Handling, Transport and Program for Post-Irradiation Examination of Special Fuel Rods

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ABSTRACT

In 2018 thirteen Special Fuel Rods were transported from Brunsbüttel to the Swedish Hot Cell laboratory at Studsvik for a Post-Irradiation Examination (PIE). The reason for this was to gain more valuable measurement data information for the dry long-term storage database. The planning for the transport, performed by DAHER NT using their NCS-45 cask, started already in 2016. This paper gives a characterization of the Special Fuel Rods and describes the examination program. Twelve of the rods are failed from debris fretting and possible Pellet Clad Interaction (PCI). Therefore, topics such as ingress of water causing residual moisture in the rods, cladding embrittlement and radial reorientation of the hydride of the rods are presented. Moreover, a summary of the efforts is given for the handling (loading and transport) of the Special Fuel Rods and the numerous licenses that are required for such a project.

Keywords: Transport and handling of defect fuel rods, Post Irradiation Examination, Fuel failure examination, Drying of defect fuel rods, Hydride reorientation

1) Introduction

The political decision in Germany not to reprocess nuclear fuel and the fact of not having a permanent disposal site available yet led to the requirement for intermediate storage over several decades. The impact of specific effects on long-term interim storage capacity and the resulting requirements for subsequent use are currently being subject of discussions in the nuclear community. Due to the possible extension of the interim storage time of possible more than the originally intended 40 years it is necessary to develop a methodology and a requirements catalogue with respect to the spent fuel behaviour over time.

In particular, the destructive investigations in hot cells on intact and defective fuel rods and on different design and operating lifetime are to be made to gain new results in order to underpin the existing data. Typical examination subjects include for example the determination of the orientation of hydrogen deposits (hydrides) for the further confirmation of models for determining the strength of cladding tubes and studies on residual moisture in the fuel rod regarding possible corrosion mechanisms. At this, one particular item of interest is to quantitatively determine residual water and evaluate the effectiveness of vacuum drying methods used in dry storage systems.

In the past Post-Irradiation Examination (PIE) of failed fuel was only aimed at root cause analysis for determining failure cause and improving future fuel designs. In fact, very limited research has been done on failed and damaged fuel. Several Nuclear Power Plants (NPP) are now shutdown for decommissioning and most plants have failed fuel stored in wet pools. Thus, interest has increased regarding characterization of the condition of the failed fuel and research into the handling, drying, transportation and storage of such fuel.

The objective of the presented research program is to respond to the international need for more information on failed fuel. Hence, the data expected by this program will support the future treatment, transport and storage of failed fuel at all plants.

2) Characterization of the fuel rods and their operation

The 13 Special Fuel Rods from the Nuclear Power Plant Brunsbüttel (KKB) are very well suited for a PIE. Twelve of the rods are defect and one is sound. The reasons for the suitability are manifold. The rods represent different fuel design from 8x8-2 to 10x10 developed over a timespan of more than 30 years and from three different vendors. The manufacturing (Hanau (KWU), Lingen (AREVA) in Germany and Västerås (WSE) in Sweden) have been performed at three different sites using different uranium powder processes and with different technologies.

The rod enrichments span over a range from 1.70 w/o up to 4.95 w/o. The irradiation time varies between two to six annual cycles and following a progressive In-Core-Fuel-Management (ICFM) by Vattenfall. The rod powers achieved were up to 420 W/cm compared to the allowed limit of 440 W/cm. The power histories of the 8 Fuel Assemblies (FA's) hosting the 13 rods are shown in Figure 1. For cycle 5 no data is available. The figure shows the span of the power levels over the cycles. The rod powers are very similar. With 49 kW/l the power density of the core is moderate.

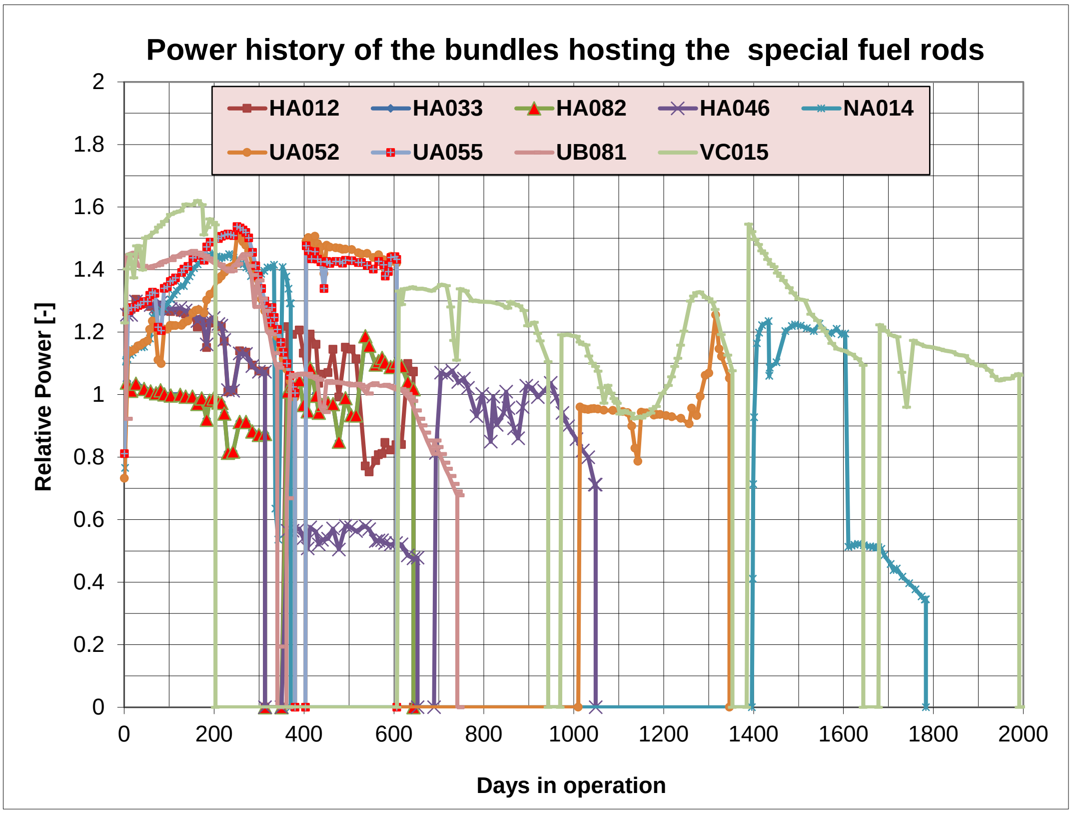

Fig 1 - Power histories of the hosting assemblies of the 13 Special Fuel Rods

Eight of the twelve failures occurred in peripheral fuel rods. The discharge exposures of the host bundles varied between 19 GWd/tU to 42 GWd/tU. The rod exposures are sometimes higher and sometimes lower than those of the hosting assemblies. Of the 13 rods one is a rod containing burnable absorber (Gd_2O_3).

The rods represent a wide range of several important failure mechanisms, including classical PCI (mainly on the rods 8x8-2 FA's), PCI with secondary degradation, fretting and fretting with secondary degradation. The defects observed are tight cladding breakthroughs, small penetrations, axial cracks, circular cracks and axial splits. A few rods have experienced significant fuel loss. These cases provide the opportunity to study fuel and fission product loss, resulting in data for operating plants with defect rods in the spent fuel pool as well as for fuel behaviour under repository conditions. The long time in water also provides an excellent test material to test drying procedures followed by evaluations of the level of dryness.

The Special Fuel Rods were operated under the same power and chemical conditions. The water chemistry in KKB was neutral without utilizing radiation reducing means like Zinc injection, noble chemistry or hydrogen injection. The Brunsbüttel plant is also a forward pumped reactor with a brass condenser.

As of cycle 13 the ICFM was performed by Vattenfall with codes from Studsvik Scandpower. The low leakage reload pattern had a high uranium utilization factor with about 10 fresh bundles per 1000 EFPH with 3.8-4.0 w/o initial fuel U-235 enrichment in annual cycles.

Some main data for the Special Fuel Rods are shown in Table 1. The 13 Special Rods are out of 8 different fuel assemblies.

Essential data for the 13 special fuel rods

Bundle	Rod 6)	Host FA type	Vendor	Initial Enrichment [w/o]	Enrichment at discharge [w/o]	Failed rod Position in the Lattice	Cycles of Operation	Date of Insertion	Date of discharge	Cooling time (Days)	Discharge Exposure of host FA (GWd/tU)	Discharge Exposure of fuel rod (GWd/tU)
HA012	A2	8x8-2	KWU	1.70	0.30	Peripheral	c05-c07	23.08.1986	31.07.1988	10778	26.45	24.67
HA033	D1	8x8-2	KWU	2.40	0.66	Peripheral	c05-c07	23.08.1986	31.07.1988	10778	23.65	21.62
HA033	A2	8x8-2	KWU	1.70	0.38	Peripheral	c05-c07	23.08.1986	31.07.1988	10778	23.65	21.62
HA082	A5	8x8-2	KWU	2.40	0.68	Peripheral	c05-c07	23.08.1986	31.07.1988	10778	23.63	23.13
HA082	B1	8x8-2	KWU	1.70	0.37	Peripheral	c05-c07	23.08.1986	31.07.1988	10778	23.63	21.55
HA082 1)	C3 (Gd)	8x8-2	KWU	3.00/2.00	1.22	Central	c05-c07	23.08.1986	31.07.1988	10778	23.63	19.43
HA082	D1	8x8-2	KWU	2.40	0.66	Peripheral	c05-c07	23.08.1986	31.07.1988	10778	23.63	23.15
HA046	D4	8x8-3	KWU	3.80	1.07	Central	c05-c08	23.08.1986	08.10.1989	10778	30.75	32.23
VC015	C6	A10B	AREVA	4.95	1.23	Central	c16-c21 5)	27.04.2001	18.07.2007	3852	42.27	45.03
UA052	J3	SVEA-96	WSE	3.00	0.97	Peripheral	c15-c17	26.05.2000	06.03.2004	5081	27.26	26.68
UB081	A5	SVEA-96	WSE	4.70	2.50	Peripheral	c14-c15	22.05.1999	01.07.2001	6060	20.9	24.32
UA055	C8 2)	SVEA-96	WSE	4.46	2.57	Central	c15-c16	26.05.2000	18.02.2002	5828	19.96	19.86
NA014 3)	B2	SVEA-64	WSE	4.95	2.10	Inner 4)	c10-c11	14.07.1991	27.07.1996	7860	20.77	20.93

1) Rod sound
2) Spacer Capture Rod
3) Rod broken in two pieces
4) On diagonal towards detector
5) Cycle 21 was only 30 days long
6) Rod orientation: KWU/AREVA Control rod corner ist rod A1
WSE Detector corner ist rod A1

Tab 1 - Essential data for the 13 Special Fuel Rods

The assemblies hosting the rods were discharged in the following outage and the failed rods were replaced by dummy rods for continued irradiation. The Special Fuel Rods were placed in a rod quiver. At the time of the transports to Studsvik, the cooling time for the rods ranged from 3850 up to 10780 days yielding very low decay heat and activity.

The cladding material was Zry-2 with Zr sponge liner. The SVEA-96 rods had a Zr-Sn liner and the Atrium rod had a Zr liner with addition of iron.

3) Legal and contractual conditions for the PIE program

Kernkraftwerk Brunsbüttel GmbH & Co. oHG (KKB) holds a license to store the irradiated fuel bundles in the storage pool in rod quivers for single fuel rods. Before the use of a fuel transport cask however, KKB must provide comprehensive technical documentation and certifications as a requirement to obtain approval from local and federal authorities. In addition, a cold handling test of the cask at the KKB site, including loading of the cask with an empty centering frame, is required. Also necessary for this project, changes on existing equipment (e.g. the channel strip machine) in order to handle the new transport cask with its equipment require an acceptance from the local licensing authority.

Vattenfall AB, as operator of KKB, chose Studsvik Nuclear AB to conduct the PIE and organize the transport of the 13 Special Fuel Rods from Brunsbüttel to their site in Studsvik, Sweden. The facility is licensed by Swedish authorities for PIE research on irradiated fuel. Studsvik has an approved route for handling and final disposal of all PIE fuel waste and secondary waste. Foreign origin fuel on which Studsvik performs PIE research is accepted for final disposal in Sweden, given that there is no reasonably realistic route of return and the amount is very limited.

As a sub-contractor DAHER NT was ordered and coordinated by Studsvik for the transportation using a NCS-45 cask. The NCS 45 cask is licensed for transportation of irradiated fuel rods in Europe and the United States. In order to meet the criteria according to the approval certificate of the NCS-45 cask and the chosen centering frame, the 13 Special Fuel Rods with a total heavy metal mass of 32.26 kg had to be distributed over three transports. For the transportation of un-encapsulated failed fuel rods the cooling time, the burnup (both for individual rods) and the total heavy metal mass for each load had to be taken into account. Given these criteria the optimal combination for the distribution of the rods resulted into three transports at the time, especially since one transport alone was needed for a single rod due to higher burnup.

Figure 2 shows an overview scheme on the different authorities and the applications that were necessary for handling, loading and transportation of the Special Fuel Rods.

The application scheme can be divided into two areas: One area comprises the international and German federal approvals needed and the other area encompasses those given by the state government authorities, i.e. local regulator, in this case the state of Schleswig-Holstein.

The Ministry for Energy Transition, Agriculture, Environment, Nature and Digitalization (MELUND) as the local regulator approved the application for rebuilding the stripping machine as well as the main application for the cold handling, the handling and loading of the laden centering frame into the NSC-45 cask. Both applications have been reviewed by TÜV-Nord SysTec as technical experts.

Covered by the operating license of KKB the Special Fuel Rods have been autonomously loaded into the centering frame of the NCS-45, although accompanied by technical experts for independent documentation purposes in the process. The work itself has been performed by Westinghouse AB which has been ordered by KKB as a subcontractor.

Since nuclear material needed to be exported from Germany to Sweden, the Federal Office of Economics and Export Control (BAFA) had to check on adherence to the Dual-Use Act and on the compliance with the Regulation on the Shipment of Radioactive Waste or Spent Fuel (AtAV).

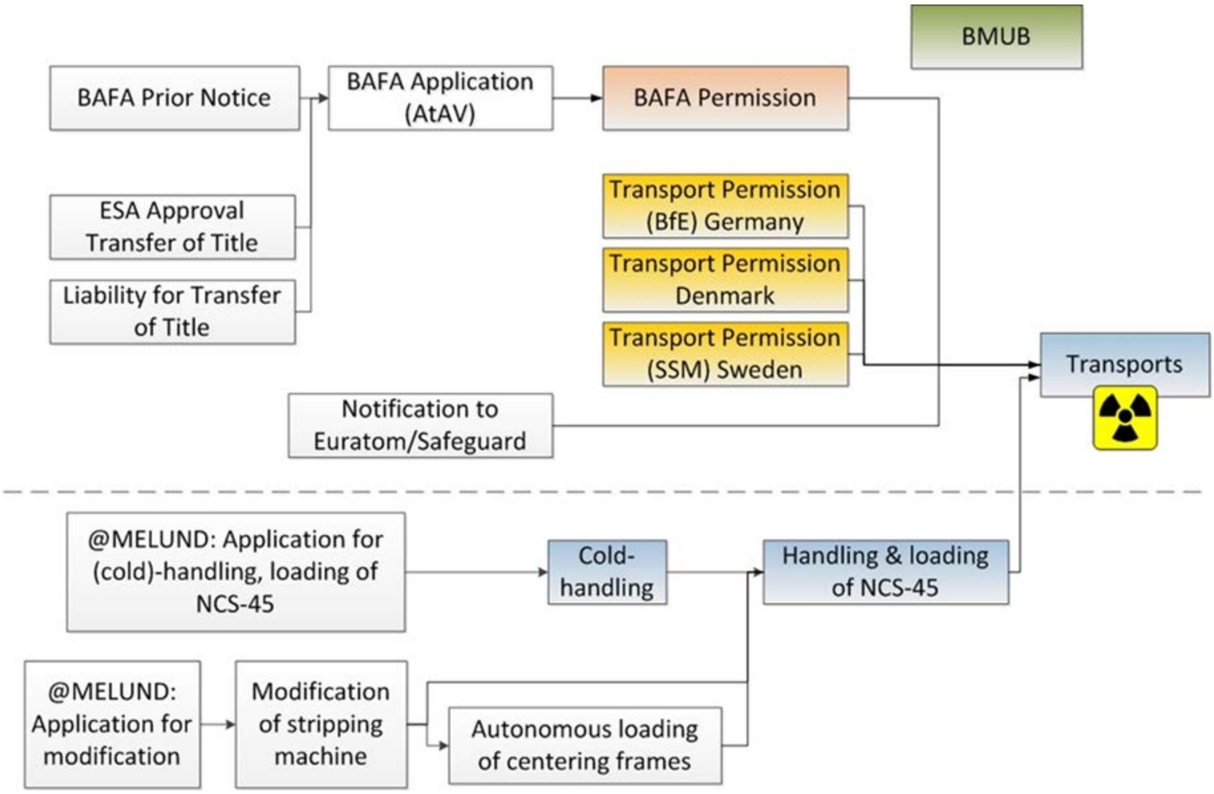

Fig 2 - Application scheme: The dotted line separates the area for international together with the German federal approvals and the area for local approvals (each given by the corresponding authorities).

The nuclear fuel permission was obtained from the European Supply Agency (ESA) for the transfer of title and the liability of the transports. Accordingly, Euratom/ Safeguard had to be informed on the activities planned at the site.

Applied by the haulage contractor DAHER NT the Federal Office for Disposal Safety (BfE) issued the transport license for Germany, as the Strålsäkerhetsmyndigheten (SSM) did for Sweden and their equivalent for Denmark, respectively. The Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB) functioned as an overall surveillance authority.

Having fulfilled all the requirements, the handling and the transports could be carried out.

4) Experience from handling of the Special Fuel Rods at KKB

Since the 13 Special Fuel Rods that have been stored for up to 30 years were intended for a PIE, they require an excellent planning for a safe handling and transportation. Suitable equipment and educated people are the basis for this goal. For the PIE-project

Studsvik Nuclear AB is the main contract partner for KKB. For the transportation of the fuel rods they engaged the company **DAHER NT** using their NCS-45 cask (see Figure 3).

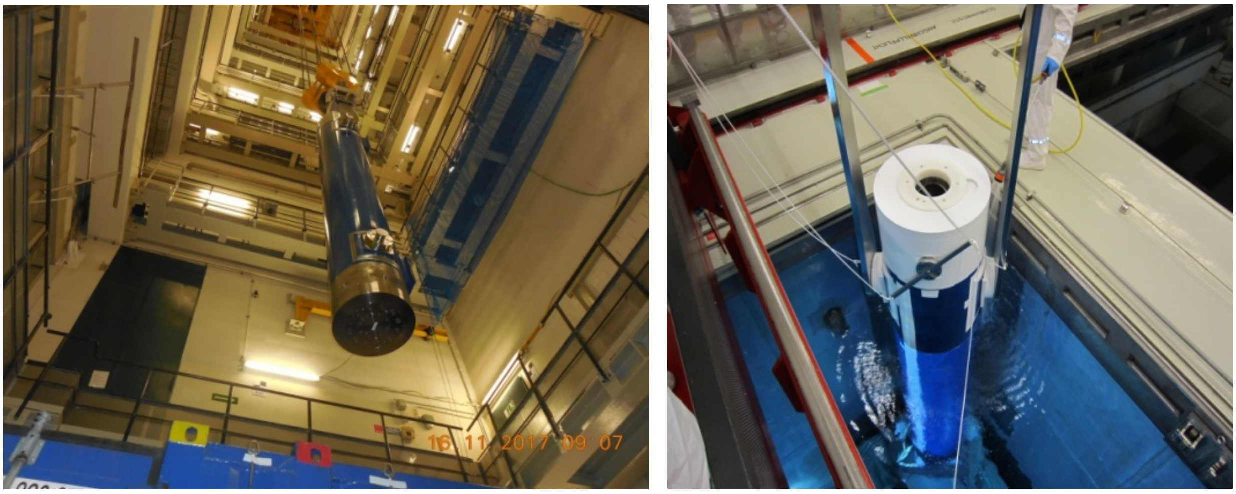

Fig 3 - Handling of the NCS-45 in KKB

KKB chooses **Westinghouse AB** from Sweden to perform the fuel rod handling at the KKB site. Westinghouse is qualified as a fuel supplier for KKB. They have handled single fuel rods in the past and used technical equipment at the site. Also, new suitable tools were developed for this purpose.

In the kick-off meeting for the PIE project in September 2016 the different tasks and the interfaces were discussed and a detailed working plan was set up with the parties. One main investigation was how to handle the Special Fuel Rods. For the process of moving the rods from the rod quiver into the NCS-45's centering frame KKB had to consider that the stability of the rods is unknown.

The loading of the centering frame should be done at KKB in the channel strip machine. Due to the unknown conditions of the cladding of the rods Westinghouse designed special friction gripper, a rescue tool, and a rescue tube for broken rods and pellets for this working position. Also, a safety tray to possible collect falling parts and pellets has been manufactured.

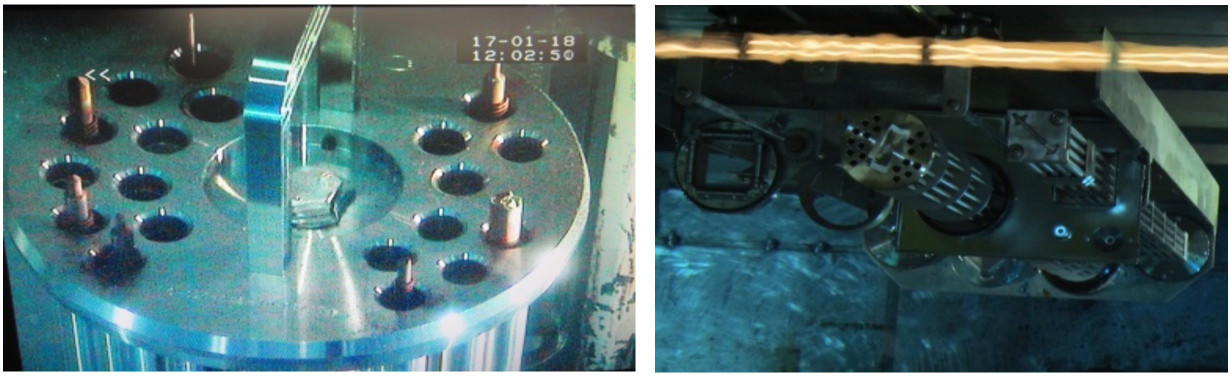

Fig 4 - The laden centering frame and the channel strip machine

Spacer distance rods which should assure that the end of the inserted fuel rod stands above the upper plate of the centering frame were designed. The fuel rods loaded in the tubes of the centering frame stuck out 25 mm above the frame so that the rods could easily be unloaded at the hot cell (see Figure 4).

KKB executed successfully the cold handling test in November 2017. A few modifications of the handling procedure to improve the loading process were introduced in the step-by-step plan. A new gripper extension for the loading of the centering frame was designed and built by KKB.

In January 2018 all licenses from local and federal authority were present so that the loading of two centering frames for the transport campaign could be carried out.

For the loading- and administrative documentation work KKB installed a team to stay standby for each transport campaign. With this team questions from licensing authority have been answered and open technical issues have been solved in a timely manner in order to adhere to the tight schedule.

The loading of the first transport cask with the first 6 Special Fuel Rods took place at the end of January 2018. The second and third transport followed in the subsequent two weeks so that all 13 Special Fuel Rods arrived in Studsvik by February 2018 for hot cell examinations.

5) Reception at Studsvik and the PIE program

Each of three transports was safely received at the Studsvik hot cell facility in Sweden. Each transport was unloaded within a couple of days of arrival and the cask was then returned for the following shipment. As each rod was unloaded, the position in the centering frame and the identity of the rod was cross-checked and verified against the loading plan from KKB. This verification was performed and documented by two separate operators. A webcam located inside the hot cell was used to take photographs of the rod identification engravings on the bottom end plugs. Images were also taken of any areas on the rods which showed failures or were damaged or which showed features deemed interesting by the operators. The observations were also noted in the reception documentation. The rods were entered into the Studsvik inventory database and the Safe Guard database. Two pictures from the unloading of the first transport are shown in Figure 5.

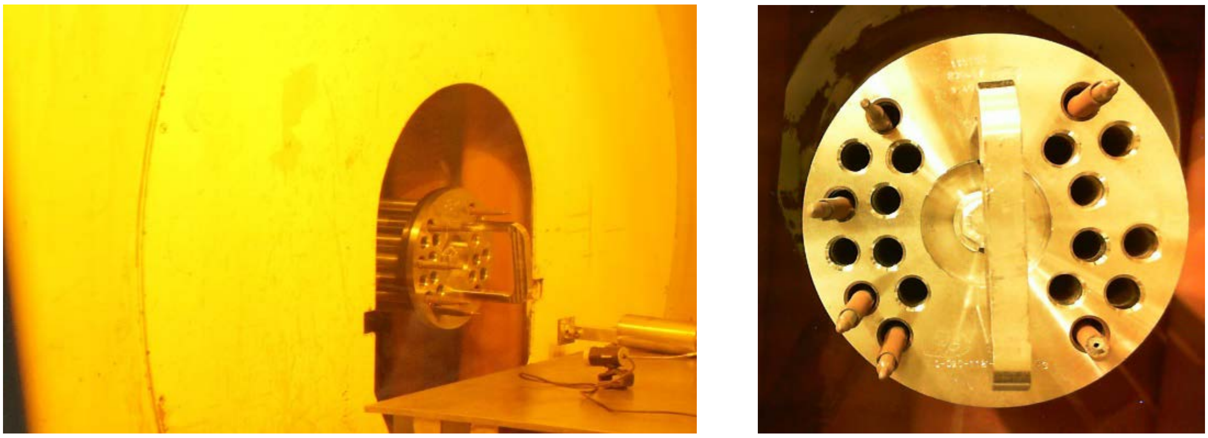

Fig 5 - The centering frame in the unloading position at the Studsvik hot cell and a front view the centering frame in the hot cell before retrieval of the rods

The visual inspection performed in connection with the unloading showed a range of damages and features on the Special Fuel Rods. Four rods had no obvious damage. Three rods were bent near the bottom end, but otherwise without obvious damage. One of these rods has been stated as intact. Five of the seven rods were suspected PCI failures. Another rod had a primary fretting failure close to the bottom end with a large secondary damage in the upper part. A white deposit extended from the location of the secondary damage to the top of the rod.

The remaining four rods had fretting damage with a primary failure near a spacer location and with secondary degradation damage close to the top and or bottom of the rod. Pictures of the apparent rod failure locations on two rods are shown in Figure 6. The left picture shows a suspected PCI failure and the right picture shows a clear fretting failure.

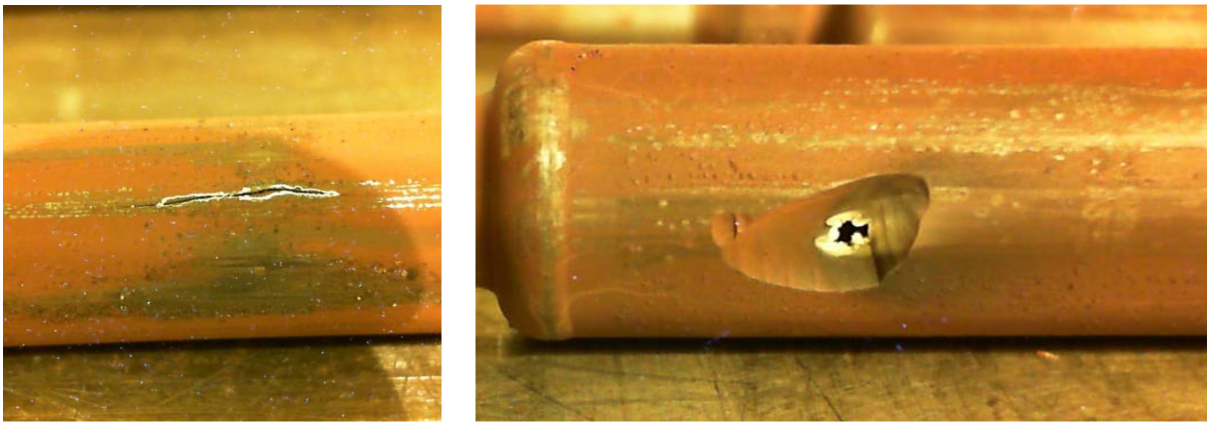

Fig 6 - Two cases of apparent primary failures in two different Special Fuel Rods

The research program on the KKB Special Fuel Rods includes three focus areas. The first area is the characterization of the conditions of the Special Fuel Rods after many years of wet storage at the NPP. This will include some root cause analysis of the defect rods, evaluation of fuel loss and of the dissolution of fission products from defects. The mechanical integrity of the sound and defect rods will also be characterised to support their safe handling and storage. Failed fuel which has been operated a period after the initial primary failure usually has experienced excessive hydriding of the cladding. This degrades the ductility and makes the rod very brittle at certain locations on the rod. By knowing the strength and residual ductility of such rods, it is possible to design mitigation strategies which may be useful when large numbers of failed rods shall be handled in the NPP pools and prepared for encapsulation. This is expected to be of particular interest for the German nuclear industry as it sets out to manage Special Fuel Rods at different NPPs. As part of this work the potential release of very fine fuel particles in connection with rod breaks will be studied. This is of interest primarily for studies of consequences in hypothetical accidents in connection with transportation of dry storage casks.

The second area is focused on the drying process for stabilization of defect rods for safe encapsulation and storage. At some occasions failed fuel rods transported to Studsvik for PIE have been observed with dark areas of moisture on the cladding surface. It should be mentioned that these observations have been made despite that conventional vacuum drying of the transport cask has been performed before shipment of the cask to Studsvik. The observations of moisture have been made at the hot cell directly after the rods have been pulled in from their transport cask quivers. Once in the hot cell, the moisture dries off quickly and the dark patches vanish. The patches of moisture are observed infrequently, but they have been observed several times for different transports of failed fuel. It was in fact observed for one of the rods in one of the transports from KKB. The rod was observed to have a dark patch of moisture as it was pulled into the hot cell. The patch dried and vanished quickly after entering the hot cell. The aim of the second research area is to determine the residual moisture content which may be hiding in defect fuel after conventional vacuum drying has been performed. Any residual moisture content may in long term storage lead to oxidation of the fuel or other materials and hydrogen generation. These phenomena have the potential to lead to degradation of the contents of the intermediate storage casks. Hence, it is of great interest to improve the understanding of these potential risks and to determine suitable criteria to rule out or mitigate these phenomena.

The third area is focused on the potential detrimental effects of hydride reorientation in fuel rods. Radial reorientation of hydrides results in an embrittlement of the cladding and poses a threat to cladding integrity during and after dry storage. The investigation will focus on both realistic and limiting conditions in terms of cladding stress and temperature cycles to assess the risk of hydride reorientation to occur. The critical parameters for hydride reorientation will be determined by performing heat treatments under applied stress followed by ring compression testing (RCT) to characterize ductility. This method will be used to identify the ductile to brittle transition threshold. The test material will be characterized before and after testing by optical microscopy, hydrogen measurement by hot vacuum extraction and examinations by Scanning Electron Microscopy (SEM).

The PIE program is organised into six individual tasks. The first two tasks involve basic PIE to characterize the rods and the failures, tasks 3-5 are dedicated to the second focus area, i.e. the drying process, and task 6 is the third focus area consisting of a hydride reorientation study. The PIE program started March 1, 2018 and is planned to last 41 months until July 2021. The overall time schedule of the PIE program is illustrated in Figure 7.

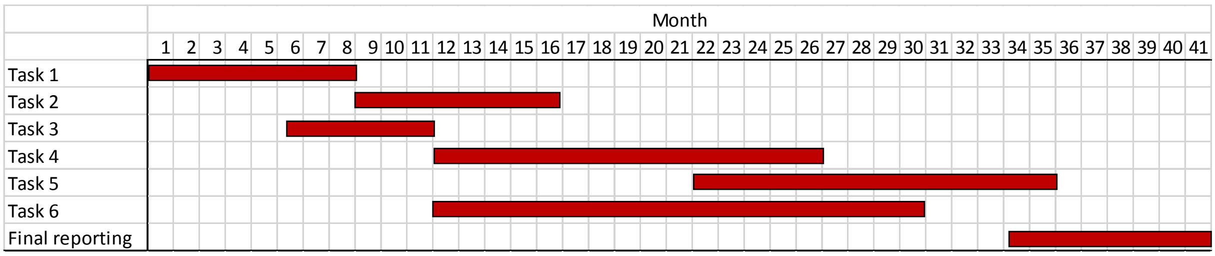

Fig 7 – Time schedule of the PIE-program

The first task is to perform basic PIE and some failure analysis of the fuel rods. This task will yield basic data important for the each of the research focus areas. The work in this task includes puncturing and gas analysis of a few rods without large secondary failures. The rods will then be cut in about 1 m lengths. The cuts will be made at locations which avoid failure positions and other locations with interesting features. Non-destructive PIE such as detailed visual inspection will be performed followed by gamma scan measurements, eddy current oxide thickness measurements and diameter measurements. Based on the data obtained from these measurements, the locations for destructive measurements, such as optical microscopy, will be decided. The PIE work has just started and the first few results are expected to be available at the time of the conference meeting.

6) Conclusion

The first two parts of the project, i.e. handling and transport, have been completed successfully in a safe and effective way as scheduled. This result was reached with educated and qualified staff from different organisations and under the given boundary conditions of the power plant conducting other projects at the time.

For the equipment and the transport cask the cold trial before use has been performed. Several technical and procedural improvements were implemented after this test.

With the 13 Special Fuel Rods, operated under the same power and chemical conditions, a variety of parameters in terms of manufacturer, design, initial enrichment, cooling time and burnup is represented.

The next step is the third part of the project that encompasses the PIE-program with its three focus areas: The characterization of the conditions of the Special Fuel Rods after many years of wet storage at the NPP, the drying process for stabilization of defect rods for safe encapsulation together with storage and in particular, the potential detrimental effects of hydride reorientation. With this PIE-program an additional valid evaluation of the long-term dry storage of irradiated fuel is expected.

Thus, the scope of this project appears to be suitable to support the future treatment, transport and storage of failed fuel at all plants.

7) References

None