Response to Sixth Request for Additional Information – ANP-10285P
"U.S. EPR Fuel Assembly Mechanical Design Topical Report"
RAI 60, 61, 62 and 63

RAI-60. *The following questions relate to demonstrating conservatism in the U.S. EPR linear heat generation rate (LHGR) limit for cladding strain and the strain capability of M5® irradiated cladding relative to the 1 percent total (elastic plus plastic) uniform strain limit, respectively.*

1. *The following is a follow-up request to the response to RAI-44. Provide test data that demonstrates fuel failure or non-failure as a function of strain and LHGR for time durations typical of an anticipated operational occurrence (AOO) event. Provide post-irradiation micrographs of the cladding post ramp along with measured strains and the local LHGR at each axial location the strains were measured.*

2. *Verify whether the uniform strain values in the response to RAI-40 (Table 40-1) and RAI-51 (Table 51-1) includes both elastic strain as well as plastic strain. If so, provide the elastic and plastic components of the total uniform strain. If not, provide the elastic component of strain. These RAIs stated that these were tensile tests, provide a drawing or photograph that illustrates the geometry of the tensile test specimen. Provide those power ramp tests with fuel rods using M5® cladding where cladding strain was measured to demonstrate the strain capability. Discuss how this test data demonstrates that there is adequate conservatism in the 1 percent strain limit to cover any possible COPERNIC underprediction in cladding strain of 0.2 percent.*

Response 60: Part 1

When the fuel-cladding gap has closed, linear heat rates (LHR) resulting in 1 percent transient cladding strain are lower than, but approach those LHRs which correspond with fuel centerline melt. Sections 4.6.1.1 and 4.6.2.2 of the COPERNIC Topical Report (Reference RAI 60-1) show **[**

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- HBC-3 was a test involving **[**

  ] is shown in Figure 60-2.

- HBC-5 was a test involving **[**

] are shown in Figure 60-5.

The LHRs achieved during these HBC ramp tests [

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Response 60, Part 2:

Mechanical Tests

The uniform elongation values provided in the Response to RAI 40 (Table 40-1) and the uniform and total elongation values provided in RAI 51 (Table 51-1) were plastic for strain only. The uniform elongation data in Table 60-1 includes both elastic strain as well as plastic strain.

Table 60-3 shows irradiated alloy M5® cladding tube uniform and total elongation data at room and elevated temperature (350ºC). The data is derived from uniaxial tensile tests. Table 60-3 shows the uniform and total elongation as a function of temperature, burnup, fast fluence, and hydrogen content. Table 60-3 also shows uniform elongation separated into its elastic and plastic components.

Figure 60-6 shows a photograph of a typical cladding tensile test specimen and a sketch showing its dimensions.

Power Ramp Tests

As part of the Studsvik Cladding Integrity Project (SCIP), Reference RAI 60-2, which investigated the main failure mechanisms during power ramp conditions, two high-burnup M5® rods of the 17x17 design with standard fuel pellets were ramped; Rodlet M5®-H1 and Rodlet M5®-H2.

- Rodlet M5®-H1 had achieved an average burnup of 67 GWd/T. It was conditioned for 18 hours at 16 kW/m and then ramped to a terminal power level of 40 kW/m for five seconds. [
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- Rodlet M5®-H2 had achieved an average burnup of 68 GWd/T. It was conditioned for 18 hours at 16 kW/m and then ramped to a terminal power level of 40 kW/m for twelve hours. [
  ]

Neither rodlet failed. These ramp tests are relevant to the fairly fast transient analyses [
] that AREVA NP performs to ensure that the fuel meets the to 1 percent (total) transient cladding strain criterion, and to demonstrate the successful performance of AREVA NP M5® cladding at high burnup under power ramp conditions.

There are also four RIA tests of M5® cladding; REP-Na11, CIP0-2, RH-1, and RH-2. Each of these tests is briefly described as follows:

- REP-Na11 was a test involving a 17x17 M5® rodlet irradiated to 60 GWd/T. The rod was pulsed to a peak fuel enthalpy of 385 J/gUO_2 with a pulse width of 31 milliseconds. Cladding maximum residual hoop strain was 0.4 percent. This experiment is described in detail in Reference RAI 60-3.
- CIP0-2 was a test involving a 17x17 M5® rodlet irradiated to 76 GWd/T. The rod was pulsed to a peak fuel enthalpy of 343 J/gUO_2 with a pulse width of 28 milliseconds. Cladding maximum residual hoop strain was 0.3 percent. This experiment is described in detail in References RAI 60-4 and RAI 60-5.
- RH-1 was a test involving a 17x17 M5 rodlet irradiated to 67 GWd/T. The rod was pulsed to a peak fuel enthalpy of 462 J/gUO_2 with a pulse width of 4.4 milliseconds. Cladding maximum residual hoop strain was 0.96 percent. This experiment is described in detail in Reference RAI 60-6.
- RH-2 was a test involving a 17x17 M5® rodlet irradiated to 67 GWd/T. The rod was pulsed to a peak fuel enthalpy of 447 J/gUO_2 with a pulse width of 4.5 milliseconds. Cladding maximum residual hoop strain was 1.06 percent. This experiment is described in detail in Reference RAI 60-6.

Each of the four rodlets survived the RIA tests. A comprehensive summary of RIA testing is provided in Appendix A of Reference RAI 60-7.

AREVA NP has previously provided information to demonstrate that COPERNIC provides appropriate predictions of transient cladding strain (refer to the Response to RAI 52).

Four main types of data were provided in response to parts 1 and 2 of this question.

1. Ramp tests (transient conditions) for fuel irradiated in the **[**

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2. Mechanical tests on M5® material (uniform strain elastic plus plastic) for a range of burnups beyond the burnup limit of the U.S. EPR. The minimum uniform strain at which the M5 material failed was **[ ]**, which is above the 1 percent strain failure criterion.
3. Ramp tests (transient conditions) for high burnup fuel with M5® cladding demonstrating that the fuel did not fail.
4. Reactivity Insertion Accident (RIA) tests for high burnup fuel with M5® cladding demonstrating that the fuel did not fail under the RIA conditions.

It can be concluded from the data shown that the fuel with M5® cladding is capable of being ramped to LHR values in excess of the limits defined for the U.S. EPR without failure, that the 1 percent uniform strain failure criterion is conservative for the M5® cladding used in the U.S. EPR, and that the M5® fuel used in the U.S. EPR can survive certain transient and accident conditions.

References for RAI 60:

1. BAW-10231P-A, COPERNIC Fuel Rod Design Computer Code, Revision 1, January, 2004.
2. Insights Into Fuel Rod Performance Codes during Ramps: Results of a Code Benchmark based on the SCIP Project, L.E. Herranz, et.al., Proceedings of Top Fuel 2009, Paper 2188, Paris, France, September 6-10, 2009.
3. Summary and Interpretation of the CABRI REP-Na Program, J. Papin et. al, Nuclear Technology, Volume 157, p230, March 2007.
4. IRSN R&D Studies on High Burn-up Fuel Behavior Under RIA and LOCA Conditions, J. PAPIN et. al., TopFuel Conference, Salamanca, October 22-26, 2006.
5. FRAPTRAN Predictability of High Burnup Advanced Fuel Performance: Analysis of the CABRI CIP0-1 and CIP0-2 Experiments, M.T. del Barrio, L.E. Herranz, Proceedings of the 2007 International LWR Fuel Performance Meeting, Paper 1046, San Francisco, California, September 30 – October 3, 2007.
6. PWR Fuel Behavior in RIA-simulating Experiment at High Temperature, Tomoyuki Sugiyama et. Al., 2008 Water Reactor Fuel Performance Meeting, Paper 8108, October 19-23 2008.
7. Nuclear Fuel Behaviour Under Reactivity-initiated Accident (RIA) Conditions - State-of-the-art Report, NEA OECD, ISBN 978-92-64-99113-2, NEA/CSNI/R(2010)1, 2010

Table 60-1—Fuel Rod Design Parameters for Rod HBC-3

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Table 60-2—Fuel Rod Design Parameters for Rod HBC-5

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Table 60-3—Uniform and Total Elongation Data for M5® Fuel Rod Cladding at Room and Elevated Temperature (350 ºC)

Figure 60-1—Axial Power Profile During Transient for Rod HBC-3

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Figure 60-2—Post-Ramp Profilometry for Rod HBC-3

Figure 60-3—Axial Power Profile During Transient for Rod HBC-5

Figure 60-4a—Micrograph of HBC-5 at Elevation 425mm, 0°

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Figure 60-4b—Micrograph of HBC-5 at Elevation 425mm, 90°

Figure 60-4c—Micrograph of HBC-5 at Elevation 425mm, 180°

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Figure 60-4d—Micrograph of HBC-5 at Elevation 425mm, 270°

Figure 60-4e—Micrograph of HBC-5 at Elevation 480mm, 0°

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Figure 60-4f—Micrograph of HBC-5 at Elevation 480mm, 90°

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Figure 60-4g—Micrograph of HBC-5 at Elevation 480 mm, 180°

Figure 60-4h—Micrograph of HBC-5 at Elevation 480 mm, 270°

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Figure 60-5—Pre- and Post-Ramp Profilometries for Rod HBC-5

Figure 60-6—Typical Cladding Tensile Test Specimen.

RAI-61. *The following question is related to clarification of Table RAI-52-2.*

Examination of Table 52-2 appears to demonstrate that the UCBW event at power is limited by departure from nucleate boiling ratio (DNBR) rather than strain limited. Confirm that this observation is correct. If this observation is not correct, provide a further discussion on why this event is not DNBR limited.

Response 61:

The departure from nucleate boiling ratio (DNBR) and linear power density (LPD) results for the uncontrolled bank withdrawal (UCBW) event in RAI 52, Table 52-2 are reported for the case that had the shortest time to a reactor trip (based on the models for the transient response of incore monitoring system). For this case, the low DNBR reactor trip time was shorter than the high LPD reactor trip time. Therefore, this case is considered to have the most limiting conditions for the UCBW event. The UCBW event, however is the most limiting of the anticipated operational occurrences (AOOs) with respect to the LPD criterion because it has the highest value of the "maximum LPD/SAFDL" ratio. This is a measure of the degree of adequate instrumentation compensation for the LPD reactor trip setting that is designed to protect the fuel centerline melt and clad strain specified acceptable fuel design limits (SAFDL). For the broad spectrum of UCBW cases studied, some had predictions of a reactor trip on high LPD before the reactor trip on low DNBR; however, these trip times occurred later than the shortest trip time which was on low DNBR. In each case, adequate compensation was verified (meaning the maximum LPD/SAFDL ratio never exceeded 1.0).

RAI-62. *The current 95/95 upper bound curve is based on low and high burnup data, this is not acceptable because the gap closure is only an issue at end-of-life (EOL), or high burnup, and not at low burnup. Propose a 95/95 upper bound curve for M5^{TM} guide tube growth that is based only on high burnup M5^{TM} growth data, greater than 40 GWd/MTU, for application to determine the gap size at EOL for the U.S. EPR.*

Response 62:

Background

The Response to RAI 49 provided Mark-B data that was used to substantiate an uncertainty for the Mark-B HTP assembly growth correlation, which was presented as applicable for the U.S. EPR design based on similarities [ ] . The data included [ ] fuel assembly growth measurements of the Mark-B fuel design at burnups up to [ ] GWd/mtU on which a proposed applicable 95/95 uncertainty was based. The data used to establish the statistical uncertainty included [ ] fuel assemblies above a burnup of [ ] GWd/mtU, in addition to fuel assemblies with growth rates considered to be both nominal and high [ ] The uncertainty was calculated using least squares regression techniques considering all of the Mark-B data in conjunction with Owens one-sided tolerance limits.

A revised upper growth limit for the U.S EPR fuel assembly design is proposed based on only high burnup data as requested in this RAI. Additional Mark-B fuel assembly growth data has been obtained since the Response to RAI 49 was submitted and is used in the development of the proposed upper bound growth curve.

<u>Applicable Mark-B Data/Conservative Uncertainty</u>

Table 62-1 provides the growth data for which the conservative assessment of the growth uncertainty is based. A total of [ ] Mark-B fuel assembly growth measurements exist for assembly burnups greater than [ ] GWd/mtU up to a maximum burnup of [ ] GWd/mtu, with the data representative of [ ] different fuel batches from [ ] reactors. These data above [ ] GWd/mtU are selected because it is at these burnups that the largest range of assembly growth has been observed. The uncertainty is determined as the product of the standard deviation calculated and the Owens K factor associated with a one-sided 95/95 confidence tolerance limit for the applicable number of degrees of freedom (i.e., [ ] in this case).

Figure 62-1 shows the Mark-B (non Mark-B HTP) fuel assembly growth data with the corresponding conservative 95/95 uncertainty of [ ] $\Delta L/L$ calculated based on the growth data above [ ] GWd/mtU burnup. Also shown in Figure 62-1 are all Mark-B fuel assembly length measurements including the Mark-B11A, Mark-B10K, and Mark-B12 designs. The data set consist of [ ] measurements encompassing [ ] reactors and [ ] different batches with assembly burnups ranging from [ ] GWd/mtU with [ ] of the data greater than [ ] GWd/mtU burnup.

The uncertainty is used to establish the conservative U.S. EPR fuel assembly growth upper limit with its application to the Mark-B HTP nominal growth model. The uncertainty established by the large quantity of empirical Mark-B fuel assembly growth data is considered to be conservatively representative of the inherent variation of all the parameters influencing growth, [

] for a given fuel design including the U.S. EPR design.

Applicable Mark-B HTP Data/Uncertainty

Additional Mark-B HTP fuel assembly length measurements continue to be obtained to further expand the data base and validate the growth limits. Mark-B HTP assembly growth measurements obtained to date are provided in Table 62-2.

A total of [ ] data points now exists for the Mark-B HTP assembly growth, including [ ] different fuel batches and [ ] reactors with a burnup range of [ ] GWd/mtU. [ ] Mark-B HTP growth measurements exist for burnups greater than [ ] GWd/mtU, including [ ] reactors and [ ] different batches.

Using the high burnup data set only, the Mark-B HTP [ ] uncertainty is calculated to be [ ] ΔL/L. Figure 62-2 shows a comparison of the conservative uncertainty based on the Mark-B high burnup data and that calculated for the Mark-B HTP high burnup data. The conservative uncertainty of [ ] ΔL/L clearly bounds the present Mark-B HTP data and the [ ] uncertainty.

Figure 62-3 shows that the corresponding Mark-B HTP upper limit, based on the [ ] uncertainty, is clearly bounded by the revised conservative upper limit and even the previous upper limit provided in the Response to RAI 38.

Application to U.S. EPR Design

As provided in the Responses for RAI 38 and RAI 47, the Mark-B HTP design is similar to the U.S. EPR design in [ ], and the empirically based Mark-B HTP fuel assembly growth design limits are applicable to the U.S. EPR fuel assembly design. Additional conservatism is used in the calculation of the Mark-B HTP growth uncertainty using only Mark-B high burnup data ([ ] GWd/mtU) in the application to the U.S. EPR design upper growth limit.

Figure 62-4 provides the revised conservative upper growth limit for the U.S. EPR design. The use of the conservative growth limit in the fuel assembly core plate gap evaluation results in a maximum U.S. EPR fuel assembly burnup of [ ] GWd/mtU, at which the maximum allowable growth of [ ] at cold conditions is obtained. AREVA NP proposes to use the revised conservative upper growth curve labeled “Revised Upper Tolerance Limit” for burnups greater than [ ] GWd/MtU. AREVA NP proposes to use the lower growth curve labeled “ANP 10285P Rev 0 RAI 38 LTL” (defined in the Response to RAI 38) for the U.S. EPR design as shown in Figure 62-4. The lower growth curve is used in the evaluations of fuel assembly liftoff and the fuel rod shoulder gap.

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Table 62-1—Mark-B Data to Define the Upper Tolerance Growth (>46 GWd/mtU)

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Reactor Cycle	Assembly Design	Average Assembly Burnup (GWd/mtU)	FA Growth (%)

Table 62-2—Mark-B HTP Fuel Assembly Growth Data ([>46] GWd/mtU)

Figure 62-1—Mark-B Fuel Assembly Growth – 95/95 Uncertainty

Figure 62–2—Mark-B HTP Fuel Assembly Growth - Uncertainty Comparison with Mark-B

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Figure 62-3—Mark-B HTP Fuel Assembly Growth – Comparison of Upper Limits

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Figure 62-4—U.S. EPR Revised Design Limits

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RAI-63. *Propose a hydride limit for M5™ and provide a justification for this limit per SRP Section II.1.A.IV.*

Response 63:

AREVA NP proposes to limit the hydrogen content in the M5® cladding to 450 ppm. The limit is based on meeting the 1 percent uniform strain criterion in the Standard Review Plan (SRP).

AREVA NP has previously provided information on the mechanical properties of M5® cladding with respect to hydrogen content in response to RAI 51. In the response to RAI 51 AREVA NP took the position that a hydrogen limit was not necessary for M5® cladding. The primary reason for this position was that the hydrogen content of M5® cladding is very low, even at the licensed burnup limit of 62 GWd/mtU, less than 100 ppm as show in the Response to RAI 51, Table 51-1. The data in Table 51-1 are based on plastic strain for both the Uniform and Total Elongation columns. The 1 percent strain criterion in the SRP is based on uniform elastic plus plastic strain. If uniform elastic elongation (approximately .5 percent) were added to the values in the Uniform Elongation column in Table 51-1 the minimum uniform elastic plus plastic strain would be about 1.6 percent up to an exposure (about 78 GWd/mtU) beyond the licensed limit. **[**

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Because the hydrogen pickup of the M5® cladding is so low there is no data available for irradiated M5® cladding at the high hydrogen levels appropriate for a limit. In order to establish a cladding hydrogen limit, data at higher hydrogen content are needed to illustrate the effect of hydrogen on cladding ductility. The recrystallized cladding (RXA) M5® ductility data are supplemented with RXA Zr-4 data in this response. This approach allows an assessment of the effect of hydrogen on M5® irradiated cladding ductility using higher levels of hydrogen in an alloy with the same microstructural condition (RXA) as alloy M5®.

Uniform plastic elongation data for irradiated Zr-4 cladding tubes in the SRA and RXA conditions are shown in Figure 63-1 for elevated temperature (300-350ºC) tests. A uniform plastic strain line of 1 percent is depicted on the plots, but it should be noted that the uniform strain limit of 1 percent is for elastic +plastic strain, and the data points plotted on these graphs is the plastic component of uniform strain only.

It is evident from this figure that uniform elongation evolves similarly for RXA and SRA Zr-4 with increasing hydrogen content over the entire range investigated. The uniform elongation drops below 5 percent almost exclusively due to irradiation, and is uniformly located on a plateau independent of hydrogen content (at values beyond 1600 ppm hydrogen).

Based on this data, it is clear that uniform elongation is not a discriminating parameter for the impact of hydrogen on the ductility of irradiated zirconium alloys, and is not useful for defining a hydrogen design limit. Total elongation data may be used to develop a basis for choosing a hydrogen limit. Therefore, the ductility data that is used to develop the hydrogen limit is in units of total plastic strain. The chosen hydrogen limit is based on when a change in strain failure is observed. It is assumed that a change in strain failure behavior occurs at similar hydrogen content for both uniform elastic plus plastic strain and for total plastic strain.

Figure 63-2 shows the total plastic strain versus hydrogen content for 1) M5® unirradiated guide tubes which have been charged with hydrogen and 2) M5® cladding which has been irradiated. The data for the guide tubes illustrate the effect of hydrogen without the effect of irradiation. The data for the cladding illustrate the effect of both irradiation and hydrogen. Because the M5® cladding only picks up about 90 ppm of hydrogen during irradiation, the guide tube data is useful to illustrate the effect of higher hydrogen content. A comparison of these two types of data leads to the conclusion that the effect of hydrogen is less than the effect of irradiation.

Figure 63-3 augments the M5® data with Zr-4 RXA data (both cladding and guide tubes). [

]. The initial decrease in the failure strain is due to irradiation rather than hydrogen, but for the purposes of developing a hydrogen limit this will be ignored. [

]. AREVA NP, therefore, proposes to use a value of 450 ppm as the hydrogen limit.

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Figure 63-1—Tensile Uniform Plastic Elongation at 300/350ºC of Irradiated RXA and SRA Zr-4 Cladding Tubes vs. Hydrogen Content

Figure 63-2—Ductility of M5® Guide Tubes and Cladding at 350ºC vs. Hydrogen Content

Figure 63-3—Total Elongation at 300/350ºC of Irradiated M5® Cladding and RXA Zr-4 Cladding and Guide Tubes vs. Hydrogen Content

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