradiation extension from 50 to 52 GWd/MT.

5. SUMMARY

As specified in the design, functional, and operational requirements (Ref. 2) for Phase IV of the average-power ATR MOX irradiation experiment, conservative thermal/hydraulic analyses (Ref. 7) of the fuel pin/capsule assemblies and experiment basket were performed. As shown in this addendum, the analyses performed for Reference 7 (and References 8 and 9) are conservative and bounding for the proposed irradiation extension from 50 to 52 GWd/MT burnup.

The thermal/hydraulic response of the experiment assembly was evaluated at an LHGR of 9 kW/ft (112.5% of the specified maximum heating rate of 8 kW/ft) for both two- and three-PCS pump operational modes for the Model-2 type basket. The estimated local fluid conditions from the thermal/hydraulic simulation of the Model-2 basket for the two-pump operating mode provided the most conservative boundary conditions for detailed thermal modeling of a complete fuel pin/capsule assembly [the surface heat transfer coefficient was further reduced by 20% (per Ref .2) for additional conservatism].

Per Reference 2, the following thermal/hydraulic criteria were also evaluated:

- the DNBR for all experimental surfaces;
- the rise in bulk primary coolant temperature along the experiment hot track flow instability ratio;
- all criteria were evaluated with two or three primary coolant pumps in operation (normal operation); and for abnormal conditions (a flow coastdown from a lobe power of 60 MW with two pumps initially running).

In all cases, the DNBR and flow instability ratios significantly exceeded the ATR technical specification minimum of 2.0.

A primary consideration in extending the burnup for some of the APT capsules beyond 30 GWd/MT was the small initial diametral gap between the pellet and the Zircaloy clad. The CARTS code provided "best-estimate" and "conservative" analyses of the fuel swelling and the resulting impact on the Zircaloy clad and the capsule stainless steel wall. These analyses showed that fuel melting is not an issue; the maximum observed temperature in Phase IV being ~1100°C, more than 1500°C below the predicted MOX melting temperature at 50 GWd/MT.

The pellet-to-Zircaloy gap is predicted to close early in Phase II, and in the "conservative" case the Zircaloy-to-capsule gap closes early in Phase IV (at ~33.3 GWd/MT). For the "best-estimate" simulation, the Zircaloy-to-capsule gap remains open through all phases of the irradiation.

Conservatively, the maximum imposed mechanical strain on the capsule wall reaches 0.38 percent, at 50 GWd/MT and the corresponding maximum mechanical strain on the Zircaloy clad is 1.16 percent. With a reduction in the heating rate in the fuel after 50 GWd/MT from 9 to a more realistic but still conservative 5 kW/ft, the imposed mechanical strains in the capsule wall and the Zircaloy clad drop respectively to 0.22% and 0.94% at 52 GWd/MT.

These CARTS analyses presented in this addendum demonstrate that Hodge's white paper (Ref. 9) on fission gas release and pellet swelling in Phase IV and Luttrell and Yahr's stress/strain calculations (Ref. 8) remain both conservative and bounding for the proposed irradiation extension from 50 to 52 GWd/MT burnup.

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