Note:
This is a translation of the RSK recommendation entitled
“Erhöhte Oxidschichtdicken im oberen Bereich von Brennstäben mit M5-Hüllrohren”
In case of discrepancies between the English translation and the German original, the original shall prevail.

RSK recommendation
(514th meeting of the Reactor Safety Commission (RSK) on 12 February 2020)

Increased oxide layer thicknesses in the upper part of fuel assemblies with M5 cladding tubes

RECOMMENDATION

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1 Background

In February 2017, increased corrosion between the eighth and ninth spacer (area which includes end of active fuel length and fission gas plenum inside the fuel rod) with partial spalling was detected on fuel assemblies in the Brokdorf nuclear power plant (KBR). This finding was reported as reportable event (ME) 17/005 “Erhöhte Oxidschichtdicke an Brennstab-Hüllrohren von Brennelementen” (increased oxide layer thickness on fuel rod cladding tubes of fuel assemblies) at the Brokdorf Nuclear Power Plant (KBR, Unit Event Number 02/2017) on 17.02.2017 (INES 0).

By advisory request [1] on factors contributing to the formation of oxide layers on fuel rod cladding tubes of fuel assemblies in German pressurised water reactors (reference number: RS I 3 - 17018/1) of the Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB) of 28 August 2017, the RSK is requested to give advice on the increased oxide layer thicknesses of M5 cladding tubes and to answer the following questions in particular for plants authorised for power operation:

1. Do additional requirements arise regarding the permissibility of load changes?
2. Are additional requirements necessary regarding water chemistry and its monitoring?
3. Do additional requirements arise regarding the specifications for the manufacture of fuel rod cladding tubes?
4. Are additional requirements necessary regarding quality assurance by manufacturers and operators?

2 Consultations

At its 496th meeting on 6 September 2017, the RSK decided to set up an ad hoc working group Cladding Tube Corrosion (AG HÜLLROHRKORROSION) to deal with the advisory request of the BMUB. Between 15 November 2017 and 11 September 2019, this working group held 13 meetings, reviewed the status quo and prepared a draft recommendation to answer the questions from the advisory request. This recommendation was discussed and adopted at the 514th RSK meeting on 12 February 2020.

3 Event description and status quo

3.1 Event KBR 2017

During the maintenance and refuelling outage at the KBR in February 2017, bright oxide layers between the eighth and ninth spacer as well as spalling at the end of the active full length and in the area of the upper fission gas plenum were detected on fuel assemblies with M5 cladding tubes [2]. While in this area, oxide layer thicknesses are usually in the range of ≤ 25 µm, significantly greater oxide layer thicknesses (up to approx. 160 µm) were detected during measurements with different measuring methods. Oxidation in the area below the eighth spacer corresponded to the expected behaviour with thermally driven corrosion considered in the design.

The fuel assemblies affected by increased oxide layer thicknesses could be assigned to subsequent delivery KBR/27/14 ERU. These are ERU (enriched reprocessed uranium) fuel assemblies with and without gadolinium of the FOCUS type, which were manufactured by the Russian company MSZ on behalf of and in accordance with the specifications of AREVA GmbH. 22 fuel assemblies of the 29 fuel assemblies of this subsequent delivery on which oxide layer thickness measurements were carried out had oxide layer thicknesses > 40 µm. With two exceptions (used only in cycle 28), the fuel assemblies of this subsequent delivery were used each in two cycles (27 and 29 or 28 and 29) or three cycles (27 to 29). A special circumstance of the 29th cycle was that it did not contain any fuel assemblies in their first cycle.

The cladding tubes of subsequent delivery KBR/27/14 ERU were manufactured from two ingots produced in Ugine (AREVA/Framatome zirconium alloy plant[1]), whose chemical composition corresponded to the M5 specification[2] [3]. 65 % of the cladding tubes of subsequent delivery KBR/27/14 ERU are made from ingot 815179, the remaining 35 % from ingot 814867 [2]. For the individual fuel assemblies, ingots were used in varying proportions.

Cladding tubes of both ingots were affected by increased oxide layer thickness, but to different degrees.

3.2 Other events

Already in 2005, the visual inspection of M5 fuel assemblies in KKP 2 (after the 20th cycle) revealed an unusual surface appearance in the area between the eighth and ninth spacer [4]. The oxide layer thickness measurements subsequently carried out yielded measured values of up to max. 70 µm in this area, while below the eighth spacer, there was normal corrosion behaviour.

The following factors were examined in the root cause analysis:

- composition and structure of the material,
- manufacturing (including agents used to clean the cladding tubes after welding on the end plug),
- thermohydraulic operating conditions (void content at the fuel assembly outlet),
- linear heat rate, and
- water chemistry.

None of these factors could be identified as the sole root cause of the unusual corrosion.

In further material tests on cladding tube samples, no differences were found between affected and unaffected metallic base material that could explain the unusual corrosion. The only thing shown was that the level of the measured oxide layer thicknesses correlated with the iron content of the base material.

[1] The part of the AREVA GmbH relevant for fuel assemblies was transferred to the Framatome GmbH on 1 January 2018.
[2] Zirconium alloy with 1 % niobium and 0.14 % oxygen as well as 20 ppm sulphur. In addition, 27 substances are declared as impurities (i.e. residual elements), including iron with < 500 ppm.

Increased corrosion between the eighth and ninth spacer was reported from the plants KKP 2, KWG and KBR as well as from Konvoi plants (to a much lesser extent). Clear root causes for the unusual corrosion behaviour were identified in none of the cases.

3.3 Operating restrictions

In the course of dealing with reportable events KBR 02/2017 and KKP 2 05/2019, the following plant-specific restrictions on operation modes for the plants KBR, KWG (partially) and KKP 2 have been defined which aim at limiting or suppressing the corrosion mechanism [2], [5], [6]:

- limitation of the reactor power to 95 %, partly in combination with a reduction of the mean coolant temperature by 3 K,
- restrictions on load-following operation,
- limitation of the power density in the upper core half (KBR) or limitation of the linear heat rate for the uppermost 12 cm of the active fuel length to 150 W/cm (KKP 2),
- adjusting the H_2 concentration in the coolant to 3 to 4 ppm.

3.4 Evaluation of operational experience

The following insights result from the evaluation of operational experience with M5 fuel assemblies within the framework of the consultations of the RSK working group on cladding tube corrosion AG HÜLLROHRKORROSION:

- Fuel rods with M5 cladding tube material are used in 96 plants worldwide. Operational experience is largely very good, the corrosion rate of thermally driven corrosion is significantly lower than with Zr-Sn cladding tube materials.
- During operation in German nuclear power plants, increased corrosion in the upper part of the fuel rods, i.e. above the eighth spacer, was repeatedly detected especially in pre-Konvoi plants (KBR, KWG, KKP 2). Increased corrosion in the upper fuel rod part was also detected in Konvoi plants, but to a much lesser extent.
- M5 fuel rods from different manufacturing periods and production sites in different plants with different operating conditions were affected.
- As the analysis of the events shows, there appear to be several possible influencing factors but clear causal or functional relationships have not yet been identified. This concerns both the occurrence of

increased corrosion between the eighth and ninth spacer and the observed maximum values of the oxide layer thickness.

- All in all, measurements have been carried out on many fuel rods over the years where increased corrosion in the upper part was identified. Only in the KBR, oxide layer thicknesses exceeding 100 µm were measured on several fuel rods. Residual wall thickness measurements carried out in the KBR show oxide layer thicknesses of approx. 200 µm locally on individual cladding tubes. These fuel rods had already been in use for two cycles.

- Fuel rod damage due to the increased corrosion has not yet been identified.

- The cycle in KBR after which particularly high oxide layer thicknesses were measured was characterised by not having used fresh fuel assemblies. As a result, almost all fuel assemblies which were in their second cycle were operated in this cycle at relatively high power and in stretch-out operation at high power in the upper range.

- The main growth of the corrosion layer was generally observed in the first two cycles, during which the fuel assemblies are typically subject to the most demanding operating conditions; from the fourth cycle at the latest, no increased growth is documented.

- The evaluation of pictures of the M5 cladding tubes with increased corrosion at the upper fuel rod end shows that this corrosion only occurs if (axially seen) there is a minimum layer thickness of thermally driven oxidation underneath. Here, a marbled or grey coloured oxide layer can be seen. No cases have been identified where increased corrosion has formed in an area where the oxide layer is otherwise dark (axially below and above). This observation indicates that increased corrosion can only occur if a minimum layer thickness of thermally driven oxidation has already formed at the relevant location.

- With a larger number of the affected ingots, the occurrence of increased corrosion is limited to the area of the upper fission gas plenum and does not or only slightly extends into the area of the active fuel rod zone. With a smaller number of affected ingots, a significant extension of the area of increased corrosion into the area of the active fuel rod zone by several centimetres has been observed.

4 Assessment criteria

Relevant requirements for fuel rod cladding tubes are found, graded according to the respective requirements on levels of defence 1 – 4a, in the Safety Requirements for Nuclear Power Plants (*Sicherheitsanforderungen an Kernkraftwerke* – SiAnf) and their Interpretations (*Interpretationen zu den Sicherheitsanforderungen an Kernkraftwerke*), the safety standards of the Nuclear Safety Standards Commission (KTA) and in the plant-specific General Core Specifications (*Kernrahmenspezifikation*).

Safety requirements

According to the barrier concept defined under SiAnf 2.2, the barrier effectiveness of the fuel rod cladding tubes shall be maintained on levels of defence 1 and 2, not considering permissible operations-induced cladding failures (2.2 (3)).

On levels of defence 3 and 4a, the barrier effectiveness of the fuel rod cladding shall be maintained to the extent necessary for achieving the applicable acceptance criteria.

With regard to the acceptance criteria of barrier integrity for loss-of-coolant accidents, Annex 2 of the SiAnf requires that a fuel rod damage extent of ≤ 1 % is demonstrated for leak sizes ≤ 0.1 A and a fuel rod damage extent of ≤ 10 % for leak sizes > 0.1 A. Furthermore, it shall be demonstrated that the zirconium-water reaction is limited to < 1 % of the total zirconium contained in the core. In addition, it is required for the fundamental safety function of fuel cooling that with regard to loss-of-coolant accidents, the maximum cladding tube oxidation depth is limited to less than 17 %. The requirement regarding the maximum permissible oxidation depth as a result of high-temperature corrosion was replaced by the RSK recommendation on the demonstration of residual ductility / residual strength using an ECR limit curve *(Nachweis einer Restduktilität/Restfestigkeit mittels einer ECR-Grenzkurve)* from the 476th RSK meeting on 24 June 2015 depending on the hydrogen uptake during operation.

KTA safety standards

Safety standard KTA 3101.3 specifies the above-mentioned requirements of the higher-level nuclear rules and regulations. The main safety-related requirements with regard to the corrosion of fuel rod cladding tubes are as follows:

- Level of defence 1 and 2:
  Proof that cladding corrosion is limited, e. g. by limiting the oxide layer thickness, as well as proof of unrestricted continued usability with regard to the fundamental safety function of fuel cooling. In this context, KTA 3101.3 also requires that the condition and operation of the fuel assemblies shall be such that the geometry (shape and position) required for heat removal and the required material properties of the fuel assemblies are adhered to.

- Level of defence 3, internal hazards, external hazards, emergency conditions:
  "a) The design of the fuel assemblies shall be such that the geometry (shape and position) required for reactivity and power density control and the required material properties are adhered to.
  b) The design of the fuel assemblies shall be such that the geometry (shape and position) required for heat removal and the required material properties or the fuel elements are adhered to.
  c) The design of the fuel assemblies shall be such that the event-related requirements for the tightness of the fuel rods is ensured."

Specifically for loss-of-coolant accidents, sufficient residual ductility of the cladding tubes during rewetting (quenching) is to be demonstrated, e.g. by means of an appropriate criterion for limiting the cladding tube oxidation depth.

General Core Specifications

The General Core Specifications of German nuclear power plants are part of their licences. The safety requirements of the General Core Specifications provide the authorised framework for the reactor core within which it must be operated.

With regard to cladding corrosion, “limitation of cladding corrosion” is required as derived criterion to prevent common-mode fuel rod failures during operation. According to the general core specifications, the expected value for the local peak value must not exceed 130 µm. Compliance with this value is demonstrated by showing a circumferentially averaged oxide layer thickness of < 100 µm for all fuel rods using deterministic best-estimate calculations.

Loading of transport and storage casks

The licences for the storage of fuel assemblies granted so far include specifications on the maximum stress in the cladding tube and the maximum creep strain. In the framework of the licensing procedures, safety proofs were provided in which conservative values for cladding tube corrosion were applied. 60 µm were used for M5 fuel assemblies. For higher oxide layer thicknesses, compliance with the maximum stress and the maximum creep strain is to be demonstrated in individual proofs. Here, the actual internal pressure (depending e.g. on the burn-up) and the position of the fuel assembly in the cask are to be considered.

5 Assessment

General conclusions

Based on the information available to the RSK it is to be stated that increased corrosion in the upper fuel rod part has so far occurred on a large number of fuel assemblies in German plants from subsequent deliveries and cladding tube ingots of the cladding tube material M5.

Against this background, the RSK draws the conclusion that for M5, a susceptibility to increased corrosion in the upper fuel rod part is given under the operating conditions as they exist in the German PWR plants. The corrosion rate depends on the fuel assembly specific operating conditions and is ingot-specific.

The root cause for increased corrosion in the upper fuel rod part has not yet been clarified. In the context of reportable event KBR 02/2017, several root cause hypotheses have been developed. From today's point of view of the RSK, the following two root cause hypotheses should be further investigated:

- The hypothesis of the oxidative boundary conditions assumes that the increased corrosion is due to a locally increased concentration of oxidative species in the coolant at the upper fuel assembly ends. The increase in concentration of oxidative species in the coolant is attributed to a depletion of the hydrogen dissolved in the coolant at the upper end of the reactor core. The reason for the depletion is seen, among other things, in the transition of the hydrogen into the vapour phase, which is formed during subcooled boiling in the upper part of the reactor core.
  From this hypothesis it has been derived that the corrosion rate can be limited by an increased H_2 concentration in the coolant [2].

- The hypothesis of the thermomechanical instability of the oxide layer assumes that the observed increased oxidation in the upper fuel rod part is caused by a disturbance of crystallisation, in particular during the oxide transition, which is attributed to fluid-mechanically induced cyclic thermal stresses due to turbulent global transverse flows in the upper core area. The disturbance of crystallisation leads to a more irregular crystal structure at the metal-oxide interface and thus to increased crack formation in the oxide. This destabilises the protective boundary layer of the oxide, which protects the metal against further oxidation, to such an extent that it loses all or part of its protective character.
  From this hypothesis it has been derived that the corrosion process can be counteracted by limiting the linear heat rate in the uppermost area of the active fuel length since this can reduce the cyclic thermal stresses [5].

Safety significance

In the context of the described findings, unexpectedly high oxide layer thicknesses were detected on fuel rod cladding tubes made of the M5 material in the area between the eighth and ninth spacer (area which includes end of active fuel length and fission gas plenum inside the fuel rod). In individual cases, the admissible operational limit of 100 µm circumferentially averaged and 130 µm locally was exceeded. Fuel rod defects did not occur due to this effect.

The findings were located at the upper end of the affected fuel rods, i.e. an area which is only subject to a comparatively low heat flux density. In contrast, the areas with the highest cladding tube temperature and the highest heat flux densities, i.e. the areas with the strongest thermally driven corrosion on fuel rods, do not show any anomalies. These are also the areas in which the highest accident-related loads occur both during reactivity initiated and loss-of-coolant accidents and which are decisive for determining the extent of fuel rod damage. In addition, measurements on two samples from the upper end of a fuel rod from the 18th subsequent delivery in KKP 2 have shown that the hydrogen uptake is low. Therefore, no pronounced ductility loss due to hydrogenation is to be expected in this area. At present, there are no indications that with the oxidation depths that have occurred so far, the acceptance criteria for accidents would no longer have been met.

The primary safety significance of increased corrosion on M5 cladding tubes is that there is a corrosion mechanism whose root cause is unknown and cannot be predicted by calculation.

The corrosion findings cannot be explained with the present understanding of thermally driven surface corrosion of M5 both in terms of their extent and their axial position. The calculation methods used so far for estimating the cladding tube corrosion to be expected in the cycle are not applicable to the oxidation findings in the upper plenum. The requirement of safety standard KTA 3101.3 to demonstrate that cladding corrosion is limited is thus currently not fully met for M5 fuel assemblies.

For the upper part of the fuel rods, it is not possible to predict the circumferentially averaged oxide layer thickness, as required according to the general core specifications, with the methods used so far. Thus, unrestricted use of M5 fuel assemblies in German PWR plants is not possible. A recommendation on this is derived in Chapter 7.

For the storage of fuel assemblies with M5 cladding tubes, it has to be demonstrated in accordance with the above-mentioned requirements from the licences that either the limit for the oxide layer of 60 µm is maintained or specific proofs have to be furnished under consideration of the actual internal pressure (depending e.g. on the burnup) and the position of the fuel assembly in the cask. The RSK points out that in the case of spalling due to increased corrosion, the residual wall thickness of the cladding tube cannot be fully deduced from the measured maximum oxide layer thickness.

6 Answers to the questions of the BMUB

Answer to Question 1 on additional requirements concerning the permissibility of load changes:

Frequent load changes, especially those where the L-bank is moved in the area of the upper end position, have been discussed by the RSK as a factor possibly contributing to the observed corrosion effect.

However, no correlation between frequency/velocity of load changes and occurrence of increased cladding tube corrosion could be determined. Thus, no additional requirements result from this.

Answer to Question 2 on the need for additional requirements regarding water chemistry and its monitoring:

Regarding the influence of hydrogen on increased corrosion in the area between the eighth and ninth spacer it is to be stated that increased corrosion has occurred both during operation with hydrogen concentrations in the coolant in the range of 2 to 3 ppm and in the range of 3 to 4 ppm. These ranges are within the standard values for normal operation from VGB guideline R 401-J for the water in nuclear power plants with light water reactor.

However, the analysis of the event in KBR showed that for many years, the plant had been operated with significantly lower hydrogen concentrations than 2 ppm for several days at the cycle end. Although the RSK does not consider this short-term operation with low hydrogen concentration to be the root cause for the significantly increased corrosion, it shows that clear regulations were missing in the operating manual. Thus, in addition to compliance with the VGB guideline for the water in nuclear power plants with light water reactor, the requirement arises that the action levels for compliance with the specified water chemical conditions for the operation of the plant must be bindingly regulated and clearly described in the operating rules. **/R1/**

Answer to Question 3 on additional requirements regarding the specifications for the manufacture of fuel rod cladding tubes:

From current knowledge, no additional requirements for the manufacture of M5 fuel rod cladding tubes can be derived by which the occurrence of increased corrosion can be prevented.

Answer to Question 4 on the need for additional requirements regarding quality assurance by manufacturers and operators:

From current knowledge, no additional requirements for quality assurance during manufacture can be derived by which the occurrence of increased corrosion can be prevented.

However, additional requirements arise with regard to operational monitoring during use of the fuel assemblies. According to the experience available today for PWR plants, fuel assemblies with M5 cladding tube material can no longer be used without restrictions in German plants. The corrosion behaviour of these cladding tubes must therefore be monitored separately.

The RSK recommends the following:

In all plants,

- before reuse, all M5 fuel assemblies after their first and second cycle,
- as well as a random sample of approx. 10 % of M5 fuel assemblies after their third cycle

should be subjected to a visual inspection in the area between the eighth to ninth spacer, including all ingots used. The results of the visual inspections are to be documented and evaluated in the form of films and/or pictures.

Regarding the classification of the findings from visual inspection in the area between the eighth to ninth spacer, the RSK is of the opinion that the following experience regarding the colouring of oxide layers on M5 cladding tubes should be referred to:

- a thin oxide layer is dark,

- marbling and speckles become visible with increasing layer thickness and the oxide assumes a grey colouring,

- increased corrosion can be recognised by the clearly lighter colouring up to a white colouring.

In the case of indications of increased corrosion, measurements of the oxide layer thickness are to be carried out. If increased oxide layer thicknesses are detected, it is to be checked to what extent the 100 µm criterion can be maintained during further operation, for example by adjusting the operating parameters. For these fuel assemblies, the development of the oxide layer thickness is to be monitored. **/R2/**

7 Other recommendations

Root cause analysis

Since the root causes of increased corrosion on M5 cladding tubes, which has meanwhile occurred several times, are still not known, i.e. the contributions of the individual factors whose involvement is suspected cannot be quantified, the clarification of the root causes should be further advanced. The RSK sees this primarily as the responsibility of the manufacturer. **/R3/**

Prediction of oxide layer thickness growth in M5 cladding tubes

For the upper part of the fuel rods, it is not possible to predict the circumferentially averaged oxide layer thickness, as required according to the General Core Specifications, with the methods used so far.

When alternatively using data from previous cycles for the prediction of oxide layer thickness growth for a subsequent cycle, it must be ensured that the operating conditions in the subsequent cycle are comparable with the cycles whose oxide layer thickness growth rates are to serve as a data basis for the prediction of a subsequent core. At least the following parameters are to be considered here: water chemistry, integral fuel assembly power and power at the upper fuel rod end, void content, and type and length of stretch-out operation. **/R4/**

8 References

[1] Schreiben des Bundesministeriums für Umwelt, Naturschutz, Bau und Reaktorsicherheit (BMUB) an das Bundesamt für Strahlenschutz, Reaktor-Sicherheitskommission
Beratungsauftrag zu beitragenden Faktoren zur Bildung von Oxidschichten an Brennstabhüllrohren von Brennelementen in deutschen Druckwasserreaktoren
Az.: RS I 3-17018/1 vom 28.08.2017

[2] PreussenElektra
Kopien der am 15.11.2017 in der 1. Sitzung der RSK Ad-hoc-AG Hüllrohrkorrosion gezeigten Folien
ME KBR-2017-02: Erhöhte Oxidation am oberen Ende von M5-Brennstäben – Status zum Wiederanfahren

[3] Framatome
Kopien der am 15.11.2017 in der 1. Sitzung der RSK Ad-hoc-AG Hüllrohrkorrosion gezeigten Folien
Erhöhte Korrosion an Brennstäben in KBR –Hersteller-Sicht

[4] EnKK
Kopien der am 10.01.2018 in der 3. Sitzung der RSK Ad-hoc-AG Hüllrohrkorrosion gezeigten Folien
Einsatz-Erfahrungen bei KKP-2 mit M5-Brennelementen

[5] Physikerbüro Bremen
KKP ME 05/2019 - Ergebnisse von Inspektionen im 33. und 34. Brennelement-wechsel sowie Festlegung von Betriebseinschränkungen für den 35. Zyklus
Kopien der auf der 13. Sitzung der RSK Ad-hoc-AG Hüllrohrkorrosion am 11.09.2019 gezeigten Folien

[6] TÜV NORD EnSys
Zulässige Stablängenleistungswerte für das obere Brennstabende
Kopien der auf der 13. Sitzung der RSK Ad-hoc-AG Hüllrohrkorrosion am 11.09.2019 gezeigten Folien