FRM II: Extension of Core Component Lifetime by Application of Fracture Mechanics

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Abstract. At FRM II a program is in place to monitor the material properties of the core components made from Aluminum in order to extend their lifetime that is limited due to the influence of radiation embrittlement without compromising on safety.

Key Words: fracture mechanics, neutron irradiation, embrittlement, damage, research reactor, Aluminum

1. Introduction

The FRM II is a multipurpose research reactor, located in Garching/Germany in the heart of one of Europe's biggest research campuses. It became critical for the first time in 2004, routine operation started in 2005. The FRM II's thermal power is 20 MW. It is a pool type reactor with one compact fuel element, cooled with light water. Neutron moderation is mainly done in the heavy water tank surrounding the fuel element. This tank also houses the tips of the beam tubes, secondary sources and irradiation facilities. An overview of the reactor pool is given in FIG. 1. The FIG. 2 shows a cross section through the reactor pool and moderator tank. Main areas of research at the FRM II lie in the field of neutron scattering, but also many other experiments from fundamental physics to life sciences, from neutron tomography to positron physics are carried out. There is also a medical irradiation facility. Radioisotope production and Silicon doping are other important activities. More details can be found e. g. in [1].

The majority of the core components of the FRM II is made from Aluminum (EN AW-5754, AlMg3). While this material offers excellent properties for neutron production, heat transfer and general machining and handling it also unavoidably undergoes embrittlement under the influence of neutron irradiation. The main mechanism here is Silicon formation through neutron capture in Aluminum. Therefore the major core components are made such that they can be replaced. However, this procedure is far from trivial or routine operation and should be avoided if possible at all: it involves lengthy shutdowns, unwanted irradiation dose for the personnel and creation of active waste. It also requires an evolved manufacturing process for the spare parts, especially when the original supplier is no longer available and alternatives have to be found.

To minimize these problems a program to extend the lifetime of such components is in place. Material samples are being irradiated and the resulting material properties are regularly being measured. Using these data in combination with fracture mechanical calculations the ultimate goal is to get more realistic and more reliable data on the deterioration of the components due to irradiation on the one hand and the true material properties required for safe operation on the other hand. Combining both yields the schedule for component replacement, which is believed to give much longer permissible operation as compared to the original over-conservative approach of 5 % minimum ductility that was limited by the limited data base available at the time of licensing.

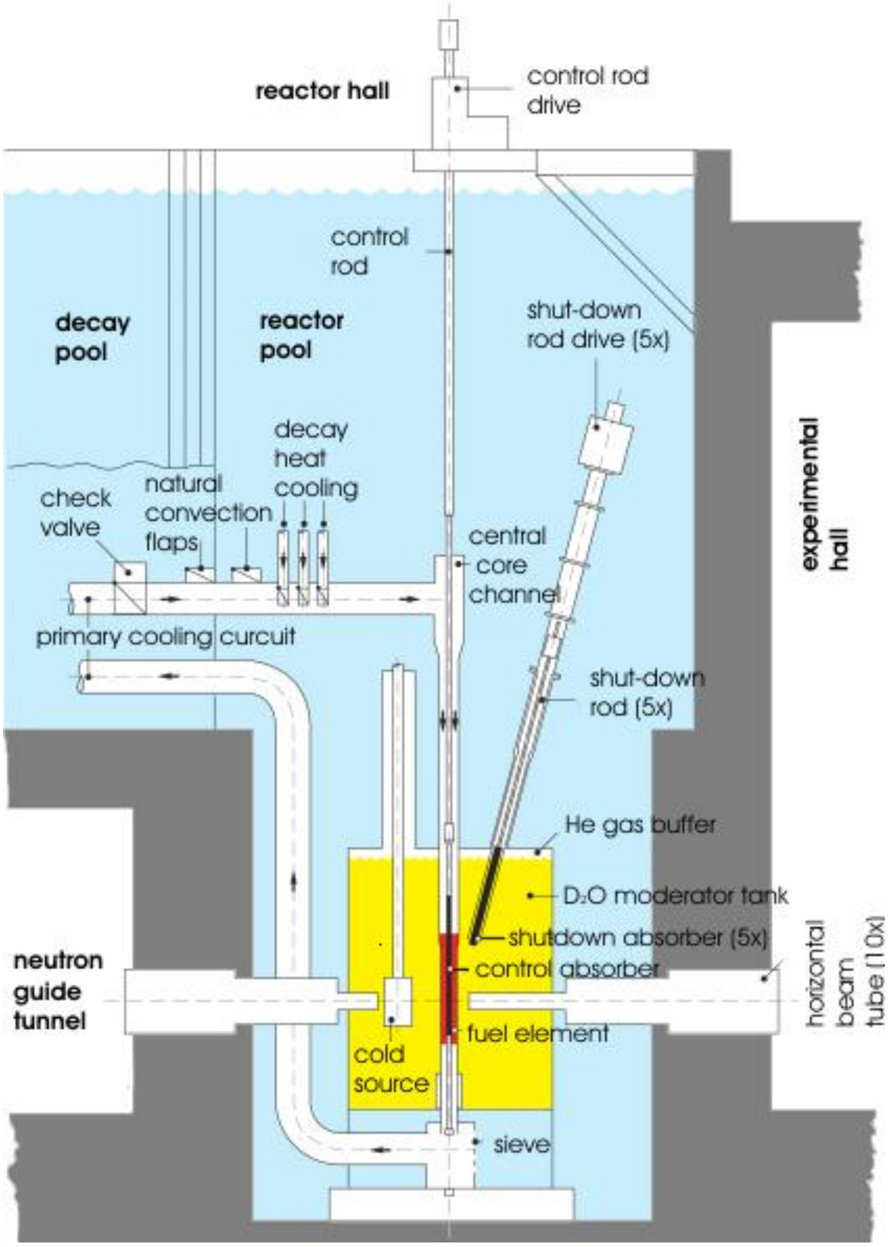

FIG. 1: Schematic view of the FRM II reactor pool.

2. The Irradiation Program

At the FRM II a designated irradiation position in the region of maximum neutron flux is available in the moderator tank. It is stocked with a total of six sets of samples arranged in layers both for tensile stress testing and for measurements of fracture mechanics parameters. Due to the highest flux and the neutron spectrum similar to the one at the position of critical core components irradiation effects on these components can in principle be measured before they become relevant for component stability. The components under investigation are mainly the central channel, the beam tube tips and the thimbles that house irradiation positions and instrumentation. The samples are removed after certain predefined accumulated fluences. At the time of writing, three sets had been removed and analyzed covering the range from fresh material without influence due to irradiation to a fluence 2.5E22 n/cm². A fourth set has already been removed after an accumulated neutron fluence of approximatively 4E22 n/cm² but has not been analyzed yet. The FIG. 3 shows a photograph of the stack of irradiation samples, the samples themselves are shown in FIG. 4. In FIG. 5 the measured data are plotted together with a tentative extrapolation using an exponential fit to higher fluences to guide the eye.

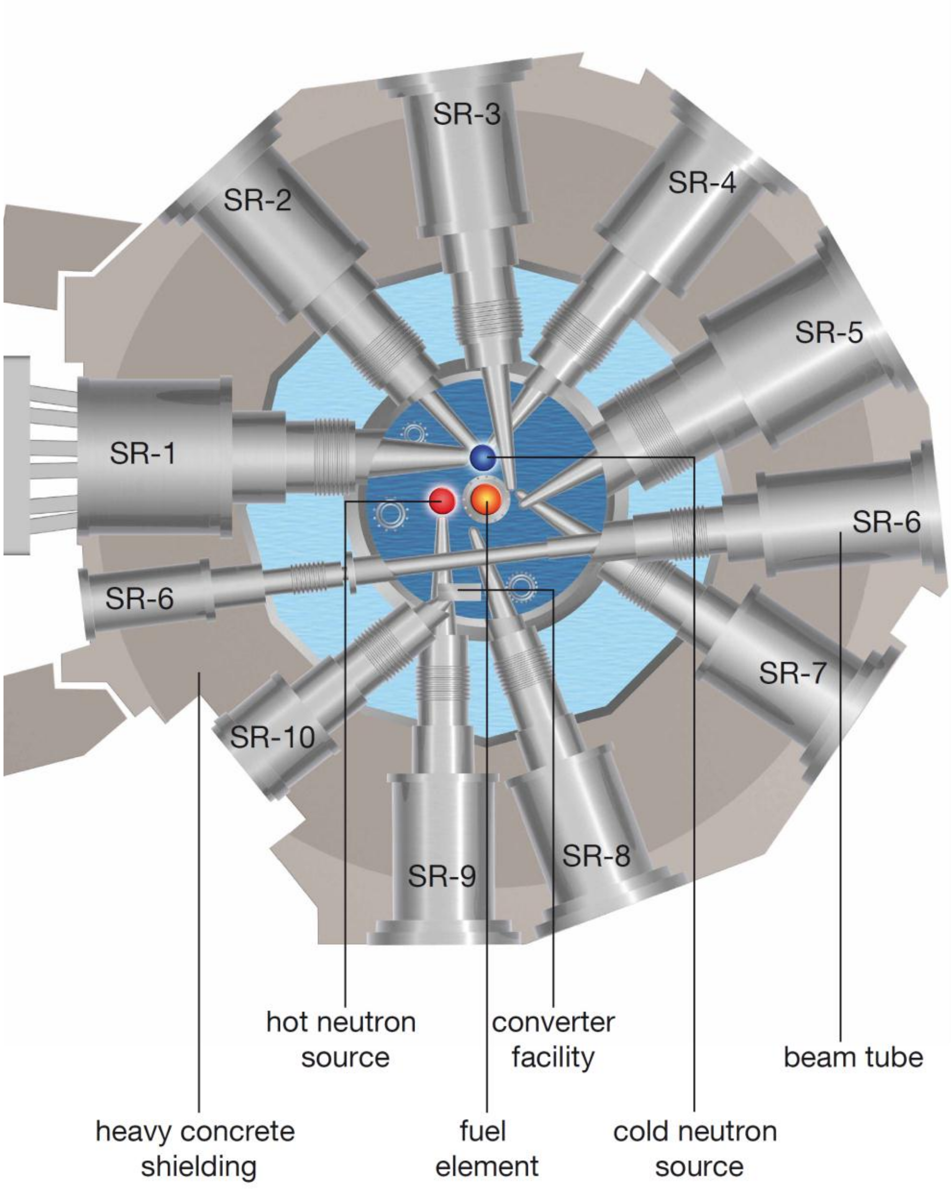

FIG. 2: Cross section through the reactor pool.

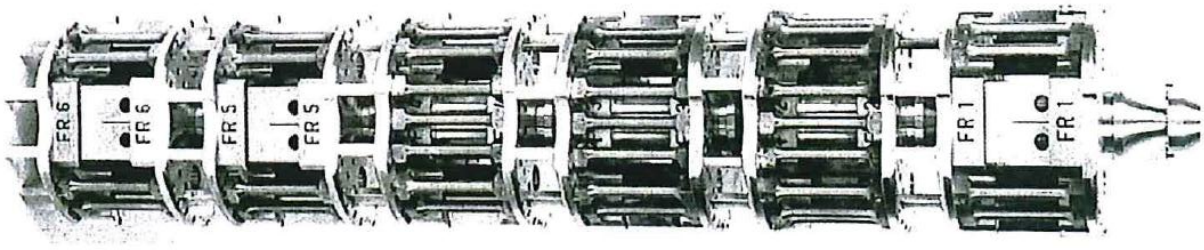

FIG. 3: Photograph of stack of 6 sets of irradiation samples before irradiation. The original height of one layer is about 100 mm. Clearly visible are different sample kinds for tensile stress testing and fracture mechanics.

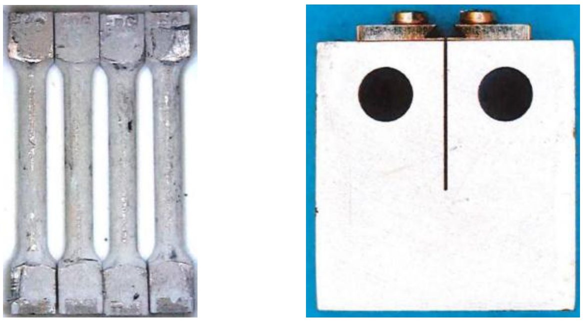

FIG. 4: Specimen (cf. FIG. 3) after irradiation and preparation for testing of tensile strength (left) and fracture mechanics (right) [2].

All the measured neutron fluence data are confirmed by calculations. A detailed and multiply validated MCNP-model of the FRM II exists [3] and is used to determine the fluence at positions where no experimental data is available.

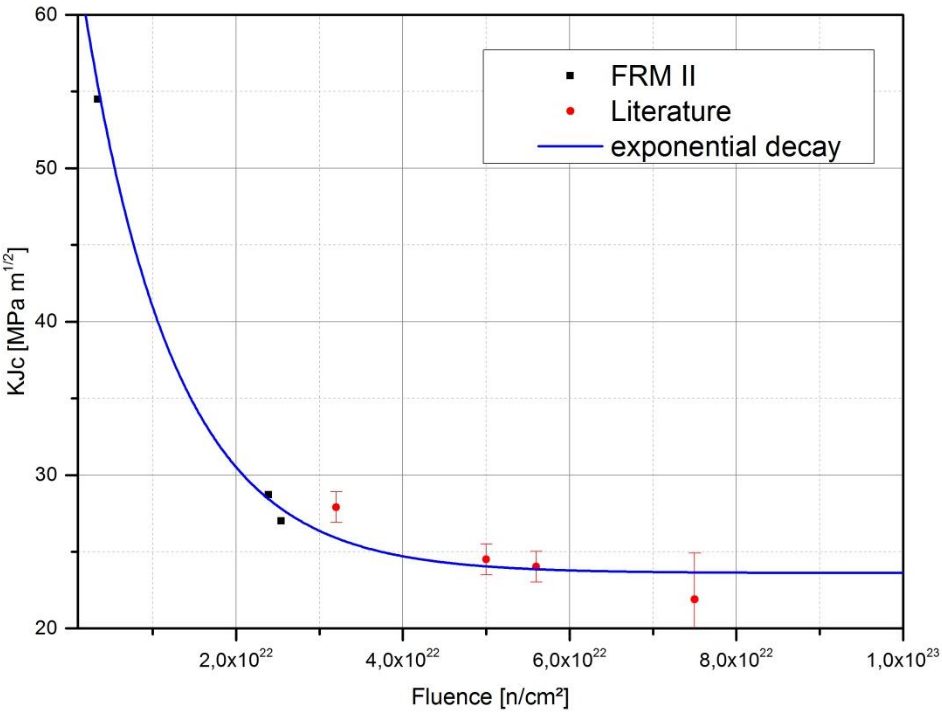

FIG. 5: Fracture mechanics data after irradiation at FRM II [2] and data available in the literature [4]. The blue line is an exponential fit drawn to guide the eye.

3. The Fracture Mechanical Calculations

In order to determine the required mechanical properties by calculations, a concept has been developed [5]: it groups the relevant components with respect to expected irradiation effects and mechanical properties (e. g. wall thickness, shape, specified load under normal, test and emergency operation conditions). Then, taking into account the tests already carried out, assumptions on maximum imperfections of the component and if required also of the welds are postulated. Such tests rely mainly on non-destructive methods (like VT, RT, PT) and have been carried out during manufacturing and regularly during operation of the component. They usually yield upper limits on length and depth of fractures and their development over time. According to the applicable rules (KTA 3201.2, KTA 3211.2, ASME XI, DIN EN 13445-3 among others) safety margins are taken into account. On top of these, conservative parameters are used, especially if no or only limited experimental data are available. Such conservative parameters can in principle be replaced by more realistic ones should they become available. A first step towards better data is the irradiation program carried out at the FRM II itself, see section 2 of this article. These are examples of conservative parameters:

- Application of the minimum specified materials properties.
- Application of maximum assumptions for fracture growth.
- Neglecting of any threshold for fracture growth under the influence of the surrounding medium (H_2O, D_2O).
- Assumption of conservative loads and torques.
- Assumption of stress in welds equal to the yield stress at room temperature.

Since all the uncertainties and safety margins have already been taken into account for the calculations, a factor of 1 between measured and calculated data is sufficient for safe operation.

The concept has been successfully applied to the beam tube SR-8 as a proof of principle first and then to all other components or groups of components:

- Moderator tank,
- Round beam tube tips,
- Rectangular beam tube tips,
- Installations in the moderator tank,
- Horizontal and vertical flanges,
- Shut down rods and thimbles and
- Special treatment of individual components (beam tube SR-11, control rod).

4. Results

By now all calculations have been carried out [6]. No facts could be identified that would limit the time for permissible operation to ten years only. In fact, for all the components outside of the area of highest neutron flux within the anticipated lifetime of the FRM II no need for component replacement has been identified.

For the components closer to the core, calculations suggest a minimum lifetime of twenty calendar years or 10.4 full power years.

All these results, however, still await confirmation by the expert organization and approval by the licensing authority. For the components not in the highest neutron flux there is consensus among all the parties involved that no immediate need to react is required and twenty years of operation are seen as uncritical. For the components in the highest neutron field a number of open points have been identified by the expert organization. The experts request

- Closer investigation of some welds,
- Revision of some of the postulates for defects,
- More detailed investigation of load assumptions of certain components during test of earthquake conditions,
- Application of additional safety margins for selected special situations and
- Improvement of the experimental data base of fracture mechanical properties of AlMg3 under the influence of H_2O.

While the first points will be addressed and most likely resolved by additional calculations a demanding task is the improvement of the existing data base. At FRM II we are currently discussing various options. Although no decision has been taken and no additional measurements have been carried out yet it already now appears obvious that such experiments will be demanding and require significant time for completion. However, since the results achieved so far from the calculations have been encouraging we are optimistic to succeed also with the experiments and hence complete the whole program in due time.

5. Conclusion

At the FRM II a program is in place to extend the permissible operation time of the AlMg3 components that undergo material deterioration under the influence of neutron irradiation. The required calculations are almost completed and no problems in principle have been discovered. An experimental irradiation program is in place but needs to be expanded to acquire data on the most important fracture mechanics parameters under the influence of water. The overall goal is to further guarantee safe operation of the FRM II but minimize the need to prematurely exchange any components because of only postulated embrittlement under neutron irradiation.

Appendix 1: References

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