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ABSTRACT

Spent fuel attribute tester, SFAT, has been constructed and tested for gross defect verification of VVER-440 type spent fuel assemblies. Based on earlier optimisation studies /1-4/, the VVER-440 SFAT is kept hanging from the mast of the fuel handling machine moved by the operator. The device tested includes a standard 2" x 2" NaI(Tl) detector connected to a commercial MCA. The results achieved with normal VVER-440 spent fuel assemblies at the Loviisa npp in Finland in November 1994 show that the method is feasible. The design of the so-called fuel follower assemblies, however, prevents SFAT verification, at least with moderate measurement times. Verification of the presence of the assemblies based on the detection of the fission product ^{137}Cs (662 keV) is possible even in 10 - 30 seconds. Measurement times of the order of 1 - 2 minutes make it possible to draw also semi-quantitative conclusions of the burnup and cooling time of the operator declared data (consistency check).

CONTENTS

1 INTRODUCTION

Safeguarding of spent nuclear fuel calls for verification of fuel assemblies. In most cases, the gross defect test, verification of the presence of an assembly or replacing it with a dummy, is enough. Partial defect methods, capable of revealing even missing or replacing of individual rods in most effective cases, are needed for achieving higher level of confidence of the presence of declared material.

Spent fuel attribute tester (SFAT) was designed for verification spent LWR fuel assemblies stored under water in cases where traditional verification with CVD doesn't work or is not enough. It is well known that low burnup or long cooling time together with facility specific conditions like non-transparent or rippling water prevents the use of CVD.

The BWR SFAT developed under the Finnish Support Programme to the IAEA Safeguards (FINSP) /4/ has been optimised for use with BWR assemblies. Dense storage geometry of square shaped assemblies requires the positioning and collimation above the assembly to be accurate and repeatable.

The water quality of many facilities storing VVER-440 type spent fuel assemblies is known to be rather poor from CVD verification point of view. Such a situation was met also at the Loviisa npp during successive inspections of the IAEA in the summer of 1994 when the transparency of the pool water was temporarily reduced due to simultaneous maintenance activities.

In addition to spent fuel assemblies, fuel follower assemblies and dummy assemblies used for radiation shielding of the pressure vessel may be stored in the VVER ponds together with other irradiated metal objects. In some cases the pool water may be non-transparent. Under such conditions verification of the presence of spent fuel assemblies and further, distinguishing them from stored dummy assemblies with similar shape and outer dimensions, is just not possible using conventional verification methods. Normally spent fuel movement or lifting is required for verification.

The VVER-440 type PWR assemblies have a hexagonal shape and no fuel handle crossing the top of the assembly. The open top structure makes it easier than in the case of BWR fuel to detect radiation emitting from the fuel zone of a normal assembly. The operator and inspector experience with different types of SFATs confirms that a rather massive SFAT moved by the fuel handling machine allows optimum use of the method for verification purposes. Contacts of SFAT with fuel assemblies may not be allowed at all and in any case should be avoided both for operational safety and to ease decontamination.

To make the use of verification instruments cost-effective, commercial electronics and hardware components together with standard handling procedures of the operator results in economical use of operator and inspector working hours without jeopardising the safety culture of nuclear facilities. The optimum handling of the device and the long development experience in addition to operator recommendations to use fuel handling machine has led to the design used for the feasibility study of VVER-440 type SFAT at the Loviisa npp in Finland.

2 MEASUREMENT TECHNIQUES

2.1 Fuel data

In total 32 test measurements were performed from 12 different fuel assemblies. Measured assemblies were chosen so that normal assemblies, fuel followers, empty storage positions and dummy assemblies, could be measured. Also assemblies with different burnups and cooling times were chosen. The fuel assemblies of a VVER-440 reactor are homogeneous. In other words, each assembly includes only rods of one initial enrichment (^{235}U). Normally used enrichments are 1.6 %, 2.4 % and 3.6 %. In future possibly also 4.4 %. Exception is fuel follower assemblies, whose enrichments are 2.4 % or 3.6 %. Data from measured assemblies are presented in Table I. The cross sectional view of the normal fuel assembly and fuel follower assembly used at the Loviisa npp is shown in Fig. 1. Steel pivots (length 120 mm), which are extension pieces of the fuel pellets in the top of the fuel rods, are used to prevent the axial peaking of the power of the reactor.

2.2 VVER-440 SFAT

The VVER-440 type SFAT main construction includes three separate parts; the uppermost part with the handle, which includes the top piece of VVER-440 assembly, the cylindrical detector housing and the collimator tube. The mechanical structure of the VVER-440 SFAT is presented in Fig. 2.

The handle is connected to the water tight cylindrical detector housing with four suspension bars. The cap of the cylinder, in which the cable connector with an electronic leed-through is located, can be opened for changing the detector and lead shielding. The shielding is made of modular

Table I. Data table of measured fuel assemblies.

Assembly ID	Fuel type	Burnup [MWd/kgU]	Cooling Time [years]	Enrichment [%]	Coordinates
13614727	normal	29.2	5.33	3.6	15.15
13617986	normal	38.9	5.33	3.6	15.1
13624638	normal	41.7	3.22	3.6	12.12
22421318	fuel follower	21.9	5.33	2.4	11.29
12414756	normal	20.1	5.33	2.4	11.41
dummy	dummy				9.29
22432046	fuel follower	27.7	2.21	2.4	9.21
empty	empty				7.21
13628285	normal	23.1	3.3	3.6	1.7
13632453	normal	35.7	1.29	3.6	20.4
13628406	normal	31.5	3.22	3.6	24.1
13628480	normal	39.8	3.22	3.6	24.12

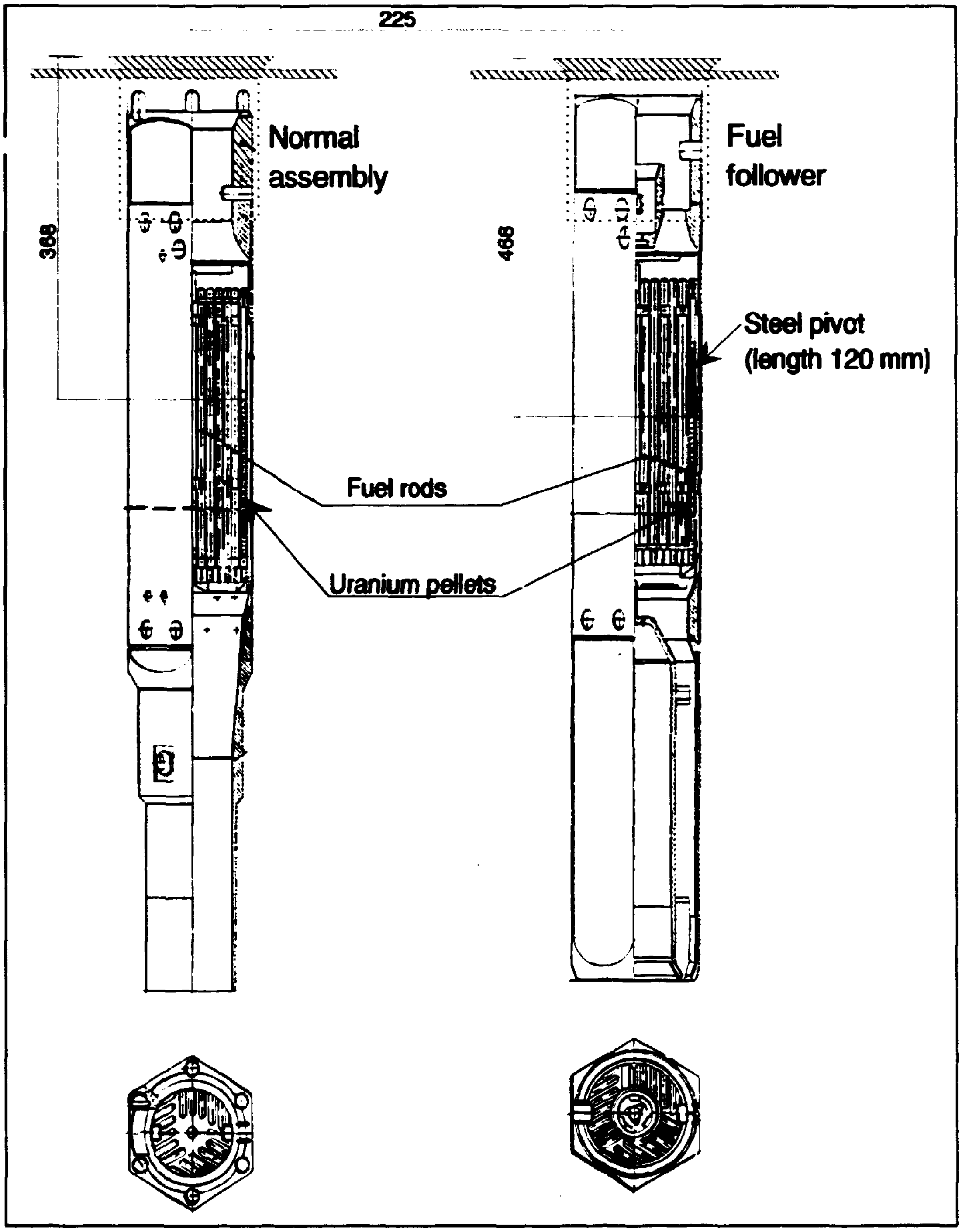


Figure 1. *The cross sectional view of the two different fuel assembly types used at the VVER-440 reactors in the Loviisa npp.*

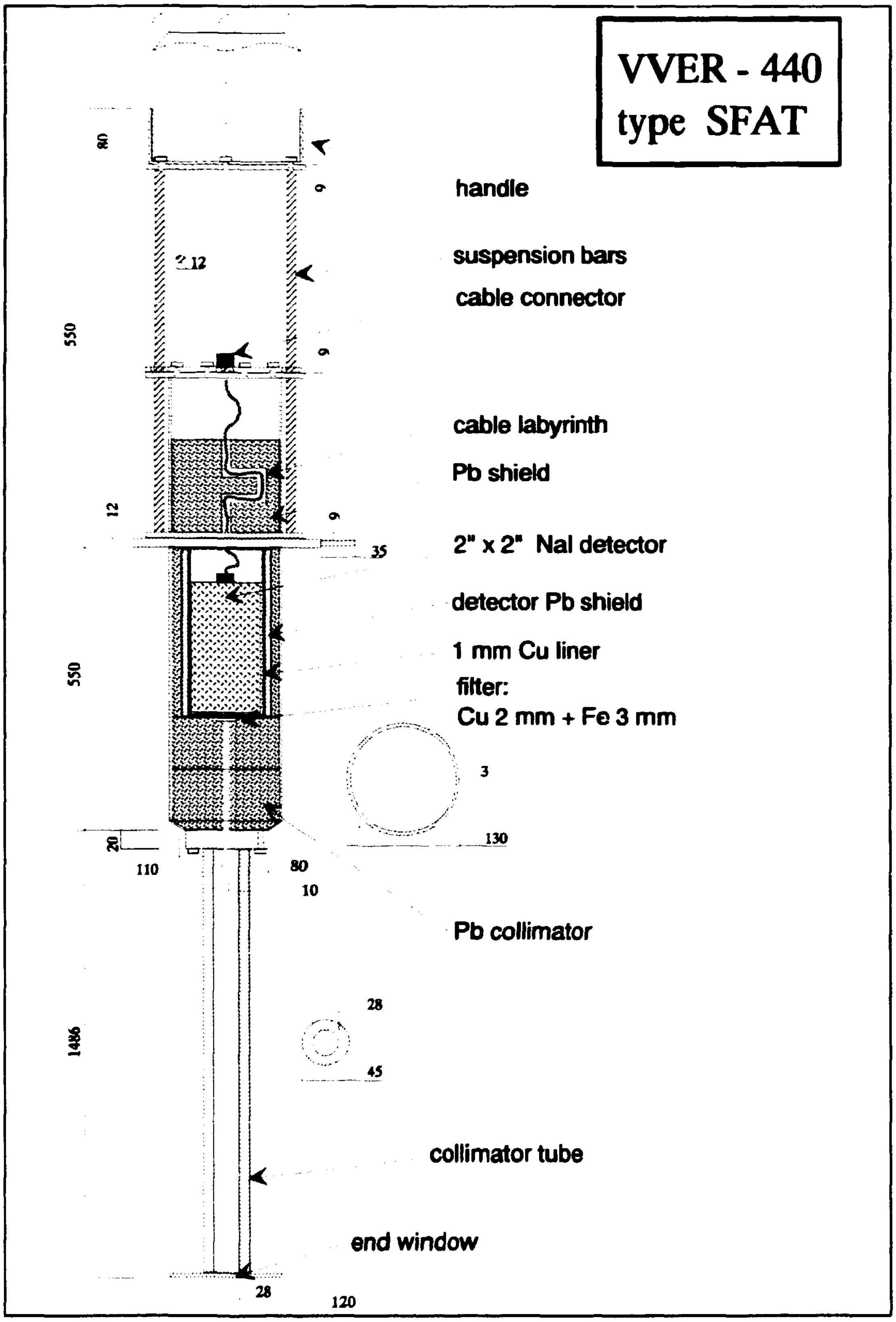


__Figure 2.__ The mechanical structure of the VVER-440 type SFAT. Marked lengths are in millimetres. Lead shielding and geometry of the collimators are also shown.

blocks, which can be chosen depending on the size of the detector used. Lead inserts with changeable collimator apertures are at the bottom of the housing. Steel filters with various thickness can be used. The lowermost part is an air filled collimator tube with an inner diameter of 28 mm and wall thickness of 8 mm for minimising scattering effects.

The detector housing is covered by a 1 mm copper liner. The cylindrical lead collimator has total length of 200 mm and an aperture of 10 mm. In addition to the 2 mm copper filter, iron filter with of thickness of 3 mm was used during measurements.

The maximum total weight of the device is about 150 kg. The heavy weight reduces the swinging of the device in water during scanning. Those parts of the device in contact with water are made of stainless steel, which allows easy decontamination.

Standard measurement electronics was used. It consisted of a Harshaw 2" x 2" NaI(Tl) detector, Ortec 459 bias supply (+500 V), Tennelec TC244 amplifier, Canberra 8077 fast ADC all in a Canberra model 1000 portable NIM-BIN power supply (7018). The Canberra S100 add-on MCA-card in a IBM PS/2 model P70 PC was used for data storing and analysis.

2.3 Measurements

The normal SFAT measurement techniques was used. This includes detection of the fission product gamma rays from above the assemblies. The detector is kept inside a water tight housing connected to an air filled collimator pipe to eliminate radiation emitted from neighbouring assemblies in the storage rack.

A top piece of a real VVER-440 type assembly was attached to the top of the SFAT allowing easy and safe connection to the grip of the fuel handling machine. Operator moved the SFAT under water in a way similar to moving fuel assemblies. After moving the device to the storage pool the vertical height of this test device was adjusted using the top of the storage rack as a reference. A photograph of the SFAT during real measuring situation is shown in Fig. 3.

After positioning the SFAT above the assembly to be verified, the measurement was started and spectrum was stored into the memory of the MCA. Detection of the presence of the ^{137}Cs gamma line at the energy of 662 keV was used for verification. For experienced user the shape of the spectrum, i.e. the presence of different gamma lines, indicates other parameters like burnup and cooling time. The activity of different isotopes and their isotopic ratios can also be used for semi-quantitative verification purposes.

In total 32 test measurements were performed in one day including installation and non-standard movements for research purposes. The sensitivity of the method both in horizontal and vertical direction was studied.

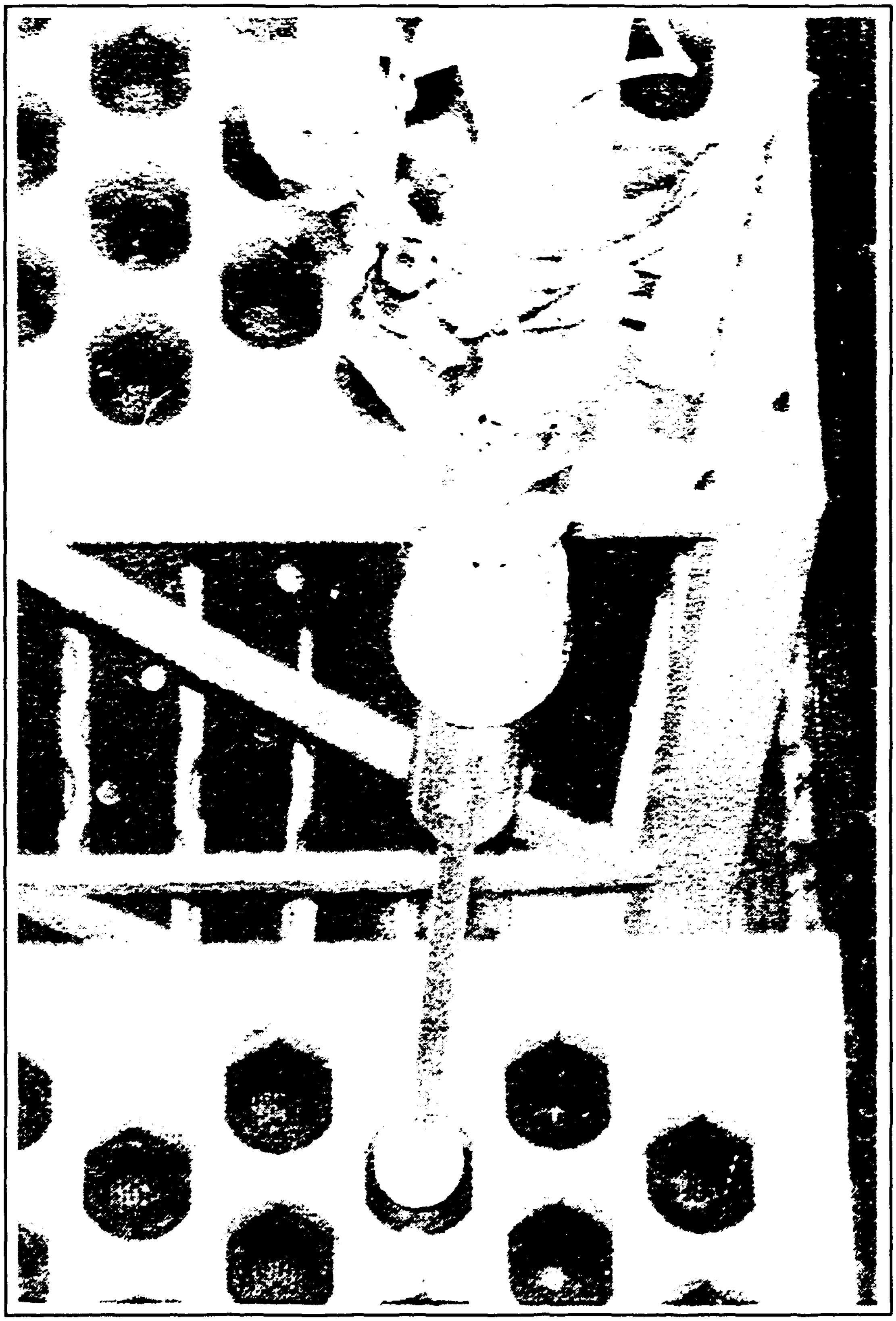


Figure 3. The photograph of the VVER-440 SFAT during real measuring situation under water in the intermediate storage pool of the Loviisa npp.

3 ANALYSIS OF SPECTRA

The analysis of the SFAT spectra has been concentrated on the ^{137}Cs signal due to its great importance for the verification of long-term stored fuel assemblies. There are two basic features in the measured SFAT spectra, which make analysing difficult. Because of the simple peak analysis procedures of standard MCA programs, they are not suitable to analyse the wide peaks measured by a NaI scintillation detector under water. Another feature in the spectra, which makes the fitting complicated, is the high background radiation caused by the photons scattered from the irradiated metal structures around the assemblies and photons scattered from the water of the storage pool. Four typical SFAT spectra measured from different kinds of VVER-440 fuel assemblies are shown in Fig 4.

For proper evaluation of the results, the measured SFAT spectra were analysed also by using special peak fitting programs.

Cs137av-code

The ^{137}Cs peak analysis of the gamma spectra was made by using a Cs137av computer program, which is a special software tailored to determine the activity of ^{137}Cs in spent fuel NaI spectra. The program has been developed for IAEA at the St. Petersburg Institute of Nuclear Physics (Gatchina, Russia).

The Cs137av calculates the number of counts in the ^{137}Cs peak and an error, which is two times the standard deviation (2*σ). A Gaussian curve (normal distribution) is fitted to a measured ^{137}Cs peak and a second order polynom is used for the background.

SigmaPlot and MATLAB

Also the comparable calculation were made by using two different types of commercial numeric computation software package, SigmaPlot for Windows /5/ and MATLAB /6/. With both of these programs it is possible to fit the given function into the experimental data points. Fitted function in both programs was same as in the Cs137av code; a second order polynom for the background radiation and Gaussian curve for to the ^{137}Cs peak.

The form of the fitted function is

$$y = A + B * x + C * x^2 + a_n * \exp\left(-\frac{(x - c_n)^2}{2 * w^2}\right) \qquad (1)$$

where
y = number of the counts in channel x
x = channel number
A , B and C are parameters for the background
a_n = amplitude of the peak
c_n = midpoint of the peak
w = width of the peak(s) (≈ FWHM/2.35)
n = number of the fitted peaks (n = 1..4)

In SigmaPlot, least-square method is used for fitting. Fitting procedure with SigmaPlot is described more precisely in reference /3/. In MATLAB, fitting is done with the Nelder-Mead algorithm, which minimises a non-linear function of several variables. Nelder-Mead algorithm is so-called approximate method, which gives no error estimations of the fitted variables.

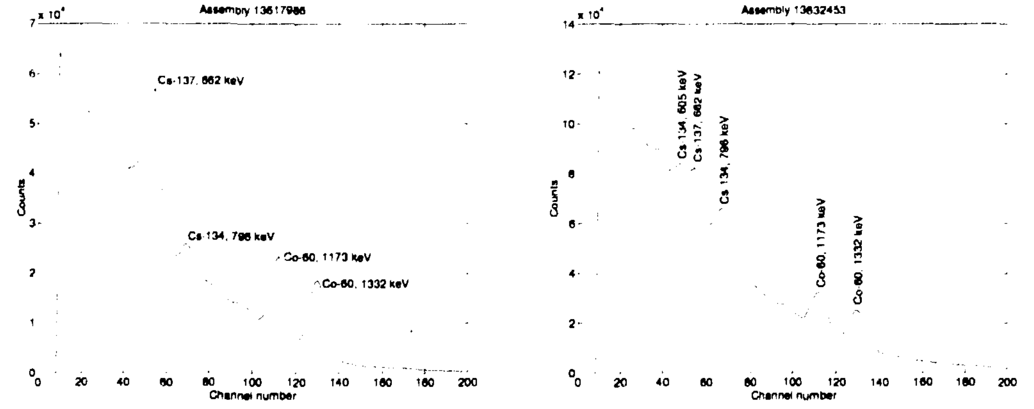
The ^{137}Cs activity (count rate) used in this report is defined by the ^{137}Cs peak area divided by the actual live time. Three different kinds of analysis were made from the measured gamma spectra. The horizontal and the vertical performance of the SFAT in addition to the burnup dependence of the measured Cs-signal was studied.

3.1 Horizontal scan over two assemblies

The ^{137}Cs photopeak activity versus a horizontal scanning position between two hot fuel assemblies was determined. Nine different measuring positions were used, so that the gap between the assemblies could be measured. The live time for the detector in each position was 60 seconds. The burnup of the first assembly, where scan was started, was 31.5 MWd/kgU and it was 39.8 MWd/kgU for the second assembly where the scan ended, respectively. The cooling time for both was 3.2 years and the initial enrichment 3.6 %. The behaviour of the ^{137}Cs peak activity versus horizontal position during the scan is presented in Fig 5.

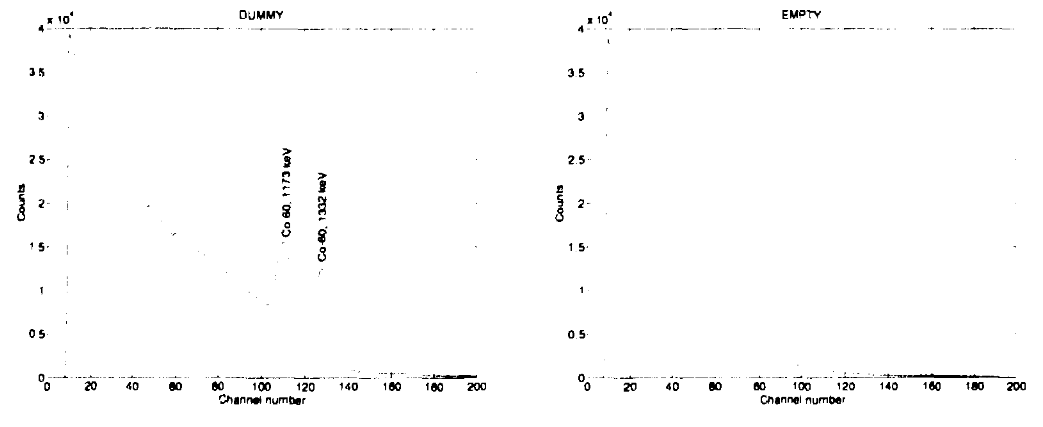
3.2 Vertical scan above an assembly

To test the sensitivity of the SFAT versus its vertical position, a scan above a fuel assembly over the interval 0...200 mm was performed. The ^{137}Cs peak activity versus the scanning height was determined. The assembly (13617986, initial enrichment 3.6 %) had a burnup of 38.9 MWd/kgU and its cooling time was 5.3 years. In each height, live time for the detector was 100 seconds. The results are shown in Fig 6.



a) VVER-440 assembly with burnup 38.9 MWd/kgU and cooling time 5.33 years

b) VVER-440 assembly with burnup 35.7 MWd/kgU and cooling time 1.29 years



c) dummy assembly

d) empty storage position

Figure 4. *Spectra measured at the Loviisa npp using VVER-440 SFAT. Measuring time for spectra a) - c) is 200 seconds (LT) and 100 seconds for spectrum d), respectively.*

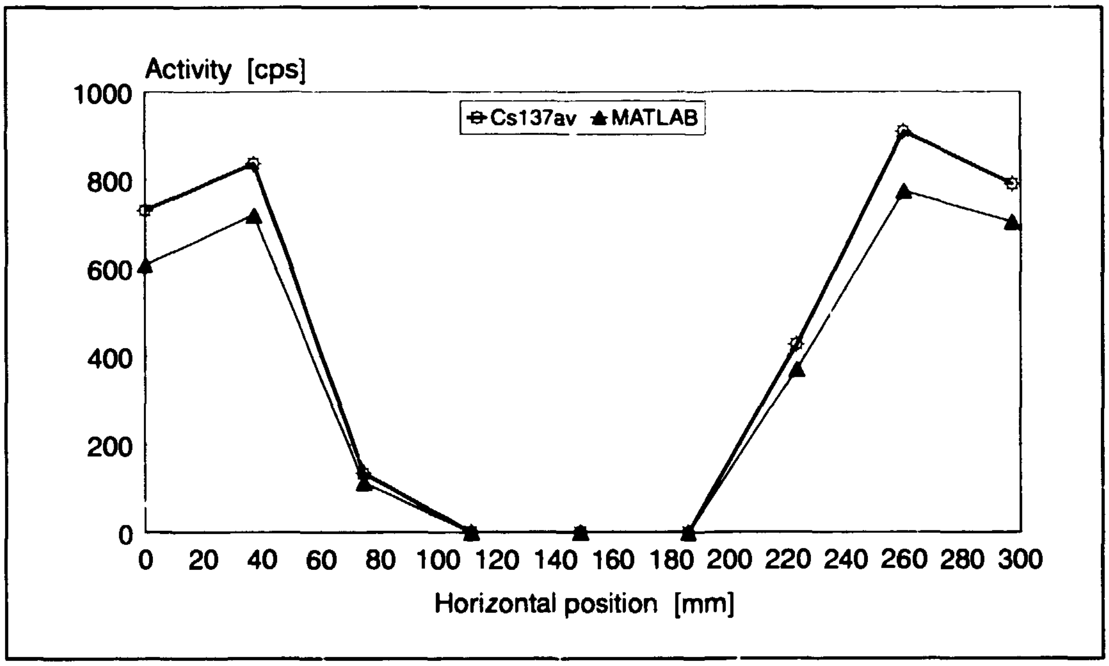


Figure 5. *The behaviour of the ^{137}Cs peak activity versus horizontal position during the scan over two fuel assemblies. Burnup of the left assembly is 31.5 MWd/kgU and 39.8 MWd/kgU for a right assembly, respectively.*

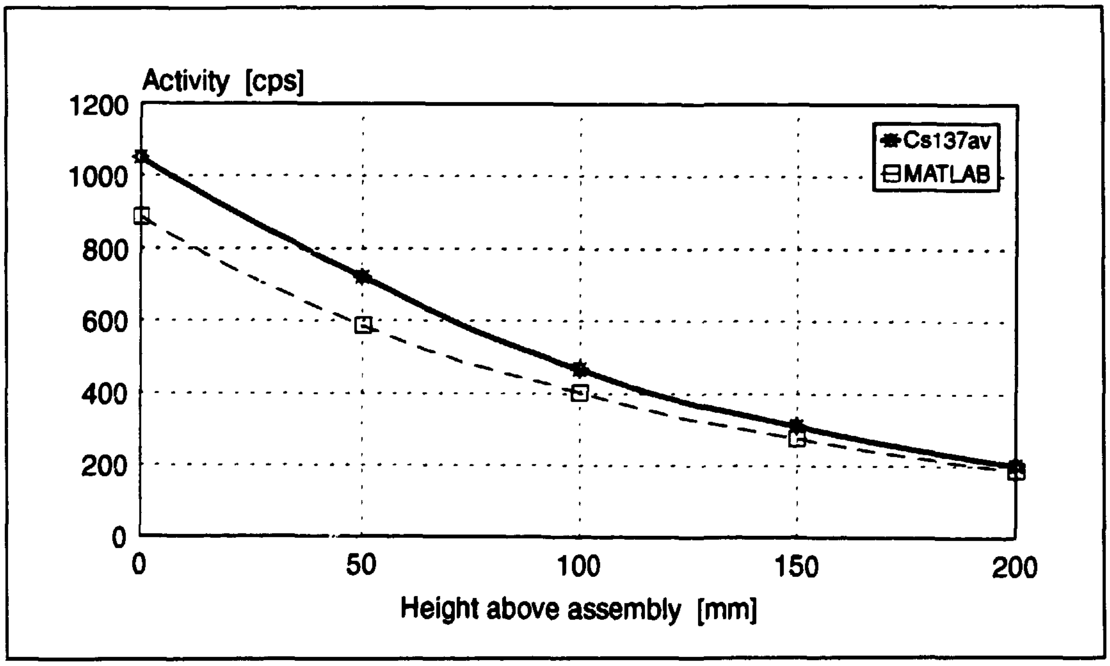


Figure 6. *The behaviour of the ^{137}Cs peak activity versus vertical position during the scan above an assembly. Assembly had a burnup of 38.9 MWd/kgU and its cooling time was 5.3 years.*

Table II. *^{137}Cs peak areas of four assemblies calculated with three different programs*

Assembly ID	Burnup [MWd/kgU]	CT [a]	LT [sec]	Cs137av Cs peak area [counts ± 2]	Sigmaplot Cs peak area [counts ±]	MATLAB Cs peak area [counts]
13628285	23.1	3.3	100	46395 ± 1636	34202 ± 2138	36020
13614727	29.2	5.33	200	154069 ± 2893	116800 ± 5571	119288
13632453	35.7	1.29	200	56896 ± 4847	150960 ± 6401	138336
13617986	38.9	5.33	200	209872 ± 3096	170690 ± 6281	168567

3.3 The ^{137}Cs activity versus burnup

The ^{137}Cs activity was determined for four assemblies with different burnups. The enrichment of each assembly was 3.6 %. The peak area was calculated with the program Cs137av, with the SigmaPlot program and the MATLAB to compare the results. Activities have been normalised to the moment of reactor shutdown. The calculated peak areas are shown in Table II and the determined activities in Fig 7.

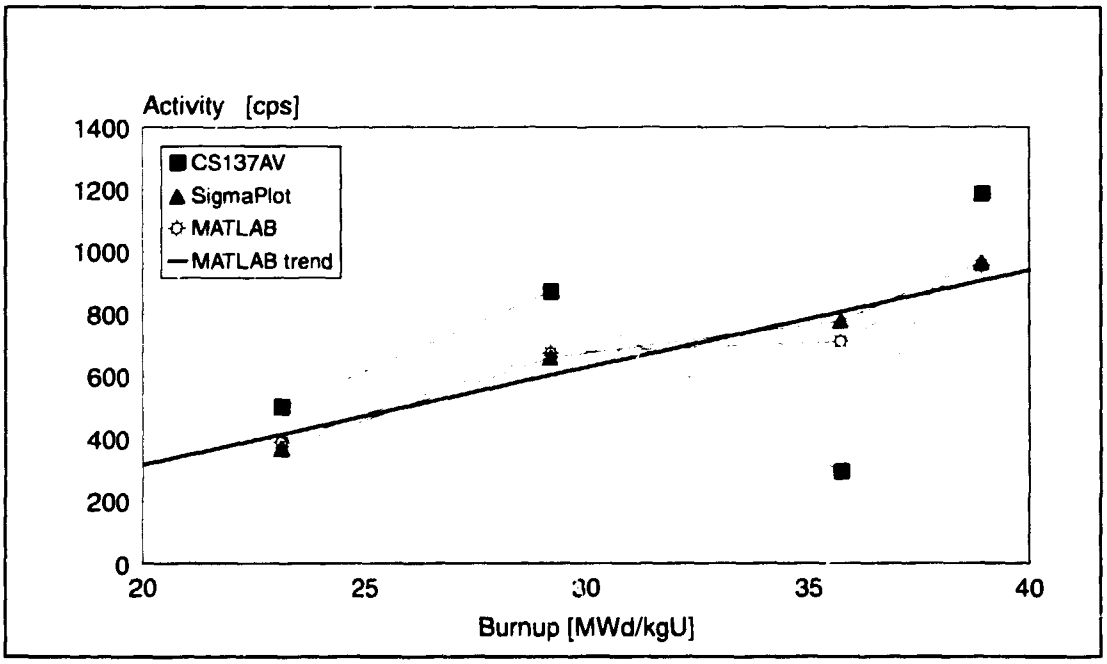


Figure 7. *The behaviour of the ^{137}Cs activity versus burnup of the assembly. Activities have been calculated with three different programs; Cs137av, SigmaPlot and MATLAB.*

4 RESULTS

4.1 Horizontal scan

The effect of the burnup of the assemblies is shown in Fig 5. The burnup for the assembly on the right is about 20 % higher than the burnup of the left assembly and this can be seen from the figure. Also the gap between the assemblies is distinct with the width approx. 50 mm. There is no detectable ^{137}Cs signal in a scanning positions 110, 150 and 185 mm. Also the ^{60}Co signal disappears in the middle of adjacent assemblies (in a position 150 mm). In a positions 110 mm and 185 mm are both gamma lines of ^{60}Co still weakly visible. The ^{137}Cs peak area has also been calculated by the MATLAB program. The results yielded by MATLAB seem to be systematically lower than the results calculated with the program Cs137av. The possible reason for this is suggested in chapter 4.3

4.2 Vertical scan

The results from the vertical scan (figure 6) show an exponential decrement of the ^{137}Cs activity when measuring height is increased. There is nothing odd in these results because they should behave in this way. Peaks of ^{60}Co are clearly visible in the all measured spectra. Because the start position of measurements (height 0 mm) is on top of the fuel storage rack, the actual distance to the beginning of the fuel pellets in this position is 368 mm (see Fig. 1). Once more the results yielded by MATLAB are systematically lower than the results calculated with the Cs137av.

4.3 ^{137}Cs peak activity vs. burnup

The measured ^{137}Cs peak activity as a function of the assembly burnup is presented in Fig 7 using three different analysing codes. If the activity calculations have been made properly, there exists a linear dependence between the activity of ^{137}Cs and the burnup of the spent fuel. In other words, from the calculated activity of ^{137}Cs, the burnup of the assembly can be determined quite precisely. From the burnup, one can get estimate about the amount of the plutonium in the spent fuel assembly.

Figure 7 shows that there is something curious in the results of the assembly with the burnup 35.7 MWd/kgU. To understand the results of peak analysis, separate gamma spectra have to be studied in more detail. The measured spectra and the curves fitted with Cs137av, with SigmaPlot and with MATLAB with the four different burnups are presented in figures 8 - 11. In these figures the spectrum a) is calculated with the code Cs137av, the spectrum b) is calculated with the SigmaPlot and the spectrum c) calculated with the MATLAB.

The cooling time has a particular influence to the measured gamma spectra. If the cooling time of the assembly is short, several ^{134}Cs peaks are also visible in the measured spectra. The half-life of a ^{134}Cs is 2.06 years. The main gamma ray energies and their intensity values, which give the abudance of gamma photons (photons per 100 decays), are shown in table III.

Table III. *Main gamma lines of ^{134}Cs /7/.*

Energy [keV]	Intensity
563.3	8.4
569.3	15.4
604.7	97.6
795.8	85.4
801.8	8.7

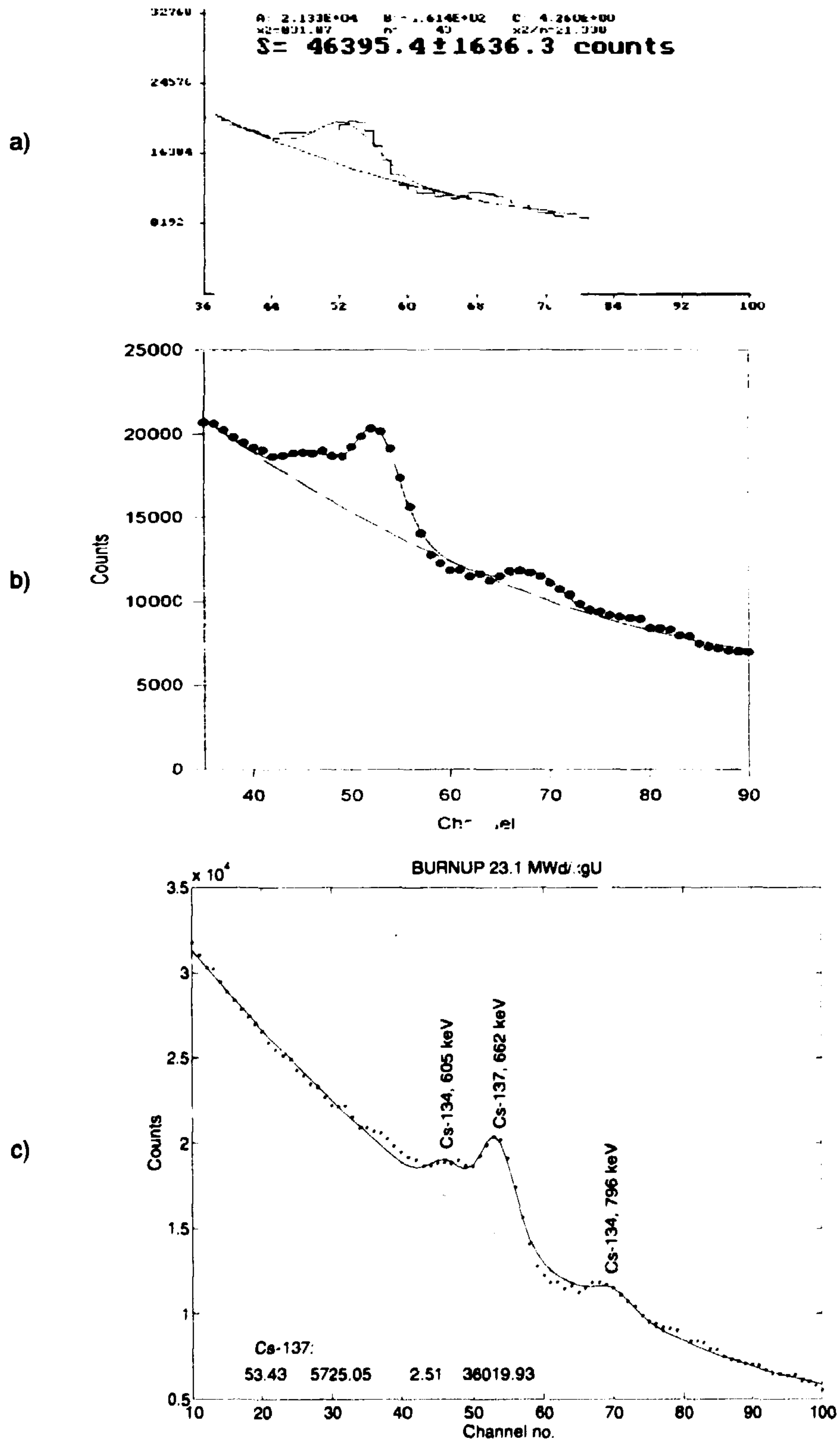


Figure 8. *The measured spectra and the curves fitted with Cs137av (a) and with SigmaPlot (b) at the energy interval 500 keV - 1000 keV. Curve c) fitted with MATLAB shows the energy interval 280 keV - 1180 keV. Burnup of the assembly (no. 13628285) is 23.1 MWd/kgU and its cooling time is 3.3 years.*

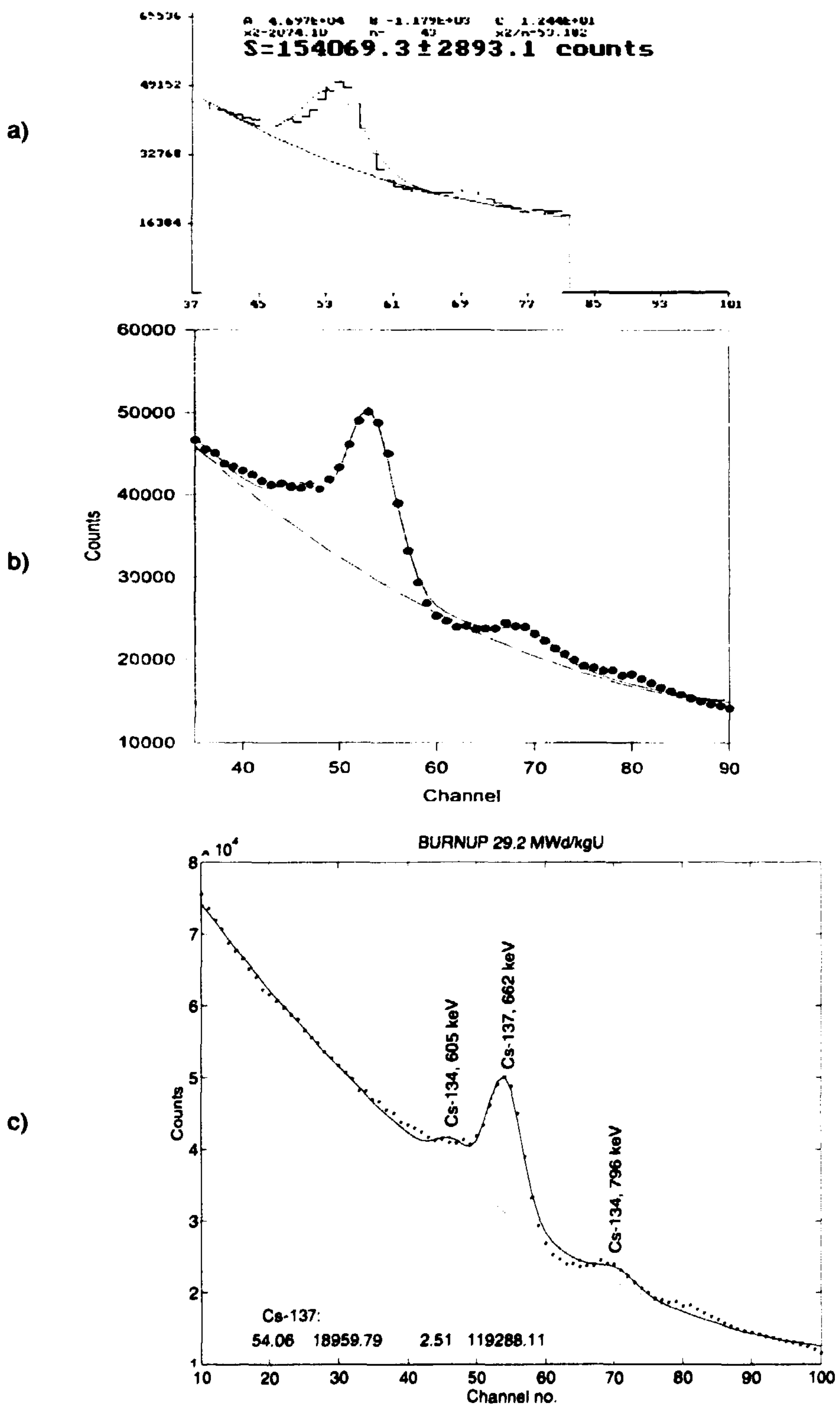


***Figure 9.** The measured spectra and the curves fitted with Cs137av (a) and with SigmaPlot (b) at the energy interval 500 keV - 1000 keV. Curve c) fitted with MATLAB shows the energy interval 280 keV - 1180 keV. Burnup of the assembly (no. 13614727) is 29.2 MWd/kgU and its cooling time is 5.33 years.*

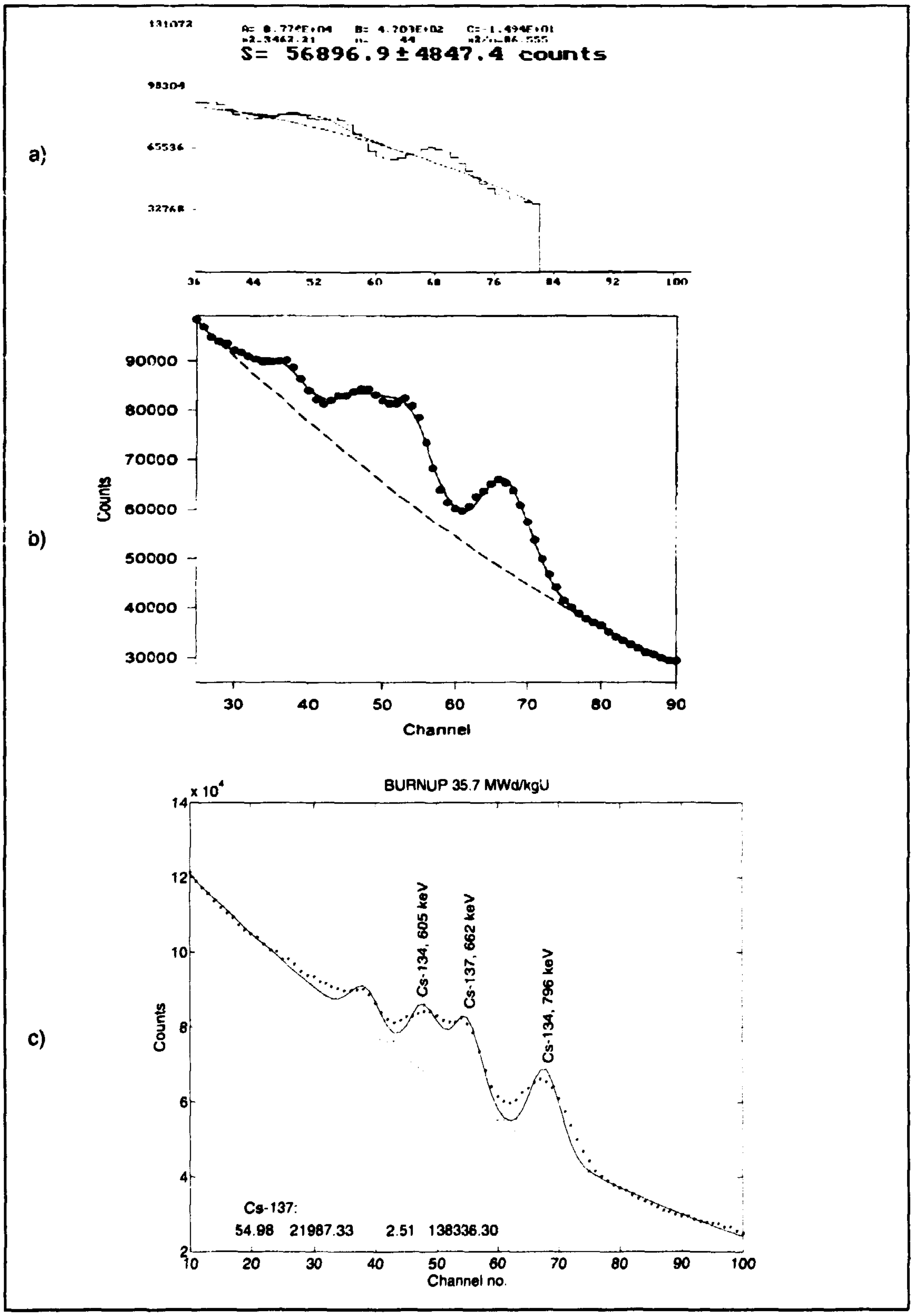


Figure 10. *The measured spectra and the curves fitted with Cs137av (a) at the energy interval 500 - 1000 keV, with Sigmaplot (b) at the energy interval 410 - 1000 keV and with MATLAB (c) at the energy interval 280 keV- 1080 keV. Burnup of the assembly no. 13632453 is 35.7 MWd/kgU and its cooling time is 1.29 years.*

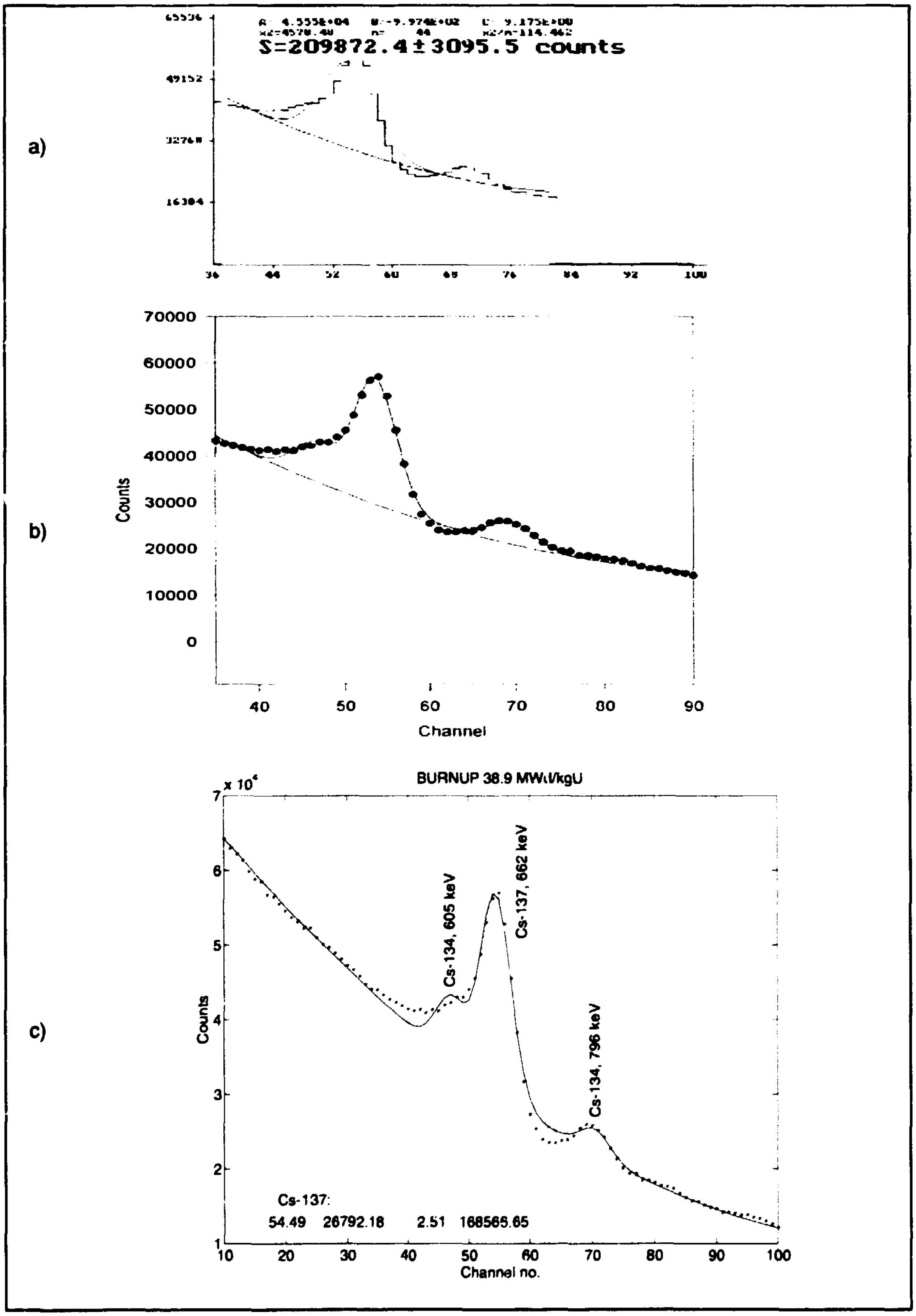


Figure 11. *The measured spectra and the curves fitted with Cs137av (a) and with SigmaPlot (b) at the energy interval 500 keV- 1000 keV. Curve c) fitted with MATLAB shows the energy interval 280 keV - 1180 keV. Burnup of the assembly no. 13617986 is 38.9 MWd/kgU and its cooling time is 5.33 years.*

Two of these peaks, 604.7 keV and 795.8 keV, can be seen very clearly from the spectra of the assembly no. 13632453 (figure 10). The burnup for this assembly is 35.7 MWd/kgU and the cooling time is 1.29 years. Because the Cs137av program fits a curve of only one gamma line to the measured points in the interval 500 keV...900 keV (2*FWHM...662 keV...3*FWHM), ^{134}Cs causes remarkable errors to the fitted ^{137}Cs peak. The unknown peak of 520 keV and the 604.7 keV and the 795.8 keV peaks of ^{134}Cs cause twisting of the background in the wrong way (fig. 10a), when the Cs137av code is used.

The inclusion of the peaks of ^{134}Cs improves the fit significantly. This has been done in the figures 10b and 10c, where four different Gaussian peaks are fitted to the measured spectra. In figure 10b fitting has been done with the program SigmaPlot to the channel interval 25...90 (10...1000 keV) and in figure 10c with the program MATLAB to the channel interval 10...100 (280...1080 keV).

MATLAB fits can be regarded as reference results, to which the other fittings should be compared. There are two reason for this; 1. the interval of fitting is widest with MATLAB, i.e. one can see that fitted background follows best the measured background. 2. Width of the peaks fitted with MATLAB has been fixed to 2.51 channels. The fixed value was received from a ^{137}Cs calibration source measurement. MATLAB cannot, however, be considered as a general method for inspection use due to the complexity of the fitting procedure itself.

In general, the peak areas calculated with the Cs137av program seems to be systematically larger than the areas produced by SigmaPlot and MATLAB (see figure 5, figure 6 and figure 7, excluding the burnup 35.7 MWd/kgU). This may be a consequence of the width of the ^{137}Cs peak, which, compared to the SigmaPlot and MATLAB fitting, is too wide. This can be seen also in the spectra of figures 8, 9 and 11. SigmaPlot and MATLAB fittings in figures 8, 9 and 11, where three different Gaussian peaks are fitted to the spectra, appear to be quite precise. Width of the ^{137}Cs peak (FWHM) in the Cs137av program is a fixed parameter and it is obtained from the peak of the ^{60}Co (1332 keV). This cannot be an accurate method since the resolution of the detector is a function of the photon energy. A FWHM of the used Harshaw detector (2" x 2" NaI) is 56.8 keV for 662 keV peak of ^{137}Cs and 64.7 keV for 1332 keV peak of ^{60}Co, i.e. the resolution is about 14 % worse in the point of 1332 keV than it is in the point of 662 keV. So, this might be the reason why the areas calculated with the Cs137av program are systematically bigger than the areas calculated with the other programs.

4.4 Detection limits

It is considered that the SFAT method can be used for verification of spent VVER-440 fuel assemblies as long as the assemblies are kept in interim storage before final deposition or reprocessing. This means that cooling times of the order at about 100 years do not limit the feasibility of the method for normal assemblies. It was found out, however, that there was no detectable ^{137}Cs signal from the fuel follower assembly (no. 22421318) at any used live time (100 - 600 seconds). Steel pivots (length 120 mm, figure 1), which are extension pieces of the fuel pellets in the top of the fuel rods, prevent effectively the emission of direct gamma radiation but they form ^{60}Co source instead. Both gamma lines of the ^{60}Co are clearly visible in the spectra of the assembly 22421318.

5 CONCLUSIONS

The VVER-440 SFAT design making use of the operator experience in moving assemblies allows safe and fast mode of verification of VVER-440 type assemblies. In normal cases measurement time of only 10 to 30 sec is needed for unambiguous verification of the presence of spent fuel.

The resolution of the NaI detector used in the VVER-440 SFAT is good enough to allow the use of 662 keV gamma lines of ^{137}Cs for the verification of the spent fuel. From the figure 5 one can see a strong dependence of the count rate of ^{137}Cs signal on the horizontal position of the SFAT during a scan. The ^{137}Cs signal vanishes totally above the gap which means that SFAT can distinguish adjacent assemblies very well. It can also be used for consistency check purposes by telling the difference between the burnup and cooling time of the assemblies next to each other.

Since the relative efficiency of the NaI detector is very good, this causes many benefits;

1. Short measurement time is needed
2. There are no strict limits for the vertical position of the SFAT so the measurement does not need to be made right above an assembly kept in the fuel storage rack.
3. Sensitivity for the low intensity radiation means also that the assemblies with long cooling times can be verified without problem.

The cooling time for all measured fuel assemblies was under 5.5 years. Because of that there exist still some ^{134}Cs activity in the all measured spectra. The 605 keV peak of ^{134}Cs makes the fitting somewhat complicated. One must fit two peaks to the energy region 550-700 keV in order to calculate the number of counts in the ^{137}Cs peak correctly. Also the other existing peaks in the spectrum have an influence to the background fitting.

These kinds of problems do not occur when the cooling time of the fuel assembly is longer.

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