AREVA

Evaluation of Advanced Cladding and Structural Material (M5) in PWR Reactor Fuel

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Nature of Changes

Item	Section(s) or Page(s)	Description and Justification
1	All	New document.

Contents

List of Tables

List of Figures

List of Acronyms

Acronym	Definition
FA	Fuel Assembly
FR	Fuel Rod
GWd	Gigawatt-Day
MTU	Metric Ton of Uranium
ppm	Parts Per Million
PWR	Pressurized Water Reactor

ABSTRACT

The purpose of this supplement is to extend the range of applicability of models and correlations for M5® and to modify the composition limits for M5® accordingly. The supplement provides evidence that implementing the modified composition limits will not have a significant effect on the performance of the material.

The modified composition limits for M5® are provided. The effects on microstructure and texture are examined and found to be insignificant.

The effects of the modification on material properties are evaluated. In each case, the effect of the modification is found to be insignificant.

Development of the modified composition limits included irradiation of test samples and test assemblies. The success of these irradiations provides further support for the appropriateness of the modification.

Because the properties and performance of M5® are unchanged, existing approved topical reports and analyses remain valid and need not be reviewed again.

1.0 INTRODUCTION

The U.S. Nuclear Regulatory Commission has approved AREVA's advanced cladding and structural material, M5®, for fuel reload licensing applications (safety evaluation of Reference 1), and M5® has been used successfully in many pressurized water reactors (PWRs).

The purpose of this supplement is to extend the range of applicability of models and correlations for M5® and to modify the composition limits for M5® accordingly. Evidence is provided that the new limits will not have a significant effect on fuel performance. Section I.20 of Reference 1 sets a maximum iron concentration of [ ] ppm Fe ([ ] µg Fe / g metal). This supplement extends the range of applicability of the models and correlations approved in Reference 1 to a maximum iron concentration of [ ] ppm. Since the supplement does not revise any models or correlations, citations of Reference 1 in Technical Specifications and Core Operating Limits Reports are sufficient; a specific reference to this supplement is not required.

Limits on alloying elements (niobium, oxygen, and sulfur for M5®) are established to determine the behavior of the alloy, whereas limits on impurities are established to ensure product uniformity. Because the modification is an adjustment to the concentration limit for one impurity element, the name "M5®" will be retained.

[ ] Iron is present as an impurity in zirconium sponge, and the current state of the art in zirconium production allows reliable production of ingots with iron concentrations no greater than [ ] ppm. [

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2.0 SUMMARY

This supplement provides evidence that increasing the maximum iron concentration to [ ] ppm will not have a significant effect on fuel performance. Because material properties determine performance, the strategy is to examine each relevant material property and show that it is not significantly affected. The details of the strategy are adjusted as needed for individual properties. For example, impurities are expected to have very little influence on density, so a simple treatment based on the rule of mixtures is appropriate. In contrast, mechanical properties could be affected by impurities, so experimental results are presented to demonstrate that modifying the iron concentration limit will not have a significant effect.

Some of the measurements reported in this supplement are for iron concentrations greater than the limit of [ ] ppm Fe. For example, data may be presented for a concentration of [ ] ppm Fe. That approach provides assurance that alloy behavior up to [ ] ppm Fe is bounded by the data.

Section 3.0 provides a modified definition of M5®, along with qualitative information to support the equivalence of material manufactured according to the new and old definitions.

Section 4.0 follows the organization of the safety evaluation of Reference 1. The material properties discussed in Sections 2.0 and 3.3 of the safety evaluation are reviewed, and in each case the modification is found to have an insignificant effect.

Section 5.0 describes irradiation experience for commercial fuel that used a variant of M5® with 1000 ppm Fe. It demonstrates that the combination of the experience and AREVA's normal product surveillance is sufficient to ensure safe operation.

3.0 MATERIAL DEFINITION

This supplement modifies the iron concentration limit for M5® and sets a maximum iron concentration of [ ] ppm. All other concentration limits remain as specified by the tables in Section I.20 of Reference 1.

The metallurgical state of the cladding remains as described in Sections 5.0, A.1.2, and I.4 of Reference 1. Effects of the modification on microstructure and metallurgical texture are discussed in Section 3.1 below.

3.1 *Microstructure and Texture*

Microstructure and texture are not considered in fuel performance analyses, but understanding of these properties provides added confidence that the effects of the iron concentration are understood.

Comparisons of microstructure and metallurgical texture for alloys with different iron concentrations provide evidence that modifying the iron concentration limit will not have significant effects. M5® has a fully recrystallized microstructure, characterized by an α-Zr matrix with two types of uniformly distributed precipitates: body-centered cubic β-Nb precipitates and hexagonal Laves phase ($Zr(Nb,Fe)_2$) intermetallic precipitates. Figure 1 of Reference 2 provides photomicrographs for samples with three different concentrations of iron (330, 412, and 900 ppm). The sizes of the precipitates and α-Zr grains are unaffected by the iron concentration (Reference 2, page 162).

Metallurgical texture, as expressed by the basal plane Kearns factors, has been examined for M5® and variants of M5® with six iron concentrations from 240 to 970 ppm (page 166 and Table 1 of Reference 2). A significant dependence of the Kearns factors on iron concentration was not seen.

4.0 MATERIAL PROPERTIES

The following subsections discuss how modifying the iron concentration limit will affect the material properties of M5®, and they provide evidence that the modification will not cause significant effects on fuel performance.

Several of the materials properties discussed below are structure-insensitive. Because of the smallness of the change in the iron concentration limit, structure insensitivity alone is considered to be sufficient to show that the effect of iron on these properties will be insignificant. Certain subsections also use the rule of mixtures to estimate the magnitude of the effect. Although the rule of mixtures is customarily applied to composites, the approach is appropriate here because the purpose of the calculations is to provide a rough, order-of-magnitude estimate. In each case, the calculated effect is much smaller than the uncertainty in the recommended value.

Density, the coefficient of thermal expansion, specific heat capacity, Poisson's ratio, and the modulus of elasticity are structure-insensitive properties (page 86 of Reference 3), so a small change in composition is not expected to have a significant effect. That statement might be questioned near a phase transformation temperature because these properties depend on which zirconium phase (alpha or beta) is present. However, it is shown in Section 4.17 that the addition of [ ] ppm Fe will not have a significant effect on the transformation temperature, so the discussions of these properties consider only the individual phases. Emissivity is also a structure-insensitive property (Table 2 on page 95 of Reference 4), but for oxidized material it is determined by the properties of the oxide, not those of the underlying metal, so the alpha-to-beta phase transformation temperature is not relevant.

Evaluations of structure-insensitive properties may report values with greater precision than could be justified from experimental data. The intention is to show the smallness of the expected change so that its magnitude can be compared to the uncertainty in the recommended values.

4.1 *Density*

Density is a structure-insensitive property (page 86 of Reference 3), so a small change in composition is not expected to have a significant effect. A rough estimate of the effect of iron on density may be obtained by applying the rule of mixtures:

$$\rho = \frac{1}{\frac{x_{\mathrm{Fe}}}{\rho_{\mathrm{Fe}}} + \frac{x_{\mathrm{M5}}}{\rho_{\mathrm{M5}}}}$$

where ρ, ρ_{Fe}, and ρ_{M5} are the densities of the mixture, iron, and M5®, respectively, and x_{Fe} and x_{M5} are the mass fractions of added iron and M5®, respectively.

Recommended values of the room temperature density are ρ_{M5} = [ ] g/cm^3 and ρ_{Fe} = 7.870 g/cm^3 (Reference 5, page 743). For x_{Fe} = [ ] and x_{M5} = [ ], the magnitude of the calculated change in density was about [ ] g/cm^3, which is much smaller than the reported uncertainty of [ ] g/cm^3.

Because the change in density is much smaller than the uncertainty, the effect of the modification will not be significant. The density of M5® remains applicable for iron concentrations up to [ ] ppm.

4.2 *Coefficient of Thermal Expansion*

The coefficient of thermal expansion is a structure-insensitive property (page 86 of Reference 3), so a small change in composition is not expected to have a significant effect. A rough estimate of the effect of iron on thermal expansion may be obtained by applying the rule of mixtures:

$$\alpha = x_{\mathrm{Fe}}\alpha_{\mathrm{Fe}} + x_{M5}\alpha_{\mathrm{M5}}$$

where α, α_{Fe}, and α_{M5} are the coefficients of thermal expansion of the mixture, iron, and M5®, respectively, and x_{Fe} and x_{M5} are the mass fractions of added iron and M5®, respectively. Because iron and zirconium both change phases at high temperature, the coefficient of thermal expansion is evaluated for a temperature range that includes normal operating conditions and again for a high temperature that is representative of accident conditions.

The coefficient of thermal expansion for M5® is anisotropic, but for a rough calculation it is acceptable to use the mean of the values in the axial, radial, and tangential directions: α_{M5} = [ ] K^{-1} [ ] Over the same temperature range, α_{Fe} varies from about $12 \cdot 10^{-6}$ K^{-1} to $17 \cdot 10^{-6}$ K^{-1} (Reference 5, Figure 16). For x_{Fe} = [ ] and x_{M5} = [ ], the magnitude of the calculated change in the coefficient of thermal expansion is limited to about [ ], which is much smaller than the reported uncertainty of [ ] for this temperature range.

The calculation was repeated at high temperature, where the beta phase of zirconium and the gamma phase of iron are stable. A temperature of 1000 °C is taken as representative. At that temperature $\alpha_{Fe} \approx 23 \cdot 10^{-6}$ K^{-1} (Reference 5, Figure 16) and α_{M5} = [ ] K^{-1}. (Both coefficients are isotropic.) For x_{Fe} = [ ] and x_{M5} = [ ], the magnitude of the calculated change in the coefficient of thermal expansion is about [ ], which is much smaller than the reported uncertainty of [ ] at this temperature.

Because the change in the coefficient of thermal expansion is much smaller than the uncertainty, the effect of the modification will be negligible. The coefficient of thermal expansion of M5® remains applicable for iron concentrations up to [ ] ppm.

4.3 *Thermal Conductivity*

Thermal conductivity is typically considered to be a structure-sensitive property. In spite of that, a small change in the iron concentration of M5® is not expected to have a significant effect. The alpha phase is evaluated first and then the beta phase. Because the additional iron does not significantly affect the thermal conductivity of either the alpha or the beta phase, the iron will likewise not affect the thermal conductivity in the alpha + beta temperature range.

At room temperature and under normal operating conditions, M5® is predominantly an α-Zr matrix with β-Nb precipitates and hexagonal Laves phase precipitates ($Zr(Nb,Fe)_2$) (page 162 of Reference 2). Heat conduction is primarily through the matrix because the volume fraction of the precipitates is small. Because the matrix is already saturated with iron, as is evidenced by the presence of the Laves phase precipitates, an increase in iron concentration to [ ] ppm will not change the composition or thermal conductivity of the matrix phase. And even at [ ] ppm Fe, the concentration of elements other than zirconium is small, so the volume fraction of precipitates will remain small.

A different approach is needed for the beta phase because niobium, iron, and oxygen will be in solid solution. The concentration of niobium in the solid solution will be [ ] ppm and that of oxygen will be [ ] ppm (Section I.20 of Reference 1). In comparison, a [ ] ppm increase in the maximum iron concentration is a minor change in composition, and the effect on thermal conductivity will be small. Because the change in the thermal conductivity is small, the thermal conductivity of M5® remains applicable for iron concentrations up to [ ] ppm.

4.4 *Specific Heat Capacity*

Specific heat capacity is a structure-insensitive property (page 86 of Reference 3), so a small change in composition is not expected to have a significant effect. A rough estimate of the effect of iron on specific heat capacity may be obtained by applying the rule of mixtures:

$$c = x_{\mathrm{Fe}} c_{\mathrm{Fe}} + x_{M5} c_{\mathrm{M5}}$$

where c, c_{Fe}, and c_{M5} are the specific heat capacities of the mixture, iron, and M5®, respectively, and x_{Fe} and x_{M5} are the mass fractions of added iron and M5®, respectively. The specific heat capacities of iron and zirconium depend in a complicated way on temperature (Figure 18 of Reference 5), so the effect of adding [ ] ppm Fe (x_{Fe} = [ ] and x_{M5} = [ ]) was evaluated at [ ] °C. Key values are given in Table 4-1. The magnitude of the largest change was about [ ], which is much smaller than the reported uncertainty of [ ]

Because the change in the specific heat capacity is much smaller than the uncertainty, the effect of the modification will not be significant. The specific heat capacity of M5® remains applicable for iron concentrations up to [ ] ppm.

Table 4-1 Evaluation of Heat Capacity of M5®

Temperature, °C	Temperature, K	Heat Capacity			
		Molar	Specific		
		Iron ($c_{\mathrm{Fe}} m_{\mathrm{Fe}}$), J / mol·K	Iron (c_{Fe}), J / g·K	M5® (c_{M5}), J / g·K	M5® with [ ] ppm Fe (c), J / g·K

4.5 *Emissivity*

Emissivity is a structure-insensitive property (Table 2 on page 95 of Reference 4), so a small change in composition is not expected to have a significant effect. A rough estimate of the effect of iron on emissivity may be obtained by applying the rule of mixtures:

$$\varepsilon = x_{\mathrm{Fe}}\varepsilon_{\mathrm{Fe}} + x_{M5}\varepsilon_{\mathrm{M5}}$$

where ε, $\varepsilon_{\mathrm{Fe}}$, and $\varepsilon_{\mathrm{M5}}$ are the emissivities of the mixture, iron, and M5®, respectively, and x_{Fe} and x_{M5} are the mass fractions of added iron and M5®, respectively.

AREVA uses various models for the emissivity of M5® that have been approved for different applications. Examples include the value given on page I-73 of Reference 1 and the correlation given in Section 10.6.3 of Reference 6.

A conservative worst case that applies to all the models is $\varepsilon_{\mathrm{Fe}}$ = 0, which corresponds to no radiation from the iron. For x_{Fe} = [ ] and x_{M5} = [ ], the magnitude of the calculated change in the emissivity is [ ], which is much smaller than the reported uncertainty of [ ]

Because the change in emissivity is much smaller than the uncertainty, the effect of the modification will not be significant. The emissivity of M5® remains applicable for iron concentrations up to [ ] ppm.

4.6 *Oxidation Resistance*

Oxidation includes both aqueous corrosion under normal operating conditions and high-temperature oxidation during a loss-of-coolant accident. The two processes are evaluated in the following subsections.

4.6.1 Aqueous Corrosion

Numerous tests have been performed to demonstrate that M5® with [ ] to [ ] ppm Fe has corrosion performance at least as good as that of M5® with up to [ ] ppm Fe:

- Five alloys with iron concentrations from 273 ppm to 1330 ppm were tested in simulated primary coolant water (360 °C and 18.6 MPa, with 650 ppm B and 1.5 ppm Li). Total exposure times were up to 890 days. Only a small effect of iron was seen, which was that the oxide thickness at intermediate times was slightly lower for alloys with high iron concentrations (page 162 and Figure 2 of Reference 2).
- The same five alloys were tested in steam at 415 °C for up to 850 days. (Tests of alloys with 360, 625 and 1330 ppm Fe were terminated after 650, 600, and 650 days, respectively.) Iron concentrations from 285 ppm to 1330 ppm provided corrosion performance better than that for 273 ppm Fe (page 162 and Figure 3 of Reference 2).
- The five alloys were also tested at 360 °C in water with 70 ppm Li for up to 300 days. Increasing the iron concentration provided progressive improvements in resistance to acceleration of corrosion (page 164 and Figure 4 of Reference 2). [ ] showed a slight improvement [ ]
- Fuel cladding made from a variant of M5® with an iron concentration of about 1000 ppm was irradiated in French and German power reactors. The fuel was tested to a fuel rod average burnup of 66 GWd/MTU, and the cladding had oxide thicknesses that were consistently in the lower range of what has been observed for M5® (pages 167 to 168 and Figure 10 of Reference 2). Because the oxide thicknesses were within the range of experience, but the iron concentration was greater than [ ] ppm, it is concluded that M5® with [ ] to [ ] ppm Fe will give corrosion

performance equivalent to that of M5® with up to [ ] ppm Fe.

- Axial oxide profiles were measured on two of the fuel rods described above. One rod had M5® cladding with 350 ppm Fe and was irradiated to 55.6 GWd/MTU; the other had a variant of M5® with 1000 ppm Fe and was irradiated to 51.8 GWd/MTU. Both rods were irradiated in the same plant during the same cycles. The cladding with the higher iron concentration had a smaller maximum oxide thickness and less variation in oxide thickness with elevation (pages 168 to 170 and Figures 11 and 12 of Reference 2). Because the iron concentration of that rod was greater than [ ] ppm, it is concluded that M5® with [ ] to [ ] ppm Fe will give corrosion performance equivalent to that of M5® with up to [ ] ppm Fe.

Together, the tests confirm that M5® with [ ] to [ ] ppm Fe has corrosion performance at least as good as that of M5® with up to [ ] ppm Fe.

4.6.2 High Temperature Oxidation

Cladding tubes with iron concentrations of 195, 350, and 715 ppm were subjected to one-sided steam oxidation at 1000 °C. The breakaway time and the oxidation kinetics before breakaway did not show an effect of iron concentration. Performance was variable after breakaway, but the results for an iron concentration of 715 ppm were similar to those for concentrations of 195 and 350 ppm (pages 174 to 176 and Figures 21 to 23 of Reference 2). Additional information about the breakaway oxidation tests is provided in Reference 7.

Section 5.1 of the safety evaluation for Reference 1 discusses (1) the use of the Baker-Just correlation for high temperature oxidation performance and (2) the criterion of 17% maximum local oxidation. Approved methods and regulatory criteria associated with the high temperature oxidation performance of M5® remain applicable with this supplement.

[ ], it is concluded that M5® with [ ] to [ ] ppm Fe has high temperature oxidation performance equivalent to that of M5® with up to [ ] ppm Fe.

4.7 *Ultimate Tensile Strength*

Recent measurements on M5® and variants of M5® with iron concentrations up to 1000 ppm show a slight trend toward increased ultimate tensile strength as the iron concentration increases (Figures 6 and 7 of Reference 2). The increase was seen at both room temperature and 400 °C (page 166 of Reference 2). However, the effect of iron concentration was small, and the results for the experimental tubes were similar to those for industrially processed M5®.

The effect of iron concentration on the ultimate tensile strength in burst loading has not been studied, but the increase in strength in uniaxial tests provides confidence that the burst strength will either remain constant or increase slightly as the iron concentration increases.

On the basis of the available data, the ultimate tensile strength of M5® remains applicable for iron concentrations up to [ ] ppm. [ ]

4.8 *Yield Strength (0.2% Offset)*

Recent measurements on M5® and variants of M5® with iron concentrations up to 1000 ppm show a slight trend toward increased yield strength as the iron concentration increases (Figures 6 and 7 of Reference 2). The increase was seen at both room temperature and 400 °C (page 166 of Reference 2). However, the effect of iron was small, and the results for the experimental tubes were similar to those for industrially processed M5®.

The effect of iron concentration on the yield strength in burst loading has not been studied, but the increase in strength in uniaxial tests provides confidence that the burst strength will either remain constant or increase slightly as the iron concentration increases.

On the basis of the available data, the yield strength of M5® remains applicable for iron concentrations up to [ ] ppm. [

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4.9 *Ductility*

Recent measurements on M5® and variants of M5® with iron concentrations up to 1000 ppm show little to no change in ductility (total elongation) as the iron concentration increases (Figure 8 of Reference 2). The lack of change in ductility applies at both room temperature and 400 °C (page 166 of Reference 2). The results for the experimental tubes fall within the range of scatter for industrially processed M5®.

No change in ductility is evident; therefore there is no effect on fuel performance. The ductility of M5® remains applicable for iron concentrations up to [ ] ppm. [

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4.10 *Creep Resistance*

Creep affects the performance of both fuel rods and guide tubes. For fuel rod cladding, tangential creep is of primary importance because it affects the size of the pellet-cladding gap and thus pellet temperature. Axial creep is less important, though it does affect shoulder gap and void volume. For guide tubes, axial creep is of primary importance because it affects fuel assembly growth. Tangential creep is not significant because the pressure difference between the inside and the outside of a guide tube is small. The following subsections discuss these two components.

4.10.1 Fuel Rod Cladding

Both in-pile and out-of-pile creep tests have been used to determine the effects of iron concentration. M5® and variants of M5® with iron concentrations up to 900 ppm were tested in 240-hour laboratory creep tests at 400 °C with hoop stress levels of 130 and 160 MPa (page 166 and Figure 9 of Reference 2). A slight trend of increasing strains was observed with increasing iron concentration. However, thermal creep provides only a small contribution to the total creep strain for steady-state operation (Section 7.1.3.1 of Reference 6), so in-pile creep tests were used to obtain more prototypical results. Sealed cladding tube segments with 310 and 935 ppm Fe, both with 1 bar internal pressure, were irradiated in guide tubes of commercial fuel assemblies (Figure 15 and page 171 of Reference 2). A hoop stress of −113 MPa resulted from the system pressure, and temperatures were 306 to 339 °C. Samples with 310 ppm Fe were found to creep at a rate that was similar to that for samples with 935 ppm Fe (Figure 15 of Reference 2). Diameter measurements were also taken on actual fuel rods during the period before contact between the cladding and pellets. The creep rates were similar for M5® and a variant of M5® with about 1000 ppm Fe (page 171 and Figure 16 of Reference 2).

Axial and tangential (diametral) creep are related by anisotropy coefficients, and the effect of iron concentration on tangential creep is small, so the effect of iron on axial creep is likewise expected to be small.

In light of these evaluations, the variation in creep rate with iron concentration is considered to be insignificant. The creep properties of M5® cladding remain applicable for iron concentrations up to [ ] ppm.

4.10.2 Guide Tubes

Guide tubes typically operate under uniaxial stresses of [ ] MPa to [ ] MPa, so the stress state is different from that of fuel rod cladding, and the absolute stress levels are lower. Tubing samples of a similar geometry, made from fuel cladding, have been tested in BOR-60 under uniaxial stresses of [ ] MPa. The iron concentrations of these samples were [ ] ppm. [ ] Guide tube samples were also tested, [ ] It is reasonable to conclude that an increase in iron concentration from [ ] to [ ] ppm would likewise not have a significant effect on creep, and that the creep properties of M5® guide tubes remain applicable for iron concentrations up to [ ] ppm.

4.11 *Poisson's Ratio*

Poisson's ratio is a structure-insensitive property (page 86 of Reference 3), so a small change in composition is not expected to have a significant effect. A rough estimate of the effect of iron on Poisson's ratio may be obtained by applying the rule of mixtures:

$$\nu = x_{\mathrm{Fe}}\nu_{\mathrm{Fe}} + x_{M5}\nu_{\mathrm{M5}}$$

where ν, ν_{Fe}, and ν_{M5} are the values of Poisson's ratio for the mixture, iron, and M5®, respectively, and x_{Fe} and x_{M5} are the mass fractions of added iron and M5®, respectively. Recommended values of Poisson's ratio are ν_{M5} = [ ] (temperatures between [ ] °C) and ν_{Fe} = 0.291 (room temperature) (Reference 5, page 757). For x_{Fe} = [ ] and x_{M5} = [ ], the magnitude of the calculated change in Poisson's ratio was about [ ], which is much smaller than the reported uncertainty of [ ]

Because the change in Poisson's ratio is much smaller than the uncertainty, the effect of the modification will be negligible. The value of Poisson's ratio for M5® remains applicable for iron concentrations up to [ ] ppm.

4.12 *Modulus of Elasticity*

The modulus of elasticity is a structure-insensitive property (page 86 of Reference 3), so a small change in composition is not expected to have a significant effect. A rough estimate of the effect of iron on the modulus of elasticity may be obtained by applying the rule of mixtures:

$$E = x_{\mathrm{Fe}} E_{\mathrm{Fe}} + x_{M5} E_{\mathrm{M5}}$$

where E, E_{Fe}, and E_{M5} are the values of the modulus of elasticity for the mixture, iron, and M5®, respectively, and x_{Fe} and x_{M5} are the mass fractions of added iron and M5®, respectively. Recommended values of the modulus of elasticity at room temperature are E_{M5} = [ ] GPa and E_{Fe} = 208.2 GPa (Reference 5, page 757). For x_{Fe} = [ ] and x_{M5} = [ ], the magnitude of the calculated change in the modulus of elasticity was about [ ], which is much smaller than the reported uncertainty of [ ]

Because the change in the modulus of elasticity is much smaller than the uncertainty, the effect of the modification will be negligible. The modulus of elasticity for M5® remains applicable for iron concentrations up to [ ] ppm.

4.13 *Meyer's Hardness*

The same equation has been used for the Meyer's hardnesses of both M5® and Zircaloy-4 (Section A.3.5 of Reference 1). It is noted on page I-54 of Reference 1 that Meyer's hardness for M5® is overestimated if the value for Zircaloy-4 is used. The result is that fuel temperatures will be slightly overpredicted, and the results of fuel rod analyses will be slightly conservative.

For M5® and variants of M5® with iron concentrations up to 1000 ppm, the ultimate and yield tensile strength increase slightly with increasing iron concentration (see Sections 4.7 and 4.8), so it is expected that Meyer's hardness will increase slightly as well. That change will reduce the amount of conservatism slightly. But M5® is used in the recrystallized state, whereas Zircaloy-4 is used in the cold worked, stress relieved state, so even with additional iron, the hardness of M5® will remain lower than that of Zircaloy-4, and using the Meyer's hardness of Zircaloy-4 remains conservative. The Meyer's hardness for M5® remains applicable for iron concentrations up to [ ] ppm.

4.14 *Growth Rate*

Growth of a fuel component reflects both free growth, which is induced by fluence and hydrogen, and creep, which results from stress on the component. The effect of iron concentration on creep is discussed in Section 4.10; this section first reviews experiments concerning the effect of iron on free growth and then discusses actual growth of fuel assembly components.

4.14.1 Free Growth

Free growth has been measured on samples of M5® and a variant of M5® with about 1000 ppm Fe (pages 172 to 173 of Reference 2). The samples were irradiated in commercial reactors to fast fluences (E > 1 MeV) of about 20×10^{25} n/m^2. Figure 18 of Reference 2 shows that the increase in iron concentration has little effect at fluences below 10×10^{25} n/m^2. At 10×10^{25} n/m^2, there appears to be slightly more growth for the variant with 1000 ppm Fe, and at fluences of about 13×10^{25} n/m^2 and up, the free growth is about 0.1% (absolute strain) greater for the variant with 1000 ppm Fe.

A second set of free growth experiments [

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A third set of free growth experiments was performed by AREVA. [

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Figure 4-1 Growth of Zr – 1% Nb Alloys

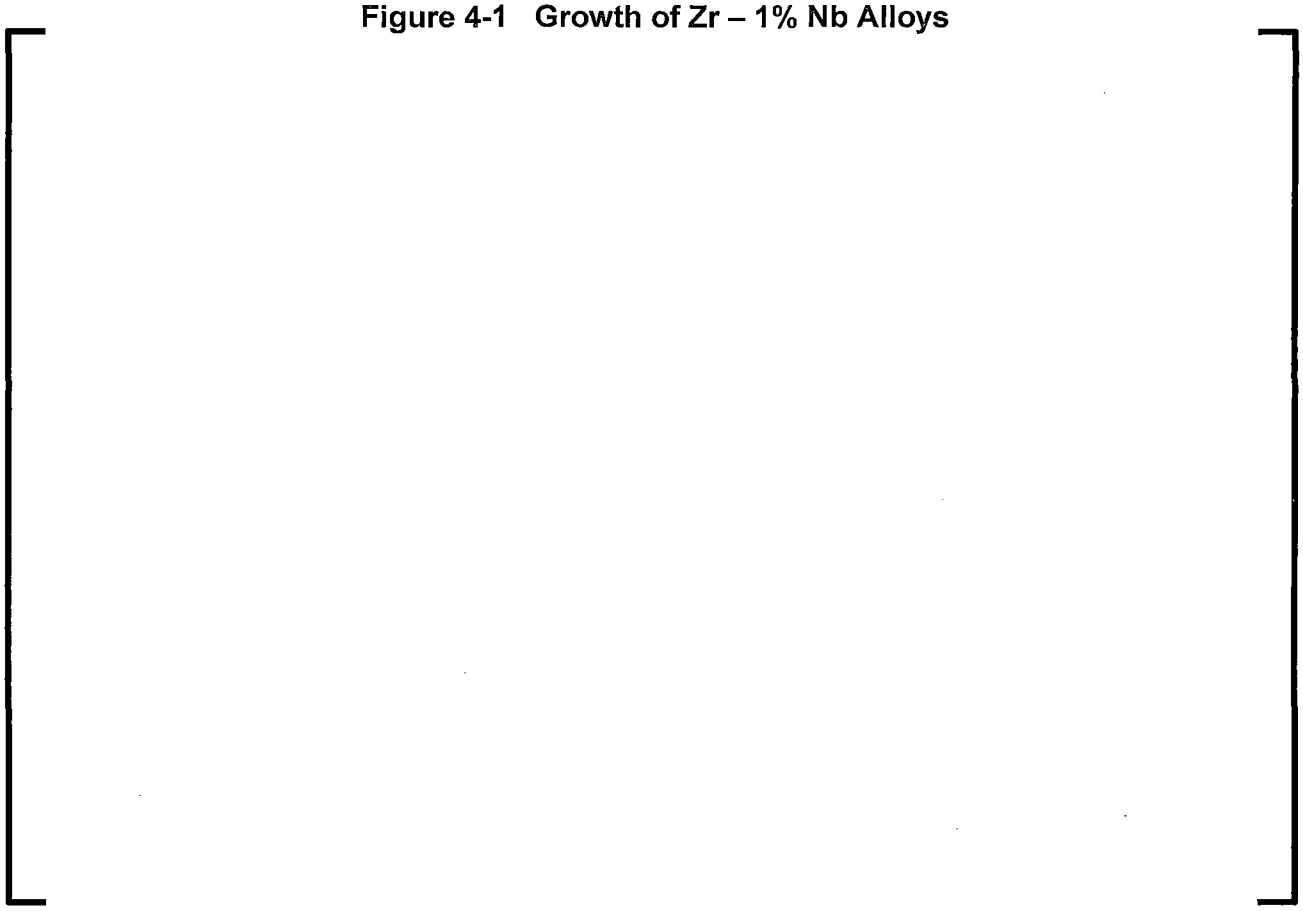

Figure 4-2 Growth of Cladding Made from M5® and a Variant of M5®

4.14.2 Growth of Fuel Assembly Components

The aspects of growth that are of interest in fuel design are fuel rod axial growth and fuel assembly axial growth. These are discussed in the following paragraphs.

The combined effects of free growth and creep have been investigated by measuring fuel rod axial growth. Fuel rods with cladding made from a variant of M5® with about 1000 ppm Fe were tested in two European reactors. As is shown in Figure 17 of Reference 2, the amount of fuel rod growth was within the scatter band for global experience with M5®, typically on the low side for the individual reactors. The slight reduction in fuel rod growth will result in a slightly larger shoulder gap, which is not detrimental to fuel performance. Therefore, models of fuel rod growth for M5® remain applicable for iron concentrations up to [ ] ppm.

Fuel assembly axial growth would be affected by changes in the rates of creep and free growth of the guide tubes. Creep is discussed in Section 4.10, and the experiments discussed in Section 4.14.1 provide various insights into the effect of iron on free growth:

- The results reported in Figure 18 of Reference 2 for samples in commercial reactors show that an iron concentration of 1000 ppm produces an increase in growth by up to 0.1% (absolute strain) at high fluences. The results suggest that the extra iron and gradually accumulating hydrogen could have a combined effect on growth. But the increase only becomes evident near the expected fluence at end of life ([ ]), and 1000 ppm Fe corresponds to [ ]

- [ ]

- AREVA's free growth tests [

]

The available results are consistent with a conclusion that existing models of fuel assembly growth in approved designs with M5® components remain applicable for iron concentrations up to [ ] ppm.

4.15 *Resistance to Hydriding*

Hydrogen concentration has been measured on a fuel rod with cladding made from a variant of M5® with about 1000 ppm Fe. The hydrogen concentration at a fuel rod average burnup of 53.9 GWd/MTU was within the range that would have been expected with M5® with up to [ ] ppm Fe (pages 170 and 171 and Figures 13 and 14 of Reference 2; also see the discussion on page 181 of Reference 2). Hydride morphology was also similar to that of M5® with up to [ ] ppm Fe (Figure 14 of Reference 2). It is concluded that current models for hydriding of M5® remain applicable for iron concentrations up to [ ] ppm.

4.16 *Stress Corrosion Cracking Resistance*

The modified iron concentration limit will not have a significant effect on stress corrosion cracking. As is discussed in Section 4.3 above, M5® is predominantly an α-Zr matrix with β-Nb precipitates and hexagonal Laves phase precipitates ($Zr(Nb,Fe)_2$) (page 162 of Reference 2). Because the matrix is saturated with iron, an increase in iron concentration will not change the composition of the matrix phase. Additional iron will result in additional Laves phase precipitates, but their volume fraction will remain small because the iron concentration is small. The number of Laves phase precipitates also remains small in comparison to the number of β-Nb precipitates (page 162 of Reference 2). Because the change in composition will have no effect on the matrix and only a small effect on the precipitates, the susceptibility of M5® to stress corrosion cracking will not change significantly. Analyses for stress corrosion cracking of M5® remain applicable for iron concentrations up to [ ] ppm.

4.17 *α → β Phase Transformation Temperature*

The effect of the modified iron concentration limit on the phase transformation temperatures has been investigated. The lower transformation temperature (α-Zr → α-Zr + β-Zr upon heating) is a eutectoid point. Because the solubility of iron in α-Zr never exceeds [ ] ppm (Figure 11 of Reference 8), an increase in iron concentration from [ ] to [ ] ppm will not affect the lower transformation temperature. The dependence of the upper transformation temperature (α-Zr + β-Zr → β-Zr upon heating) may be estimated from the zirconium-iron phase diagram (page 1129 of Reference 9). The upper transformation temperature varies from 863 °C at 0% Fe to 795 °C at (100 − 97.80)% Fe = 2.20% Fe = 22000 ppm Fe. The estimated effect of an extra [ ] ppm Fe on the transformation temperature is therefore [ ] °C. For comparison, variations in heating rates comparable to those in a LOCA can change the observed transformation temperature by tens or even hundreds of degrees Celsius (Figures 7 to 9 of Reference 10), so the effect of modifying the iron concentration is not significant, and there will not be a significant effect on fuel performance. The phase transformation temperatures of M5® remain applicable for iron concentrations up to [ ] ppm.

4.18 *Fatigue Strength*

The O'Donnell and Langer design curve (Reference 11) was developed for Zircaloy-2 but has been applied to a variety of zirconium-base alloys, including M5® (Sections 3.6, K.2.2, and K.11 of Reference 1) and Zircaloy-4 (page 4 of Reference 11; Section 4.2.7.2 of Reference 12). Because the differences in composition between the alloys listed above are large in comparison to an addition of [ ] ppm Fe, the fatigue design curve for M5® remains applicable for iron concentrations up to [ ] ppm.

5.0 IRRADIATION EXPERIENCE

[ ] test assemblies (16×16) were inserted into the German reactor [ ] (Page 171 and Figure 17 of Reference 2 refer to [ ] as reactor C.) [ ] for which the cladding was a variant of M5® with about 1000 ppm Fe. [ ] The assemblies were irradiated [ ], attaining a maximum fuel assembly burnup of approximately 53 GWd/MTU.

[ ] test assemblies (17×17) were inserted into the French reactor [ ] (Page 171 and Figure 17 of Reference 2 refer to [ ] as reactor Q.) [ ] with the same variant. [ ] The assemblies were irradiated [ ], attaining a maximum fuel assembly burnup of approximately 63 GWd/MTU.

Table 5-1 provides a summary of the commercial experience with these assemblies. Burnups reported in the table are the maximum for the set of assemblies under irradiation. The experience provides confidence that the commercial experience with M5® remains applicable for iron concentrations up to [ ] ppm.

Table 5-1 Summary of Commercial Experience

Reactor	FA Design, Lattice	Number of FAs	Date Inserted	Maximum FA Burnup (GWd/MTU)	Examinations					
					Cycle Number	Number of FAs Examined				FA Burnup (GWd/MTU)
						Visual	FR Length	FR Diameter	FR Oxide	
[										]

6.0 REFERENCES

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