POOLSIDE FUEL ASSEMBLY INSPECTION CAMPAIGNS PERFORMED AT KERNKRAFTWERK LEIBSTADT DURING SUMMER 1997

H.U. ZWICKY, C.G. WIKTOR
Kernkraftwerk Leibstadt AG,
Leibstadt, Switzerland

D. SCHRIRE
ABB Atom AB,
Västerås, Sweden

XA9848400

Abstract

In order to minimise fuel cycle costs, fuel assembly discharge burnup and average U-235 enrichment were increasing over past years in the Kernkraftwerk Leibstadt (KKL) plant. In parallel, high burnup verification programs were defined in collaboration with fuel suppliers. The aim of these programs is to demonstrate safe and reliable fuel performance up to the designed burnup limit and to identify any problems in due time. This is not only achieved by detailed poolside inspections of lead test assemblies, but also by hotcell post-irradiation examination of selected rods.

In the frame of a hotcell examination campaign, enhanced localised corrosion in the vicinity of spacers on SVEA-96 fuel rods was identified in May 1997 as a potential problem. The average rod burnup of the investigated rods was around 50 MWd/kgU after 5 one year cycles of operation. As fuel operation up to six cycles is foreseen in KKLs fuel management plans, the risk of fuel failures caused by enhanced localised corrosion could not be excluded. An action plan was therefore developed in order to identify the root cause. Part of the action plan were two poolside inspection campaigns:

1. Visual inspection of 38 assemblies unloaded during refuelling outage 1996 after 5 cycles in operation. This campaign was performed in June 1997. It gave a broader data base to develop a concept for fuel management for the upcoming refuelling outage scheduled in August 1997.
2. Visual inspection, oxide layer thickness measurements, crud sampling and rod diameter measurements on 29 assemblies with different operation histories. This campaign was performed during the outage. A large portion of the inspected bundles was re-inserted for continued operation. The collected data confirmed that assumptions made for reload licensing and safety analyses were conservative.

The inspection campaigns performed at KKL during summer 1997 by ABB Atom demonstrated that it is possible to address unexpected problems in a short time. Planning and data evaluation done in close co-operation between fuel supplier and plant, and a well trained, highly motivated inspection team, supported by experienced operators of the fuel handling equipment, applying well proven equipment, are the prerequisites for a successful inspection campaign.

1. INTRODUCTION

Under Swiss conditions, more than 50% of fuel cycle costs are backend costs. In a first approximation, they are proportional to the amount of spent fuel. By increasing the U-235 enrichment of fresh bundles, the average burnup of assemblies discharged from the Leibstadt reactor was raised from around 20 to well above 40 MWd/kgU (Fig. 1). In parallel, several fuel performance programs have been established in close collaboration with the fuel suppliers. The aim of these programs is to demonstrate safe and reliable fuel performance up to the designed burnup limit and to identify potential problems in due time. This is not only achieved by detailed poolside inspections of lead test assemblies, but also by hotcell post-irradiation examination of selected rods.

In the frame of a hotcell examination campaign, enhanced localised corrosion in the vicinity of spacers on SVEA-96 fuel rods was identified in May 1997 as a potential problem. The average rod burnup of the investigated rods was around 50 MWd/kgU after 5 one year cycles of operation. As fuel operation up to six cycles is foreseen in KKLs fuel management plans, the risk of fuel failures caused by enhanced localised corrosion could not be excluded. An action plan was therefore developed in order to identify the root cause and ameliorating actions. Part of this plan were two poolside inspection campaigns, the first one in June 1997, during normal reactor operation, where 38 discharged bundles were visually inspected, the second one during the refuelling outage in August 1997. The aim of this paper is not to discuss results obtained during these campaigns, but to show that it is possible to address unexpected problems in a short time, when work planning and data evaluation are performed in close co-operation between supplier and plant.

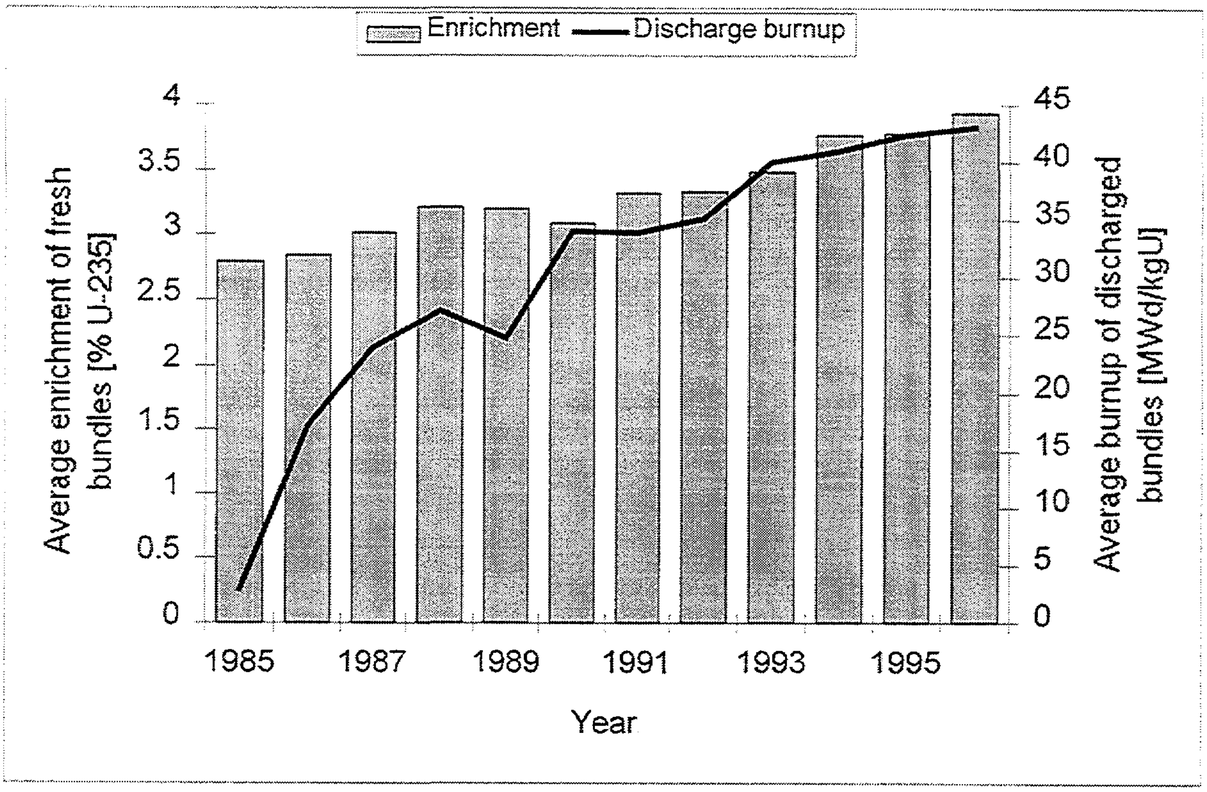

FIG. 1. Development of fresh fuel enrichment and discharge assembly burnup at KKL

2. FUEL IN THE LEIBSTADT REACTOR

The Leibstadt reactor, a General Electric BWR/6 Mark 3 boiling water reactor, started commercial operation in 1984. The core contains 648 fuel assemblies and is operated at a thermal power of 3138 MW. The initial core contained GE6 assemblies with fuel rods arranged in an 8×8 array. In cycle 3, the first fuel assemblies with a zirconium liner as a PCI remedy were loaded. With the aim to qualify alternative fuel vendors, ABB Atom SVEA-64 and Siemens-KWU 9-9Q lead use assemblies were introduced in cycle 3 and 4 respectively. In cycle 8, the first reload of ABB Atom's SVEA-96 10×10 assembly was introduced. The SVEA-96 bundle is composed of four 24 rod subassemblies placed in a fuel channel with a central diamond shaped water channel and water wings between the subassemblies. The spacers consist of Inconel-750. During cycle 10, a mid-cycle outage was performed in order to unload some failed fuel assemblies. The 13th one year cycle was completed on July 28, 1997. An overview of fuel assembly types in the KKL core up to cycle 13 is shown in Table I.

TABLE I. FUEL ASSEMBLY TYPES LOADED IN KKL CORE UP TO CYCLE 13

Assembly type	KKL Cycle													
	1	2	3	4	5	6	7	8	9	10A	10B	11	12	13
GE6	648	648	540	384	268	109	88	56	4					
GE7B			104	104	104	103	8				5			
GE8B				152	268	428	436	348	290	170	168	64	8	
GE10							104	144	144	144	142	142	70	
GE11-LUA							4	4	2	4	4	4	2	2
KWU-9-9Q				4	4	4	4	4						
SVEA-64			4	4	4	4	4	4						
SVEA-96								88	208	330	329	430	448	414
SVEA-96/L													64	64
SVEA-96+/L												8	56	168

3. INSPECTION CAMPAIGN PERFORMED IN JUNE 1997

The first 38 SVEA-96 fuel assemblies had been unloaded from the KKL core after 5 cycles of operation during the 1996 refuelling outage. They had reached average assembly burnups between 46 and 49 MWd/kgU. Within the frame of a high burnup verification program, 6 similar assemblies had been inspected in the pool during the outage. Four of them were re-inserted for another cycle. From the remaining two assemblies, one rod was selected from each one for detailed hotcell post-irradiation examinations. One of the rods showed extensive crud and oxide spalling at the lower spacer positions. The second rod was considered to be a "typical" five cycle SVEA-96 rod of that generation. The results of destructive hotcell examinations were available in May 1997. They showed that localised enhanced corrosion in the vicinity of the lower spacers had led to a wall thickness reduction of about 50% in the "typical" 5 cycle rod. The rod showing extensive spalling had as little as 25% remaining wall thickness at some spots. Moreover, some local surface hydride concentrations were found. Later on, the examinations were extended to a 3 cycle and a 4 cycle rod already in the hot cell. The latter locally showed a wall thickness reduction of about 25%, whereas the 3 cycle rod revealed a normal behaviour with an oxide layer thickness below 50 µm even within spacer positions.

As a basis for the development of a fuel management concept for the next cycle scheduled to start at the beginning of September 1997, a broader data base was needed. It had to show whether the observations made in the hotcells were representative for all rods or for some single cases only. Within a few days, a campaign was initiated and planned for the visual inspection of all 38 discharged SVEA-96 fuel assemblies. All peripheral rods in each subassembly were inspected (60 of 96 rods). A qualitative assessment of the nature of the oxide near and under the spacer grids was made for each rod in all six spacer positions. A scale from 1 to 6 was applied (1 = extensive spalling, 3 = onset of spalling, 6 = thin oxide). The whole inspection was documented by video tape. The work was performed from June 9 to June 19, 1997. Fuel assembly transfer from storage pool positions into the fuel handling equipment and back to the storage rack was performed by operators belonging to the regular KKL staff. Subassembly handling and inspection work was done by two ABB Atom inspectors. Two shift groups worked from 6 a.m. until 10 p.m. The data were evaluated in close co-operation between KKL and ABB Atom. They are plotted in Fig. 2. The results showed that about 4% of all inspected rods were at least once rated with 1. The affected rods were more or less evenly distributed across all inspected bundles with no clear preference for certain positions, but heavy spalling was not seen in the uppermost spacer positions.

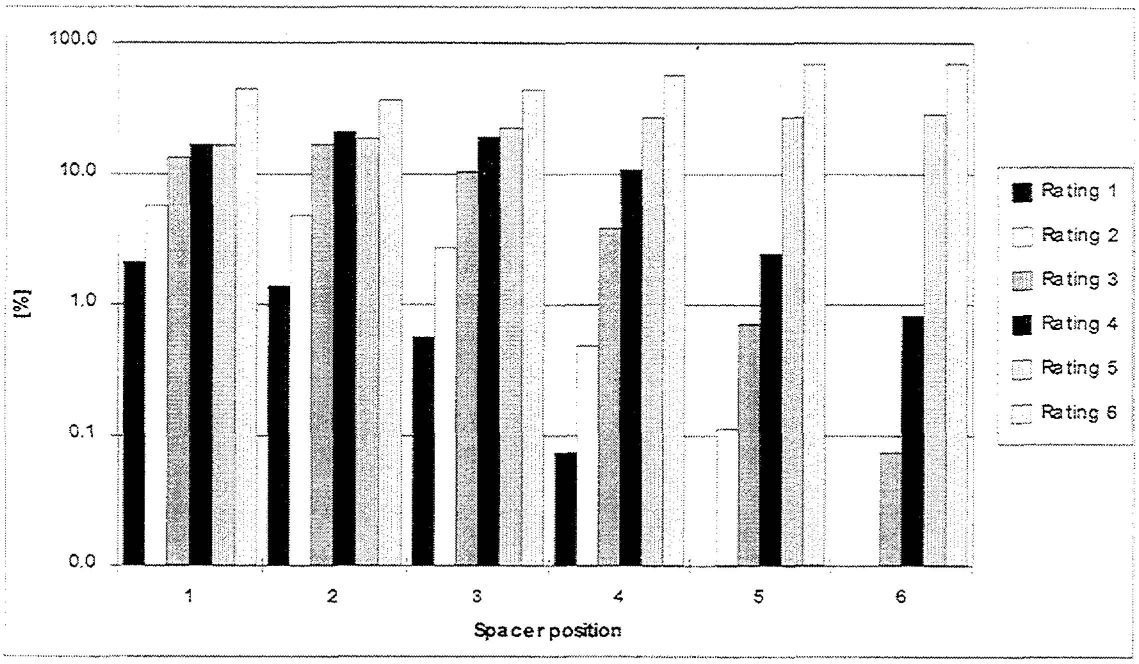

FIG. 2. Visual inspection of 5 cycle SVEA-96 fuel assemblies and qualitative assessment of nature of oxide near and under spacer grids (rating 1 = extensive spalling, 3 = onset of spalling, 6 = thin oxide). Observe logarithmic scale!

4. INSPECTION CAMPAIGN DURING THE REFUELLING OUTAGE 1997

4.1. Scope of inspections

The discharged bundle inspection performed in June 1997 showed a picture of the enhanced localised corrosion as it appeared at "end-of-life" for a group of assemblies with very similar irradiation histories. In order to learn more about the development of the phenomenon and possible influencing factors like rod power history, residence time, core location, time of fabrication and of introduction into the core, data from assemblies with differing irradiation histories and residence times are needed. Moreover, assumptions made on the basis of the hotcell examination results in order to establish a revised thermal mechanical operating limit (TMOL), taking into account enhanced localised corrosion, had to be confirmed by measurements performed on a significant amount of assemblies. As it was decided in an early stage of core design work for cycle 14 to unload all four and five year old SVEA-96 bundles in order to save time for a detailed analysis of the consequences of enhanced localised corrosion, the inspection program focused on three and four year old bundles. Bundles with as different irradiation histories as possible were selected, including bundles from core symmetry positions. Fuel rods with slightly different Zircaloy-2 cladding fabrication processing variables were included. An overview of selected bundles to assess enhanced localised corrosion is given in Table II.

In addition, two GE11 assemblies and a prototype SVEA-96 debris filter were visually inspected. Finally, in three defective assemblies the failed rod had to be localised and the primary failure cause identified.

TABLE II. FUEL BUNDLES SELECTED FOR DETAILED POOLSIDE INSPECTIONS FOR ENHANCED LOCALISED CORROSION ASSESSMENT

Residence time [cycles]	Number of bundles	Burnup range [MWd/kgU]	Remarks
1	4	11.2-11.8	1 assembly LK2, 1 assembly LK2+
2	2	23.5-23.8	1 assembly LK2, 1 assembly LK2+
3	10	25.2-34.8	2 assemblies with LK2, LK2+ and LK3 cladding 3 symmetry pairs
4	12	23.1-32.6	1 quad. symmetry, 3 symmetry pairs
5	3	28.6-41.6	1 symmetry pair

4.2. Inspection techniques

On two subassemblies per bundle, spacer 3 was shifted downwards. On a selection of subassemblies, spacers 1, 2, 5 and 6 were also shifted.

An underwater TV camera and video recording was used for visual inspection. Special attention was paid to the occurrence and lateral extent of spalling. At the same time, the general appearance and geometry of subassemblies were checked.

For oxide thickness measurements, a standard eddy-current (EC) lift-off (Fischerscope) equipment was used. Outside spacer regions, pointwise measurements were taken. In the spacer regions, continuous measurements of 100-200 mm length were performed. Special attention was paid to the problem of erroneous EC measurements caused by the magnetic properties of tenacious crud formed on part of the cladding, because zinc injection is applied at KKL [1, 2]. Therefore, soft and at least part of the tenacious crud layer was removed on some selected rods by mechanical grinding over a length of 20 mm. Zirconium oxide is not significantly affected, as it is much harder than crud. Comparison of EC signals within and outside the grind marks revealed whether the measuring signal was disturbed or not. If it was disturbed, the true oxide and crud layer thickness was always overestimated. Profilometry over the edge of the grind marks resulted in an estimation of the crud layer thickness, allowing for a (conservative) calculation of the net oxide layer thickness from the EC signal.

Mechanical metrology was applied for fuel rod diameter measurements. The profilometry results were used to verify EC oxide layer thickness measurements, to determine the crud layer thickness and to calculate the remaining metal wall thickness.

Four inspection teams consisting of 2-3 ABB Atom inspectors and two KKL operators were formed. During refuelling, when fuel assembly inspections were on the critical path of the outage activities, work at the spent fuel pool went on during 24 hours a day. Afterwards, the schedule was reduced to two shifts of 8-9 hours. The fact that the spent fuel pool and refuelling floor are in different buildings at KKL, was a big advantage, allowing for more or less interference free activities at both sites. The whole campaign took place between August 5 and August 28, 1997.

4.3. Evaluation procedures

Based on oxide layer thickness measurements in non-spalled regions with uniform oxide, the cladding inner diameter was determined as follows:

$$t_w = t_{orig} - \frac{t_{ox}}{PB}$$

$$ID = OD_{ox} - 2 \times (t_{ox} + t_w)$$

where

t_w is cladding metal wall thickness,

t_{orig} is original cladding wall thickness (0.63 mm),

t_{ox} is oxide layer thickness,

PB is the Pilling-Bedworth ratio for the conversion of oxide thickness into corroded metal layer thickness,

ID is cladding inner diameter,

OD_{ox} is outer cladding diameter including oxide layer, measured by profilometry.

The minimum remaining metal wall thickness in the spacer region, assuming axisymmetrical corrosion and spalling, was calculated as follows:

$$t_{w(\min)} = \left| \frac{OD_{ox} - ID}{2} - (t_{ox} + t_{crud}) \right|_{\min}$$

where

$t_{w(\min)}$ is minimum remaining metal wall thickness,

t_{crud} is crud layer thickness.

As it was difficult with the applied measuring techniques to exactly match the oxide layer thickness and diameter measurements, a conservative approach was chosen by using a maximum value for t_{ox} and a minimum local OD_{ox} value within each spacer region. The calculation is applicable for spalled and non-spalled positions.

4.4. Some results

Data evaluation is still going on and far from being completed. Moreover, this paper does not aim at presenting and discussing inspection results. Nevertheless, a selection of results is presented in order to show that the campaign was not only a heavy work load for all involved people, but also led to important conclusions. The following assumptions were made, when a revised TMOL for cycle 14 operation was established:

- No influence of enhanced localised corrosion on the TMOL up to a local burnup of 36 MWd/kgU (typical for 3 cycle fuel), provided that the average enhanced oxide thickness within the spacer region does not exceed 100 µm.
- Minimum remaining wall thickness of 50% at a local burnup of 50 MWd/kgU (typical for 4 cycle fuel).
- Minimum remaining wall thickness of 25% at a local burnup of 60 MWd/kgU (typical for 5 cycle fuel).

As can be seen in Fig. 3, maximum oxide layer thickness values, corrected for the crud layer and averaged over the enhanced corrosion spacer region, are smaller than 100 µm in all measured spacer grid positions for all measured 3 cycle rods. In Fig. 4, the minimum remaining wall thickness values in all measured spacer grid positions for all measured 4 cycle rods are plotted. The remaining metal wall thickness is well above 50% of the as-fabricated wall thickness. Therefore, the assumptions for establishing the revised TMOL and one of the prerequisites for cycle 14 operation were fulfilled and the authority, the Swiss Federal Nuclear Safety Inspectorate HSK, was able to give their cycle operation release.

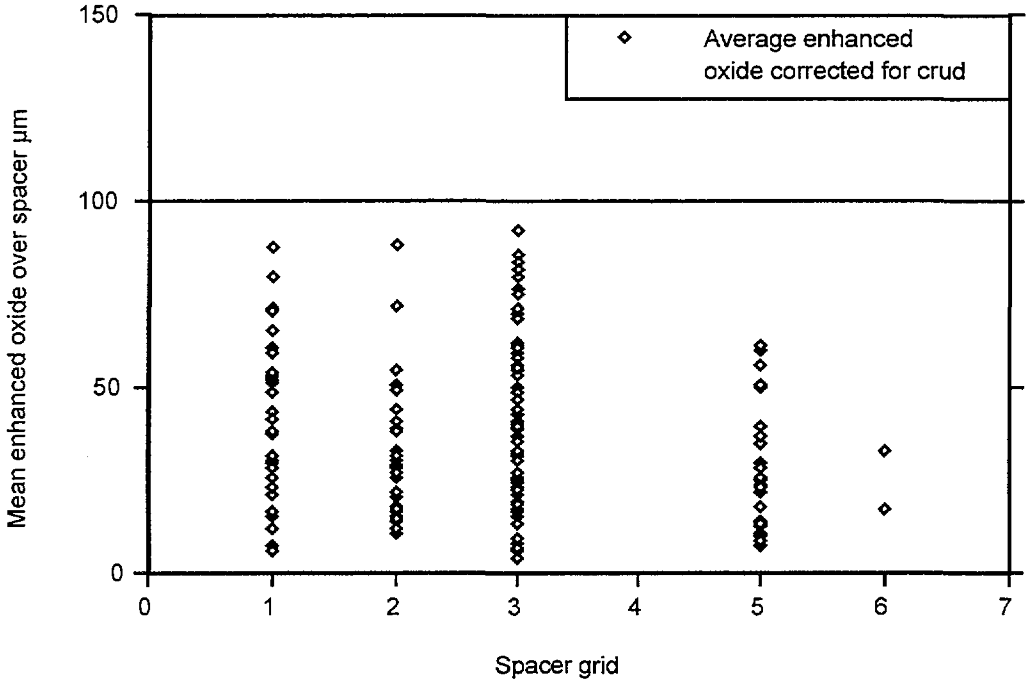

FIG.3. Mean enhanced oxide layer thickness averaged over spacer region in all measured grid positions for all measured 3 cycle rods.

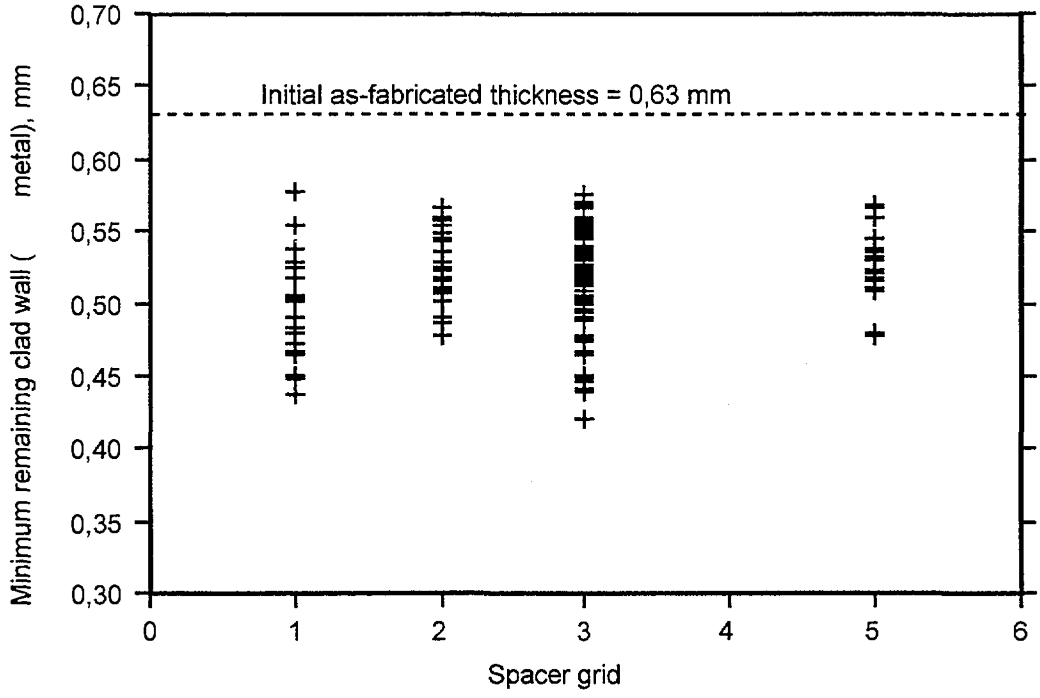

FIG. 4. Minimum remaining metal wall thickness in all spacer grid positions for all measured 4 cycle rods.

5. CONCLUSIONS

The inspection campaigns performed by ABB Atom during summer 1997 at KKL demonstrated, that it is possible to address unexpected problems in a short time,

- when planning and data evaluation are performed in close co-operation between fuel supplier and plant representatives,
- when a well trained, highly motivated inspection team, supported by experienced operators of the fuel handling equipment, is applying well proven equipment,
- when technically competent representatives of the authority are willing to closely follow the measurements, data evaluation and analysis.

ACKNOWLEDGEMENTS

Poolside inspection campaigns as they were performed during summer 1997 in KKL are only possible thanks to a large, versatile team working all out. Major contributions were made by

- A. Flühler and H.R. Gerber, KKL, who planned the campaigns, co-ordinated the efforts and organised support whenever needed,
- R. Lundmark, KKL, who assisted in setting up the inspection programs and prepared all necessary assembly handling lists together with E. Obst,
- J.O. Erling, who performed a great job as ABB Atom's inspection team leader,
- all the ABB Atom inspectors and KKL operators, working long shifts at the spent fuel pool under difficult and demanding conditions, and
- B. Andersson, ABB Atom, who co-ordinated data handling and evaluation.

The willingness of H. Wand, HSK, to closely follow-up work progress by frequent visits on site is highly appreciated.

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