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Final report on the joint Task JNT61
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Support Programmes to IAEA Safeguards

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ABSTRACT

In 1989 the Support Programmes of Finland (FSP) and Sweden (SSP) initiated a joint task to cross calibrate the burnup of the IAEA spent BWR reference fuel assembly at the TVO AFR storage facility (TVO KPA-STORE) in Finland. The reference assembly, kept separately under the IAEA seal, is used for verification measurements of spent fuel by the GBUV method (SG-NDA-38). The cross calibration was performed by establishing a calibration curve, ^{244}Cm neutron rate versus burnup, using passive neutron assay (PNA) measurements. The declared burnup of the reference assembly was compared with the burnup value deduced from the calibration curve. A calibration line was also established by using the GBUV method with the aid of high resolution gamma ray spectrometry (HRGS). Normalization between the two different facilities was performed using sealed neutron and gamma calibration sources. The results of the passive neutron assay show consistency, better than 1 %, between the declared mean burnup of the reference assembly and the burnup deduced from the calibration curve. The corresponding consistency for the HRGS measurements is within ± 2 %. A summary of the main results has been presented before /1/. This report compiles all the measurement data and results of this task.

PREFACE

This is the final report to the joint task no. JNT61 of the Support Programmes of Finland and Sweden to the IAEA safeguards. This task, called Calibration of a BWR Reference Spent Fuel Assembly, was carried out as three partite cooperation between the two support programmes and the IAEA.

Anders Bäcklin and Ane Håkansson from the University of Uppsala, Sweden, have been responsible for the gamma spectrometric measurements of the calibration. Matti Tarvainen from STUK, Finland, working in the IAEA Department of Safeguards till 31.1.1991, has been responsible for the passive neutron assay measurements as well as for the overall coordination of the task.

The authors are thankful to the many people who took part in the measurements and helped in many ways during this task. They are Tencho Dragnev, Vladimir Fotin and Mark Harris from the IAEA, Annette Axelsson, Per Grahn and Lars-Åke Gustafsson from CLAB, Helmuth Zika and Lars Hildingsson from SKI, Käthe Sarparanta, Aarne Kaakinen and Juha Vastamäki from TVO and Arja Tamminen, Erja Kainulainen and Heimo Takala from STUK. Martti Hannikainen from the University of Helsinki, Department of Radiochemistry, performed the transmission tests of the TVO gamma collimator.

CONTENTS

1 INTRODUCTION

Verification of the fissile contents of spent nuclear fuel is the ultimate goal of the verification activities performed by authorities for spent LWR fuel. The parameter normally verified in the practical work is, however, the mean burnup.

It is impossible to verify both these parameters by direct passive ways. The fissile contents cannot be measured directly because the plutonium and uranium gamma activities to be measured are both low in intensity in comparison with the dominating gamma radiation of the fission products. Direct information of the burnup i.e. the energy released per unit mass of uranium, is available only during the irradiation of the fuel in the reactor core. Any method used afterwards to verify the energy release is based on indirect parameters.

The problem description of the task JNT61 makes a general statement that the IAEA needs a reliable NDA method for quantitative or at least semi-quantitative measurements of spent fuel. A method called GBUV (SG-NDA-38) /2/, Burnup Verification of Spent Fuel, is a step towards this goal. GBUV makes use of the passive gamma emission of fission products, mainly ^{137}Cs, and correlates it linearly with the burnup. GBUV also makes use of a separately sealed reference fuel assembly that can be measured by the Agency to normalize the measured data of different measurement campaigns. The reference assembly is also used for authentication of the GBUV method i.e. to obtain assurance of the correct functioning and absence of tampering of the measurement system.

Quantitative verification methods need to be calibrated. Direct and independent comparison of the declared parameters of irradiated fuel assemblies is impossible in practice. This is why the cross calibration of the reference assembly using PNA and HRGS was considered by the IAEA to be a method to increase the verification level of the GBUV.

The cross calibration calls for fuel assemblies of identical design. This is why the TVO reference assembly was decided to be cross calibrated using BWR fuel of the same design in an other country, i.e. the spent fuel of the AFR storage CLAB in Sweden. Both PNA and HRGS measurements (GBUV) can easily be performed at these facilities.

Under the task JNT61 three separate measurement campaigns took place. A pre-test was arranged at CLAB for testing the hardware and measurement methods 1. - 4.10.1990. The actual measurements were performed at CLAB 5. - 9.11.1990. After transporting the measurement equipment to Finland, the measurements at the TVO KPA-STORE took place 9. - 15.1.1991.

2 FUEL DATA

2.1 Reference assembly

The spent BWR reference fuel assembly of the TVO KPA-STORE is made by ABB-Atom, Sweden. This type of assembly /4/ has 63 fuel rods and one water filled inner rod arranged in a square pattern of 8x8. The outside diameter of the rods (fuel pellets) is about 12.2 mm (10.5 mm) or 11.7 mm (10.0 mm) depending on the position of the rod inside the assembly. The rods are assembled in a bundle by means of top and bottom tie plates and six evenly distributed spacer grids. The active fuel length is 3680 mm.

While each fuel rod in an assembly contains pellets of one initial enrichment, the complete assembly is put together of rods of typically five different enrichments. This implies a mean initial enrichment between 1.1 and 3.8 % of ^{235}U. Some inner rods have pellets including burnable Gd_2O_3 neutron poison mixed with normal pellets. The reference assembly which is mounted inside a standard ABB-Atom zircalloy fuel channel has a mean initial enrichment of 2.748 % of ^{235}U.

The reference assembly has been irradiated at TVO I during four successive cycles starting in June 1980 and ending in June 1984. This gives a cooling time during the calibration measurements at TVO of about 6.5 years.

For analysis purposes the core is divided into 25 vertical zones called nodes. For an assembly the nodewise burnup calculations of the operator are stated to have an accuracy of ± 5 %. The operator declared mean burnup of an assembly is stated to be calculated with an accuracy of ± 2.5 %.

2.2 Selection of assemblies

Table 1 shows the main parameters of the assemblies selected for cross calibration. The assemblies were selected according to certain criteria.

First, a requirement of neutron assay states that the initial enrichment should be as close as possible to that of the reference assembly. Assemblies with low initial enrichment need higher neutron fluence to yield the same burnup than assemblies with higher enrichment. Higher neutron fluence means higher concentration of actinides and thus higher neutron emission. If the enrichments are the same or close enough, no correction is needed for the irradiation history supposing the irradiation cycles and conditions in the core are comparable or normal.

Second, the cooling times should be longer than about 3 years. This requirement is less stringent, as soon as the lower limit is exceeded. The reason is the neutron emission. The main neutron emitter in the reference assembly is ^{244}Cm with half life of 18.1 a. The dominating neutron emitter in assemblies with short cooling times, ^{242}Cm with half life of 163 days, has already decayed. In order to verify the declared cooling time using gross gamma measurements, the selected assemblies should have cooling times below and above the reference assembly. This allows a more reliable curve fitting to the measured data.

Third, the burnup range of the selected assemblies should be large enough to allow line fitting to the HRGS data and curve fitting to the PNA data. For a reliable fit, both the minimum and the maximum burnup range should include several data points.

Fourth, regarding the PNA measurements the burnup profiles should be regular. In practice this requirement means successive irradiation cycles and no unusual interference e.g. from the control rods. Assemblies with similar irradiation conditions give more reliable results. This can, however, be compensated to a certain degree by measuring and averaging several points in the PNA measurements.

Fifth, because the reference assembly is mounted inside a fuel channel, it is preferable to measure assemblies also mounted in such a channel in order to avoid corrections. This is the case for all PNA measurements and for all but one (1405) HRGS measurements.

Table I. Characteristics of the assemblies measured at CLAB and at TVO. Measurements with the fork detector include neutron and gross gamma detection. R indicates the reference assembly.

Meas. at / No.	ID	Meas. with n = Fork g = HRGS	Irradiated at	IE (%/ ^{235}U)	BU (MWd/ kgU)	CT (days)
CLAB						
1	5711	n + g	Ringhals 1	2.745	34.89	1879
2	5769	n + g	"	2.756	32.62	1176
3	1196	n + g	"	2.644	31.17	1880
4	4922	n + g	"	2.683	32.24	1880
5	4921	n + g	"	2.685	32.24	1880
6	1179	n	"	2.642	33.68	1880
7	5808	n + g	"	2.754	35.99	1177
8	5762	n + g	"	2.746	33.19	1881
9	5717	n	"	2.747	34.59	1881
10	4855	n + g	Barsebäck 2	2.788	23.89	2766
11	4854	n + g	"	2.789	24.82	2766
12	4857	n	"	2.788	24.16	2262
13	5721	n	Ringhals 1	2.750	34.75	1883
14	4858	n	Barsebäck 2	2.787	25.44	2767
15	1405	g	Oskarshamn II	2.210	19.83	3020
TVO						
16 R	6782	n + g	TVO I	2.748	31.28	2340
17	4538	g	"	1.941	18.03	2340
18	7501	g	"	2.817	33.06	1980

3 MEASUREMENT TECHNIQUES

The cross calibration of the reference assembly is needed mainly for the GBUV method /2/ that is using gamma spectrometry for verification. It is well known that especially the low energy gamma radiation is strongly absorbed by the fuel and the contribution of the innermost rods to the measured signal is much smaller than that of the outer rods. Furthermore there may be asignificant gradient of the burnup in the horizontal plane. In verification measurements the latter effect can, however, be compensated for by measuring different corners of the assembly /3/. In this way the measured average activity can better be related to the real activity concentration of the assembly measured.

Passive neutron detection has not a strong self shielding. Based on earlier measurements with VVER-440 type LWR fuel /5/ that has a size comparable to the BWR assembly, it is estimated that the difference in the contribution of separate rods to the measured neutron signal using a fork detector is within ± 10 %.

Based on the differences in the principles of the HRGS and the PNA method, both of them were used to give independent calibration data. The PNA measurements took place in the storage hall while the HRGS measurements were performed on a floor about 7 m below the water level of the storage pond.

3.1 Fork detector measurements

The PNA equipment used by the IAEA consists of a fork detector, a set of steel pipes to hold the detector during measurements and the GRAND I electronics package. The equipment is used according to the user manual IMI #42 /6/. Figure 1 shows the detector head and the electronics unit.

3.1.1 Hardware

The standard IAEA fork detector pipe set was used. It consists of several 2.45 m and 1.25 m long sections made of stainless steel pipes and a 0.45 m long extension piece (dogleg) to be assembled to the required length using standard connecting clamps. O-rings are used to make the pipe watertight to protect the cables inside it. Figure 2 shows the overall fork detector arrangement. At CLAB, the fork detector system was attached to the railing of the pool with a mounting bracket according to Figure 2. At the TVO KPA-STORE, the pipe system was supported by a custom made support plate fixed to the operators instrument stand above the pool.

3.1.2 Detector system

The IAEA BWR fork detector has a head that can be folded 90 degrees for transportation as shown in Figure 3. The detector head was connected to the pipe section by a standard connecting clamp.

The detector housing includes four fission chambers, type Reuter Stokes RS-P6-0805-134, for neutron detection and two ion chambers, type LND IC 52113, for gross gamma detection /6/. Figure 4 shows how the detectors are positioned symmetrically inside the two prongs that surround the assembly to be measured. Two of the fission chambers are inside a Cd layer (Cd) and two of them are outside it (bare). Detectors of the same kind, i.e. the Cd wrapped fission chambers, the bare fission chambers and the ion chambers, are connected in pairs to each other in the round shaped junction box seen in Figure 4.

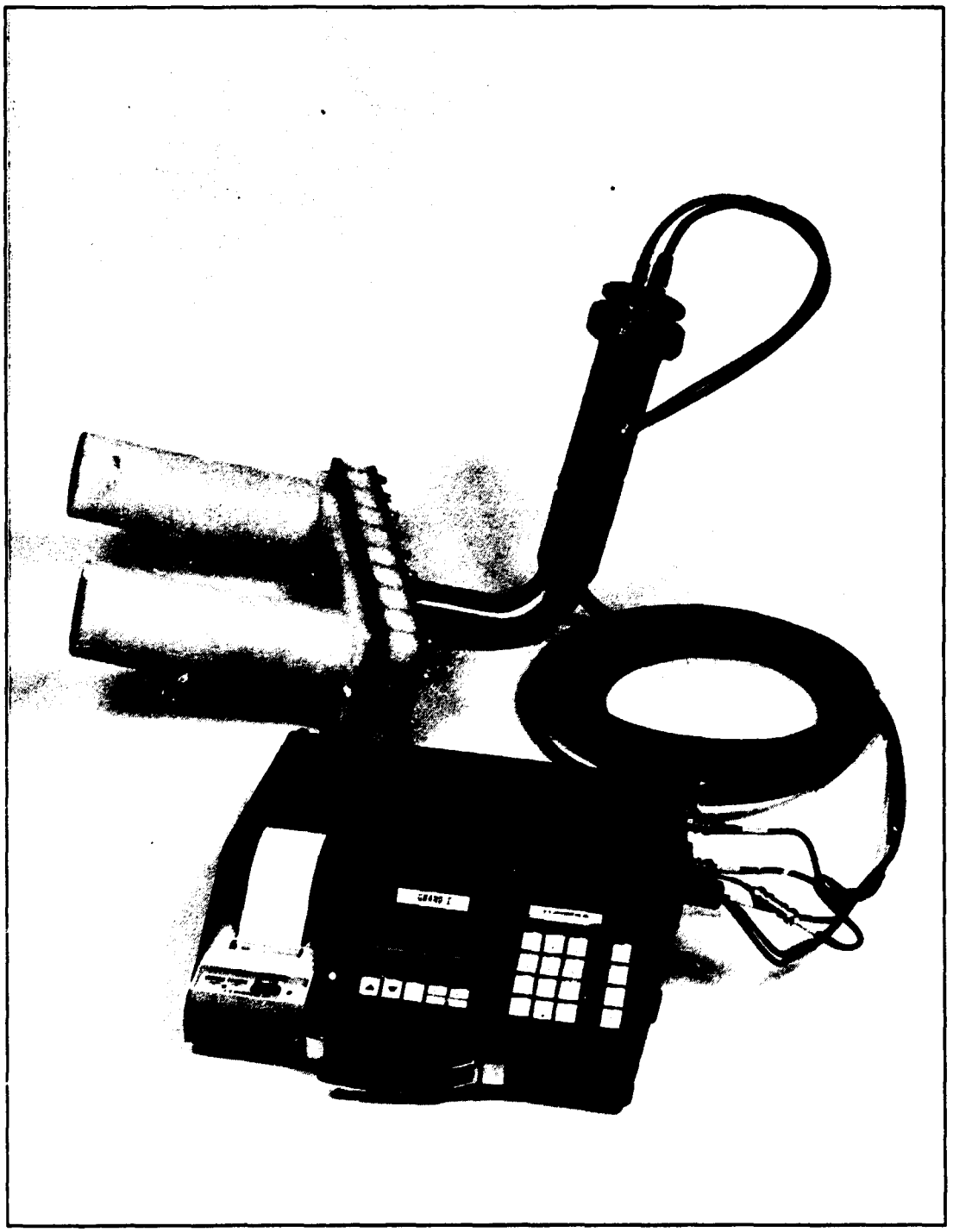

Figure 1. The new folding head BWR fork detector of the IAEA connected to the GRAND I electronics unit.

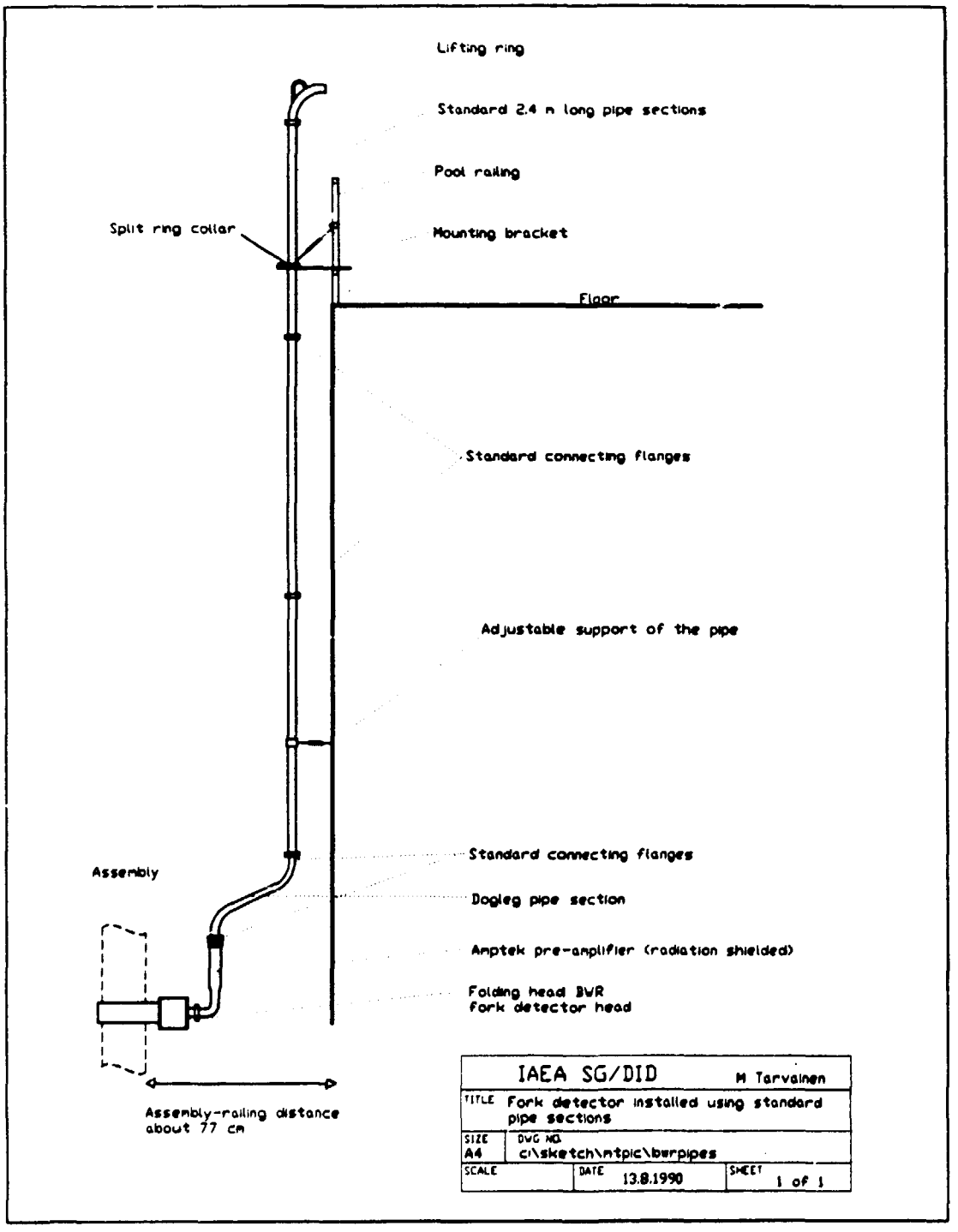

Figure 2. Schematic arrangement of the BWR fork detector system used at CLAB. The assembly was hanging from the mast of the fuel handling machine during measurements.

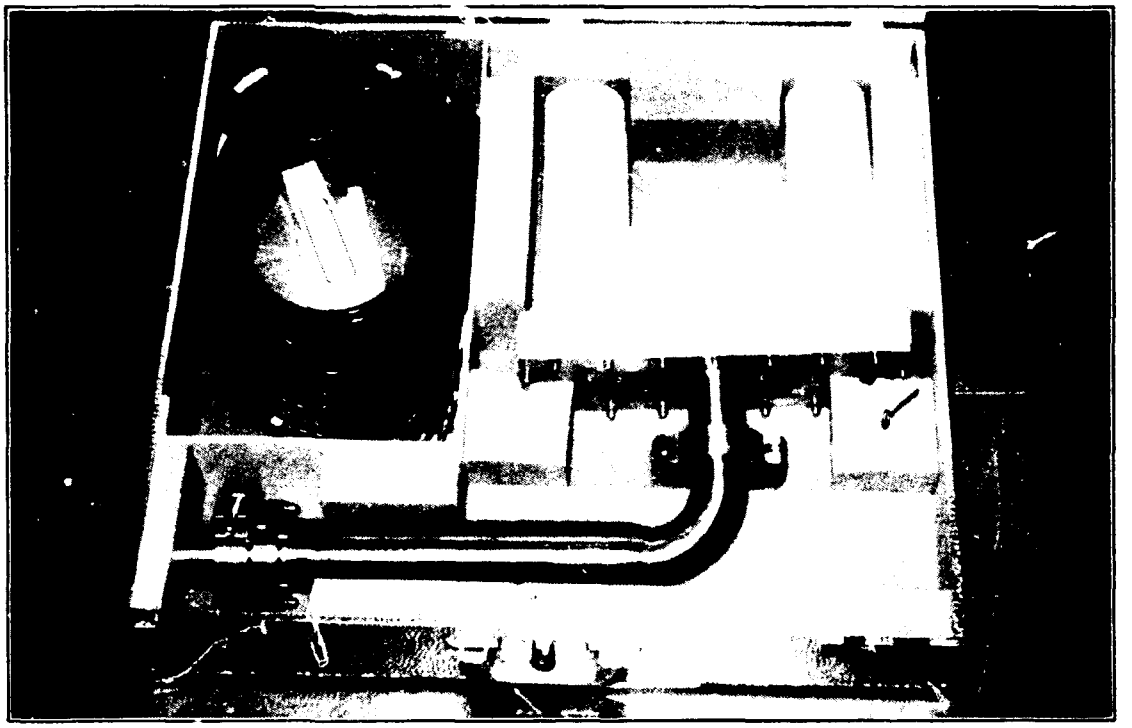

Figure 3. The new folding head BWR fork detector of the Agency in the transport case.

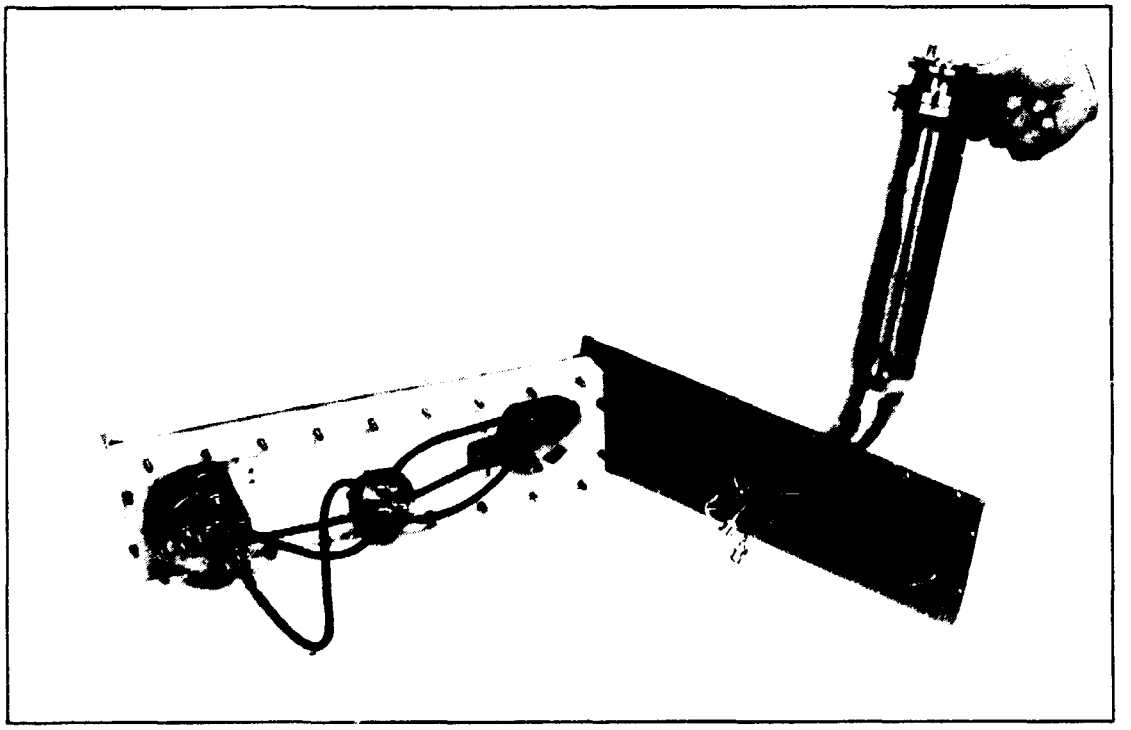

Figure 4. Inserts of the folding head BWR fork detector.

Figure 4 shows also the steel back plate with a feed through flange to be connected to the pipe section. Inside the 45 cm pipe section between the connectors of the junction box and the feed through flange there is a tungsten shielded AMPTEK A-111 hybrid charge sensitive preamplifier, discriminator and pulse shaper circuit. This circuit provides a logical signal for each neutron event exceeding the input threshold. The circuit has also an analog monitor point for checking the operation. Figure 5 shows the effect of the threshold adjustment of the AMPTEK circuit for neutron detection using a neutron source /7/.

The battery powered GRAND I is used for supplying power for the preamplifier, biasing the ionization and fission chambers and for displaying and printing the neutron rates and the ion chamber current. Further, GRAND I has the software needed to subtract the background of the chambers. The count rates for the fission chambers as well as for the gross gamma signal were manually keyed into a prefilled Symphony spreadsheet in a PC for data handling.

3.1.3 ^{252}Cf calibration source

The neutron calibration source of STUK has 2 μg of ^{252}Cf with a half life of 2.64 a. On 25 February 1985 the neutron emission rate of this spontaneous fission source was calibrated to be 4.99×10^{6} s^{-1}. The measurement time for 10 000 counts was about 200 sec. The source is doubly-encapsulated in welded cylindrical stainless steel capsules. The outer diameter is 7.8 mm and height of 10 mm. This pellet is used for spent fuel verification purposes inside a watertight cylindrical container made of stainless steel. For the cross calibration, the container was kept inside a special case made of a 35 cm long piece of standard ABB-Atom fuel channel. This case allows a repeatable geometry inside the fork detector with the source position in the mid-plane of the fork detector prongs.

The gross weight of the neutron calibration source is about 10 kg. It was kept hanging from a rope and manually lowered inside the fork detector for measurements. Figure 6 shows the ^{252}Cf calibration source in the measurement position inside the fork detector.

3.1.4 PNA and GG measurements

The vertical coordinates for the fork detector were determined by lowering a dummy assembly slowly into contact with the top of the detector. By knowing the dimensions of the fork detector and the fuel assembly, the bottom of the fuel zone was determined and fixed as the vertical zero level.

Two assemblies were measured in the middle of each odd numbered node, totalling 13 vertical points per assembly (see 3.1.7). The series of measurements was repeated after rotating the assembly 90 degrees. Based on these preliminary studies, nodes 11, 13, 15, 17, 19 and 21 in the burnup plateau were selected for the calibration measurements. The measurement time for each node varied between 15 and 150 sec depending on the burnup and the cooling time. At least 10 000 counts were collected in each of the two neutron channels (Cd wrapped and bare).

The gross gamma signal is a number proportional to the average of 16 consecutive readings of the ion chamber current, about 0.5 ms each. The measurement time is thus not critical. The counting was not started right after the assembly was brought into the fork detector. This allowed an annealing irradiation of a couple of minutes before starting the ion chamber measurements.

The ^{252}Cf source was remeasured for normalization between the CLAB and the TVO KPA-STORE as well as for controlling the proper functioning of the whole PNA measurement chain. Repeated measurements every morning and every evening made it possible to calculate the precision of the fork detector measurements. Each time two measurements were performed, one with the source positioned next to the left and the other with the source next to the right corner of the detector. Measurement time of 200 sec yielded about 10 000 neutron counts.

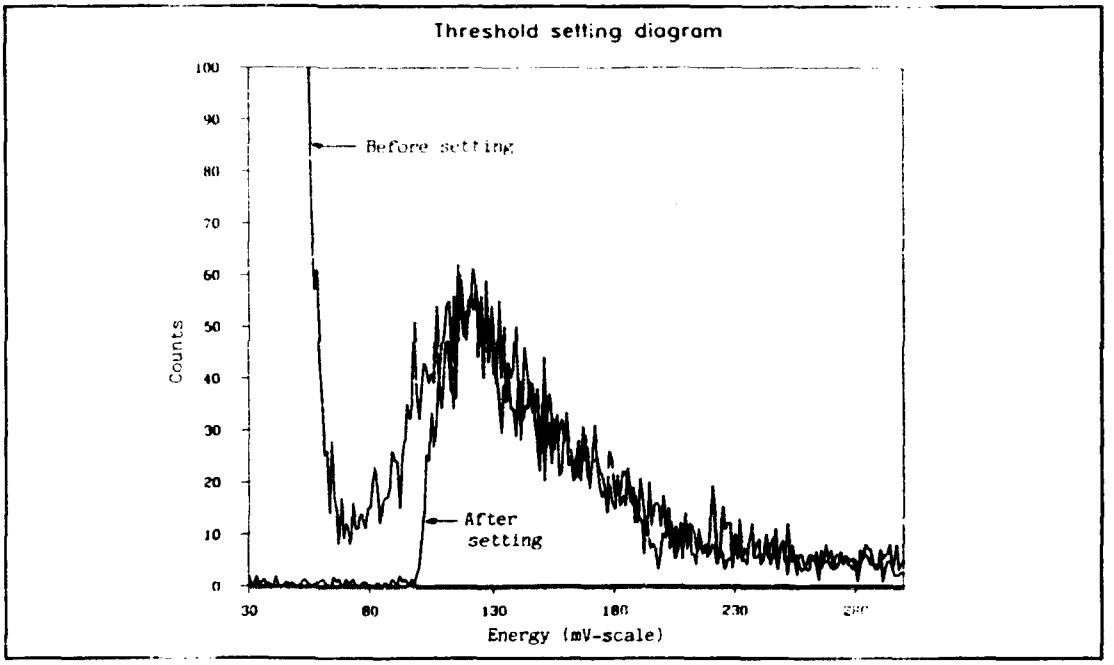

Figure 5. Energy spectrum of the fission chambers using an Am(Li) neutron source. After the neutron channel discriminator of the AMPTEK circuit is set properly, only the (high energy) neutron counts are detected.

Figure 6. The ^{252}Cf calibration source inside the fork detector at CIAB.

3.1.5 Neutron data handling

Because the measured assemblies were selected according to certain requirements (see 2.2), the data analysis could be simplified. The PNA measurement chain, from fission chambers through AMPTEK to the GRAND I, tolerates, without counting losses, count rates that are even two orders of magnitude higher than what is the case with the fuel measured. This is why no correction for counting losses was needed.

Because the cooling times are long enough (in all cases more than 3 years) and the mean burnups are relatively high (about 24 MWd/kgU or more), no correction is needed for ^{242}Cm contribution or any other neutron emitter. The behavior of actinide isotopes calculated for irradiated PWR fuel /8/ can be assumed to be applicable also for the irradiated BWR fuel.

The fuel assemblies measured at the two countries have similar design, irradiation history, initial ^{235}U enrichment and measurement conditions. The use of the ^{252}Cf calibration source corrects for differences in the measurement geometry and possible changes in the performance of the measurement equipment. The half life of 2.64 a was used for decay correction of the ^{252}Cf source between the two campaigns. Due to their negligible influence in this cross calibration exercise, there is no need to correct for multiplicity or factors like differences in the fuel density or different irradiation power levels /8/.

The background corrected count rates with errors, calculated by the GRAND I, were keyed into a Symphony spreadsheet for handling. The uncertainty of the neutron rate is the square root of the net counts divided by the counting time. Both the Cd and the bare (fission chamber) neutron data were treated in the same way.

The half life of 18.1 a of ^{244}Cm was used to correct the detected neutron count rate for decay back to the discharge date. The uncertainty of the declared cooling time was considered negligible if compared to the other error sources. Each assembly was measured at six vertical positions on two sides with 90 degrees rotation in between. This procedure minimizes the influence of the small changes in the burnup profile which do have a strong influence (see equation 1) to the neutron rate. All these 12 points were used to calculate the arithmetic mean that was used for the calibration purposes.

The statistical uncertainty of the PNA measurements is only one of the error sources. Because the cross calibration is based on the normalization using the ^{252}Cf source, the repeatability achieved by the source measurements was also taken into account as an error source in deducing the uncertainty of the reference assembly burnup.

Deming code

The PC version QPDR_9 of the Deming code /9/ was used for curve fitting. The Deming method allows fitting of any function to the data set. It is a least-squares process that minimizes the sum of the weighted squares, both X and Y, of deviations between measured and calculated values. Uncertainties in both variables are used to weight the data points. The weighting factors are the reciprocals of the squares of the uncertainties.

The curve fitted was of the form

$$CR = a * BU^{b} \qquad (1)$$

where CR is the corrected neutron rate for bare or Cd-wrapped fission chambers and BU is the declared mean burnup of the assembly. Parameters a and b are obtained by the QPDR_9. The 2.5 % uncertainty of the declared mean burnup and the statistical uncertainty of the corrected neutron rate were used to weight the data points. The Deming code was used also to calculate the 95 % confidence Miller intervals for the fitted curve.

3.1.6 Gross gamma data handling

Supposing the build-up of the fission products is a linear function of the burnup, dividing the gross gamma signal with burnup should result in a constant for a given cooling time /10/. This behavior of the gross gamma signal was studied by fitting a function by the QPDR_9 code to the

measured values versus cooling time. The curve fitted was of the form

$$GG/BU = a * T^{-b} \quad (2)$$

where GG is the measured gross gamma signal, BU is the declared mean burnup, T is the declared cooling time and a and b parameters calculated by the code.

The error of the GRAND 1 gross gamma reading is relatively low, about 0.03 –0.06 % in most cases, and doesn't give a realistic view of the precision of the relative gross gamma flux density. Calculation of the error is explained e.g. in /11/.

The uncertainty used for the cooling time values was ± 30 days. For weighting the data points, 3 % uncertainty of the BU/GG ratio was used in the fit. The curve (2) was used for rough cooling time verification of the measured reference assembly.

3.1.7 Activity profiles

Selection of the measurement points used for cross calibration was based on activity profile measurements at both facilities. Assemblies 1405 and 5711 of CLAB were measured in the middle of each of the odd numbered nodes (1, 3, .., 25) using the fork detector. The midpoints of the nodes 11, 13, 15, 17, 19 and 21 used for calibration measurements are numbered in Figure 7. PNA measurements of the assembly 1405 were used only for checking the activity profiles. Figure 7 shows the neutron and gross gamma profiles for sides C and D of the assembly 5711. One can infer from the data that there is no real difference between the detected count rates of the two sides with 90 degrees rotation in between.

Figure 8 shows the neutron and gross gamma profiles for the TVO assembly 4538 side C. It can clearly be seen that all the profiles in Figures 7 and 8 are similar in shape which increases the reliability of the cross calibration measurements.

The activity profiles of Figures 7 and 8 are normal. The measured data reveal how sensitive the neutron rate is to changes in the burnup (see Eq. 1). The curves are not fitted but just drawn to connect the data points to each other.

Reference assembly profiles

The activity profiles of the reference assembly 6782 of the TVO KPA-STORE were measured in more detail. All the four sides were measured with the fork detector. Figures 9 - 11 show the measured neutron and gross gamma profiles for this assembly. One can infer from the data that all sides give similar, practically the same, activity profiles. Any side alone could thus be selected for verification and the result would still be representative.

3.1.8 Repeatability of ^{252}Cf measurements

The measured ^{252}Cf source count rate served as a normalization factor between the PNA measurements of the two facilities. This is why the source was measured every morning and evening during the measurement campaigns. The source was measured always twice, first positioned in the left hand corner of the fork detector and then in the right hand corner. These measurements helped also to keep the operation of the PNA system under control. All in all, 21 repeated neutron source measurements were performed at CLAB and 14 at TVO. After decay correction of ^{252}Cf, the normalization factor between the count rates measured at CLAB and at TVO was 1.004 ± 1.6 % for Cd-wrapped fission chambers and 1.011 ± 1.6 % for bare fission chambers. Figure 12 shows the reproducibility of the ^{252}Cf measurements when the source was positioned in the left hand corner of the fork detector. The one sigma errors of statistical origin are also shown for two points.

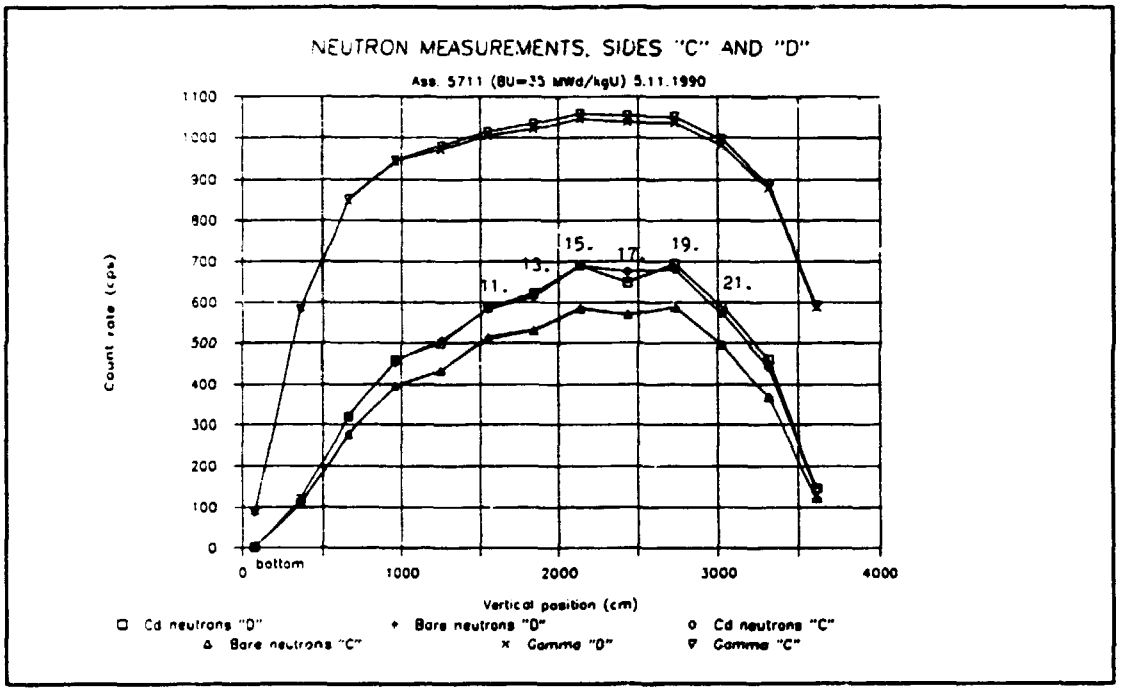

Figure 7. Neutron and gross gamma profiles for sides C and D of assembly 5711 measured at CLAB. The nodes numbered were used for actual calibration measurements.

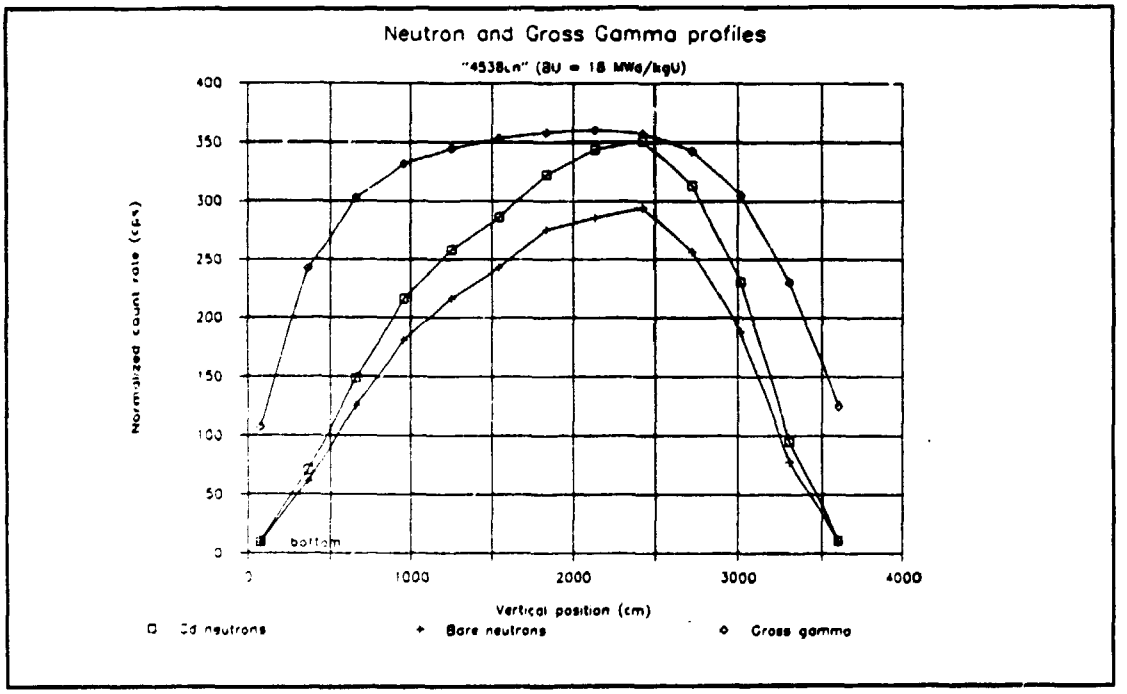

Figure 8. Neutron and gross gamma profiles for side C of assembly 4538 measured at the TVO KPA-STORE.

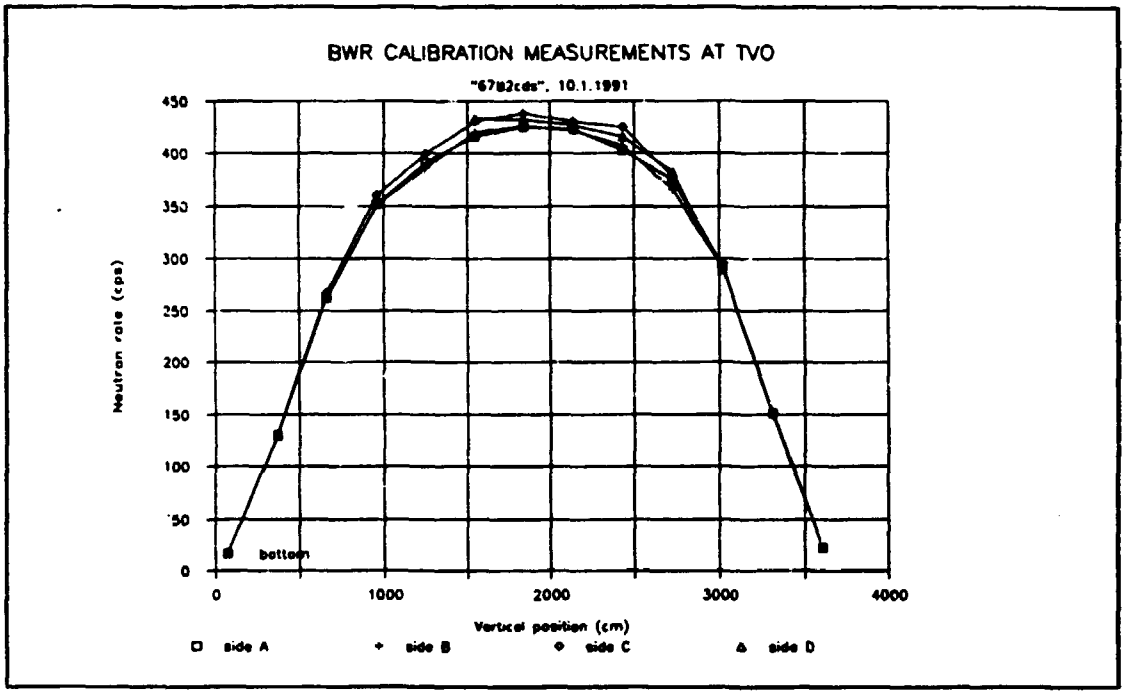

Figure 9. Neutron profiles for sides A – D of the TVO reference assembly 6782 measured with Cd-wrapped fission chambers.

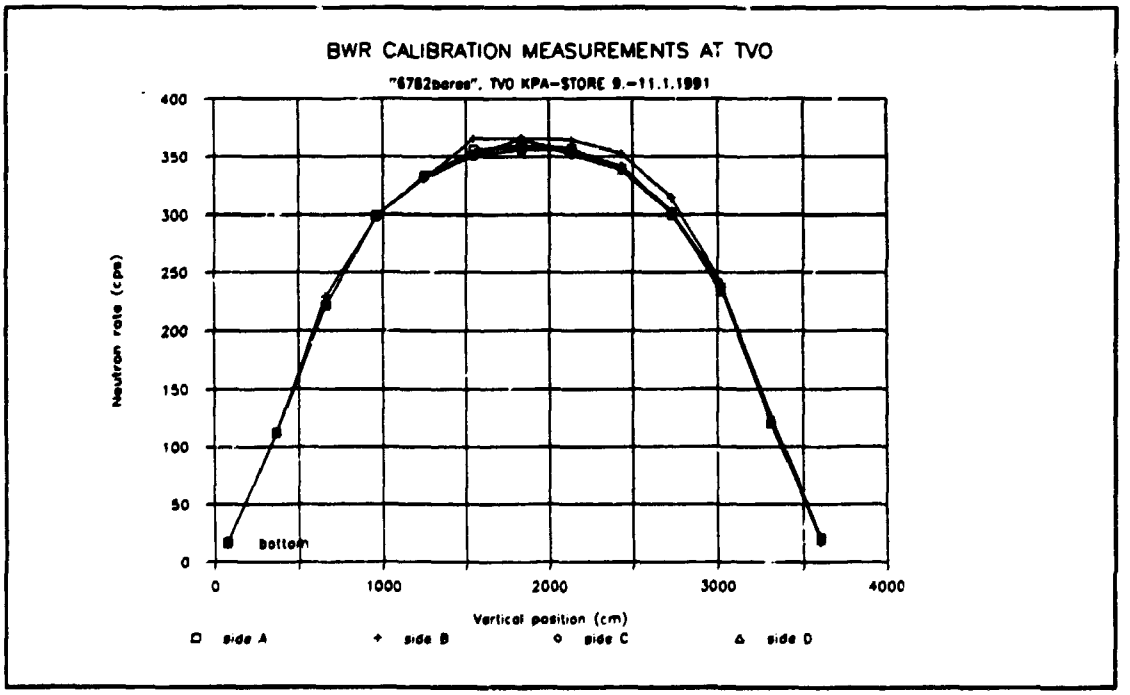

Figure 10. Neutron profiles for sides A – D of the TVO reference assembly 6782 measured with bare fission chambers.

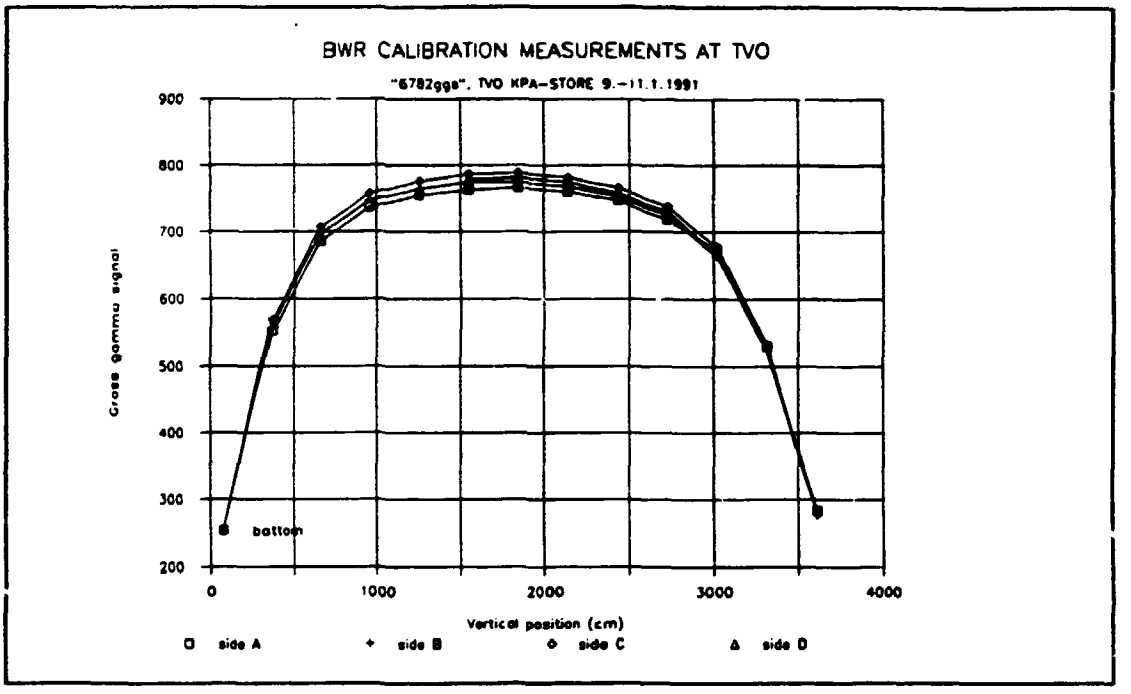

Figure 11. Gross gamma profiles for sides A – D of the TVO reference assembly 6782 measured with ionization chambers.

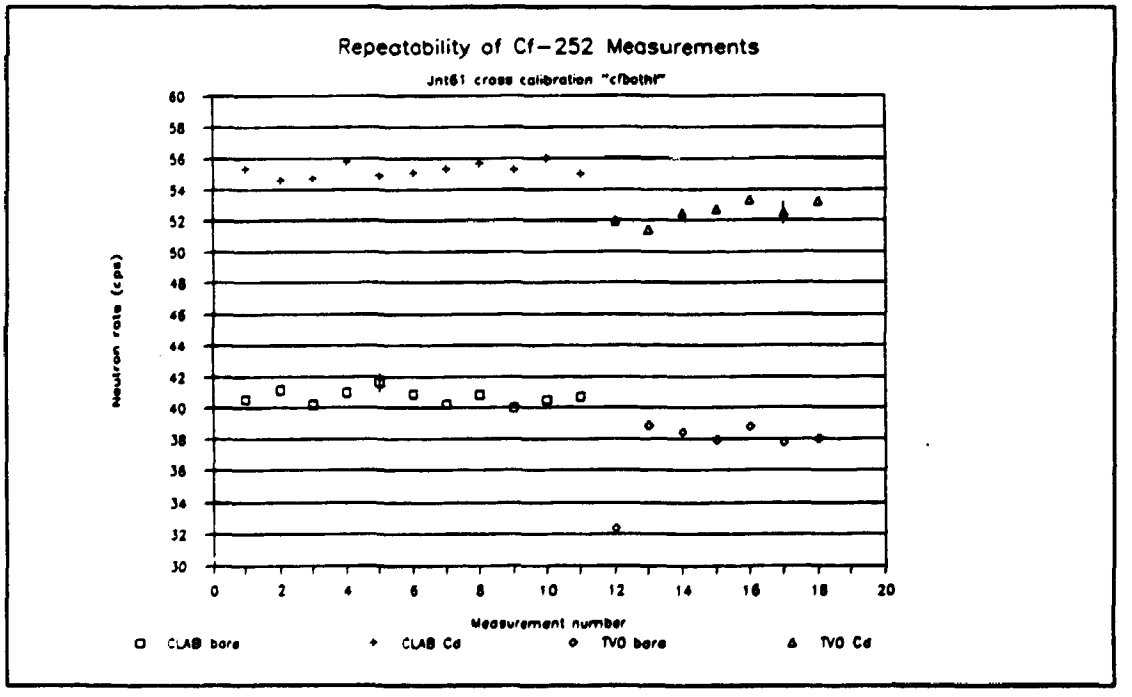

Figure 12. Reproducibility of the ^{252}Cf measurements between the CLAB and the TVO KPA-STORE. Measurement no. 12 (TVO bare) is an outsider.

3.2 HRGS measurements

3.2.1 Principle of using a ^{137}Cs reference source

The HRGS method for verification of the burnup of spent nuclear fuel makes use of the fact that the contents of the long-lived fission product ^{137}Cs in a fuel assembly is at a given time after the end of the irradiation, to a high degree linearly related to the burnup. The method also assumes a linear relationship between the cesium contents and the intensity of the 662 kev radiation emitted from the assembly, e.g. in a plane perpendicular to the axis of the assembly. The intensity is measured with HRGS, preferably as the average of several measurements in many directions and from various parts of the assembly, e.g. as a scan over a part or the full length of the assembly. Thus one may write

$$i_f = k * BU \qquad (3)$$

where i_f is the average number of quanta per second, unit length and unit solid angle emitted from the surface of the assembly in a plane perpendicular to the axis, and BU the average burnup of the fuel assembly. The proportionality constant k is specific for each type of assembly and depends on geometrical factors.

The experimental arrangement used is shown in Figure 13. The assembly is mounted vertically in a water pool and viewed by a gamma-ray detector through a horizontal collimator slit with a height of a few mm and a length of about 1.5 m. The full width of the assembly can be seen through the slit. Before entering the collimator slit the radiation has to pass through about 0.5 m of water and the steel lining of the pool. The gamma-ray detector is situated immediately behind the collimator as shown in Figure 14.

The count rate in the detector may be factorized as

$$R_f = i_f * h_f * T_f * O_f * e_f \qquad (4)$$

where

h_f is the effective height of the assembly as seen from the detector. This factor is the height of the collimator slit multiplied by a factor making up for the shadowing effects.

T_f is the transmission of the radiation through the absorbing media between the fuel assembly and the detector.

O_f is the solid angle covered by the part of the detector that can be seen through the collimator by the source.

e_f is the intrinsic efficiency of the detector for 662 keV radiation, i.e. the probability that a quantum hitting the detector will result in the storing of one event in the full-energy peak in the spectrum.

Inserting Equation (3) in Equation (4) one obtains

$$R_f = K * BU \qquad (5)$$

where

$$K = k * h_f * T_f * O_f * e_f \qquad (6)$$

The graph of Equation (5) is a straight line through origin with the slope K. The value of K (in counts per second/MWd per kgU) can be determined by measuring a fuel assembly with a known value of the burnup. Other fuel assemblies of the same type measured with the same equipment are then expected to yield points which, within the errors, lie on the straight line.

Problems occur if one wants to compare burnup measurements made at different facilities, since the slope coefficient K contains factors that are likely to be different for different sites. One way to correct for this would be to measure the same fuel assembly at the two different facilities. If the facilities are indexed 1 and 2 one may write Equation (5) as

$$R_{f1} = K_1 * BU \qquad (7)$$

$$R_{f2} = K_2 * BU \qquad (8)$$

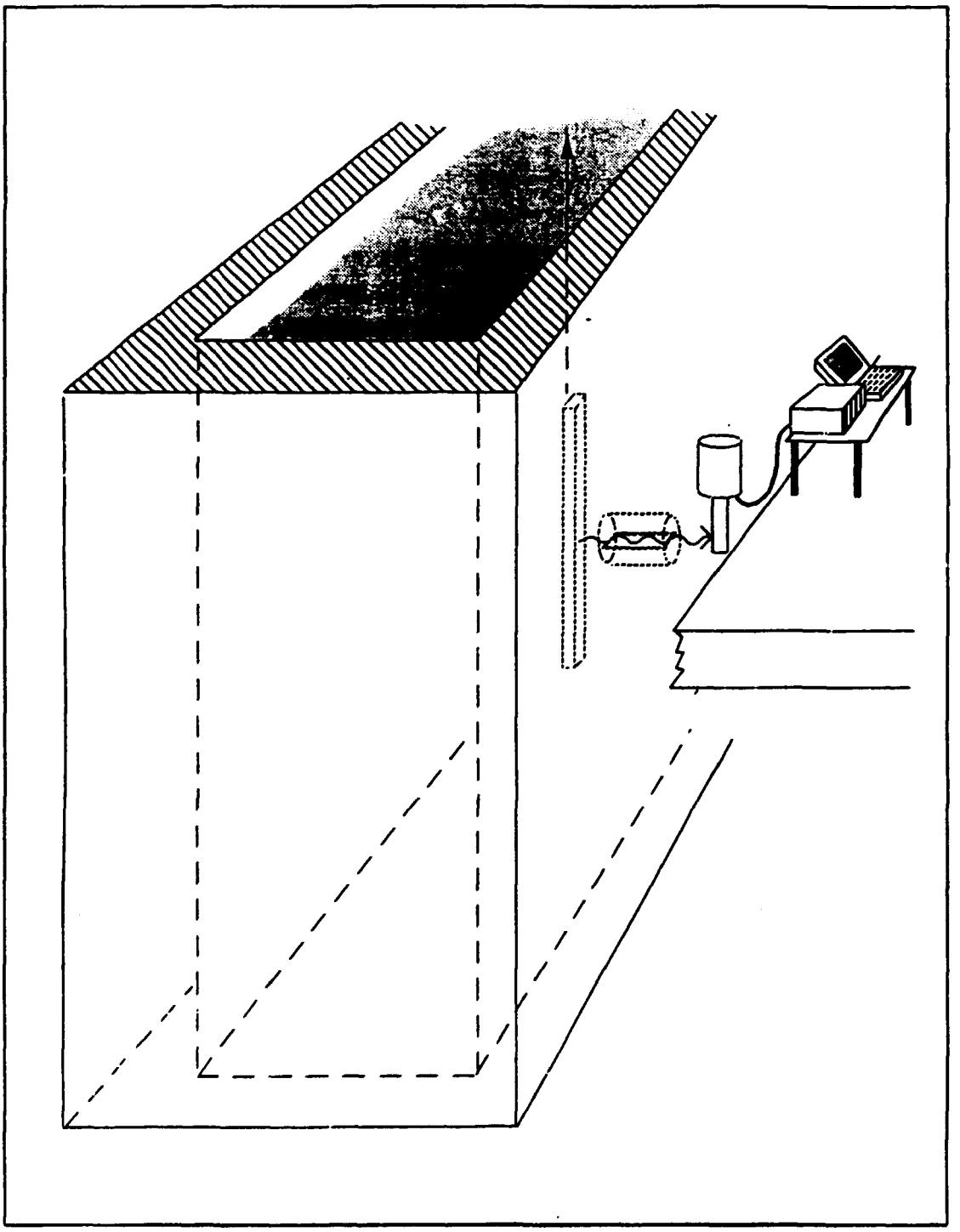

Figure 13. Schematic view of the HRGS measurement arrangement.

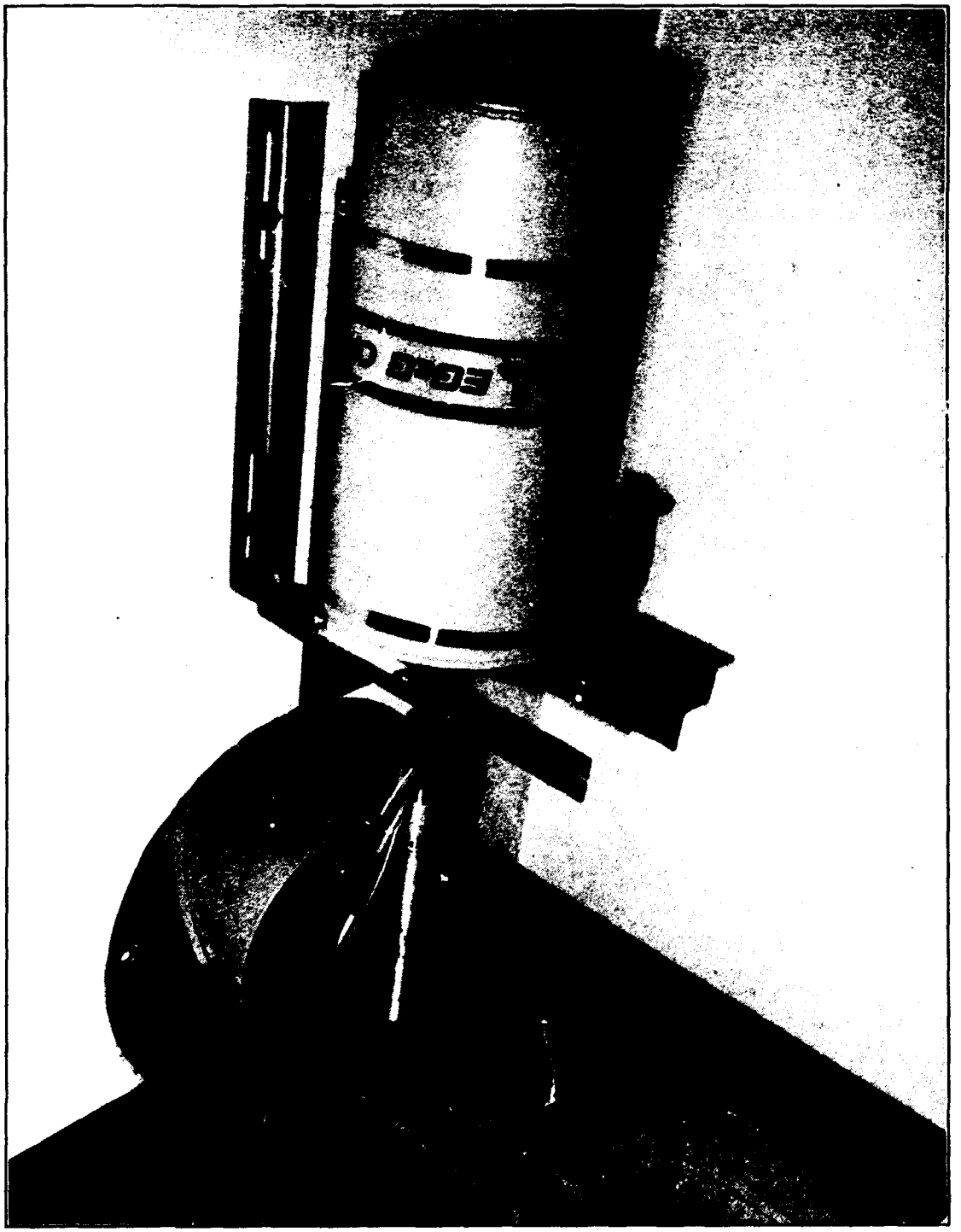

Figure 14. The HPGe detector in the measurement position in front of the sealed collimator at CLAB.

Assuming that one wants to make the comparison by using the diagram of facility 1 (Eq. (7)) one must correct the count rate obtained at facility 2 with a factor C_f:

$$R_{f2} * C_f = K_1 * BU \quad (9)$$

where

$$C_f = R_{f1}/R_{f2} \quad (10)$$

This method of comparison between measurements at different facilities is very straight-forward in principle but suffers from the great disadvantage of implying transport of a fuel assembly between the sites. This can be avoided by using a smaller, more easily transportable radiation source. Such a source has been developed in a cooperation between the Swedish (SKI) and Finnish (STUK) nuclear power authorities /3/. The source consists of a pellet of ^{137}Cs mounted inside a piece of a fuel channel. It can therefore be positioned in front of the collimator in the same way as a fuel assembly. The pellet is mounted on a mechanical drive in such a way that it can perform a vertical oscillatory motion with an amplitude of the order of 10–20 cm. The movement of the pellet is made with a velocity that is constant within fractions of a percent.

During a measurement the source is positioned in front of the collimator and made to symmetrically oscillate a number of times around the collimator axis with an amplitude considerably larger than the sum of the slit width and the vertical extension of the source, while a spectrum is recorded. The procedure is repeated with the same parameter values at the facilities that are to be compared.

The average count rate R_c during a measurement with the Cs source can be written:

$$R_c = i_c * h_c * T_c * O_c * e_c \quad (11)$$

where the symbols have the same meaning as in Equation (4).

Analogously with Equation (10) one may define a ratio

$$C_c = R_{c1}/R_{c2} \quad (12)$$

In the following it is shown that $C_c = C_f$ provided certain conditions are fulfilled. This is done by forming the ratio

$$Q = C_f/C_c \quad (13)$$

Inserting Equations (4), (10), (11) and (12) in Equation (13) one obtains

$$Q = (k_1/k_2) * (h_{f1}/h_{c1}) * (h_{c2}/h_{f2}) * ((T_{f1}/T_{c1}) / (T_{f2}/T_{c2})) * (O_{f1}/O_{c1}) * (O_{c2}/O_{f2}) * ((e_{f1}/e_{c1}) / (e_{f2}/e_{c2})) \quad (14)$$

The right hand side of Equation (14) is a product of 7 factors. If each of them can be shown to be equal to 1 then $Q = 1$ and $C_c = C_f$.

- $(k_1/k_2) = 1$ if the assemblies in the two facilities are of identical type as discussed above.

- The ratios $(h_{f1}/h_{c1}) = 1$ and $(h_{c2}/h_{f2}) = 1$ if a) the same collimator is used at each facility during the measurement of the reference source and the assemblies and b) the value of h is independent of the position of the radiating surface along a horizontal line perpendicular to the collimator axis. In other words, h must not depend on the size of the object measured. This sets a condition on the flatness of the collimator surface. According to the mechanical specifications of the collimator used this is met within less than 20 μm which with a slit height of the order of a few mm implies that the condition h_f/h_c should be fulfilled within less than 0.5 %. A special measurement was made to check that this requirement was fulfilled, see section 3.2.4.

- $((T_{f1}/T_{c1}) / (T_{f2}/T_{c2})) = 1$ if a) no changes of the absorbing conditions are made during a campaign at a facility and b) the position of the Cs pellet relative to the assemblies is the same at both facilities. Since the pellet is mounted in the center of a standard fuel channel, this condition holds within the

precision of the positioning of the assemblies in the fixture used for the measurements. In the present case this is ± 0.5 mm, which introduces an uncertainty in the above factor of ± 0.5 %.

- (O_{n}/O_{c1}) and (O_{c2}/O_{n2}) = 1 if the geometry of the measurement is kept constant during each campaign. One should note that the detector must not move relative to the collimator slit. Due to the relatively large distance between the source position and the detector, the difference in solid angle as seen from the small pellet and from the larger assembly is less than 0.1 %.

- (e_{n}/e_{c1}) / (e_{n2}/e_{c2}) = 1 if no change is made of the detector or the evaluation procedure of the spectrum during a campaign. Note that different detectors may be used at different campaigns.

In the comparison measurement reported here a number of fuel assemblies were first measured together with the reference source at the CLAB facility in Sweden. From these data a calibration line of count rate versus declared burnup values was established, Equation (7). Later a number of assemblies were measured at the TVO KPA-STORE in Finland. In order to compare these count rates with those obtained at CLAB, the former were multiplied with a correction factor C_c, Equation (12), obtained as the ratio of the reference source count rates at CLAB and TVO KPA-STORE.

3.2.2 Facility installations

All BWR power plants and interim storage facilities in Sweden and Finland have a collimator and a specially designed elevator for scanning the fuel assemblies /3/. An overview of this equipment is shown in Figure 13.

The equipment is mounted in a fuel handling pool and it consists of the following parts: 1) A fixture which holds the fuel assembly during measurement. The fixture allows for rotating the assembly around the vertical symmetry axis. 2) A horizontal gamma-ray collimator mounted in the pool wall.

Fixture

The fixture holding the assemblies in measuring position is made up of a stainless steel frame in which two collars, separated vertically by a distance of approx. 4 m, are mounted in such a way that they can be rotated 360° around the vertical axis. This rotation is performed via a geared drive and a specially designed hand held tool. The assemblies are loaded into the fixture from above by the fuel handling machine. The width of the collars allows for placing the assemblies with a precision within ± 0.5 mm in the horizontal plane.

The fixture is shown in Figure 15. It can slide vertically, driven by a hoist motor, on two rails fixed to the pool wall. This enables a vertical movement of the assemblies with a variable speed of 0 – 4 m/min. The scanning speed depends on the scanning direction (up or down). This fact is of no principal significance as long as the speed in both directions is constant. The speed was checked at both facilities at several occasions and was found to be constant within 1 %.

Collimator

The collimator at CLAB is made of steel and consists of two massive half-cylinders, each about 120 cm long and 27 cm in diameter. The weight is approximately 500 kg. The half-cylinders are bolted together with an interleaving slit plate defining the height, width and length of the collimator slit. The height of the collimator can be altered from 1 to 5 mm by changing the slit plate. This operation does not affect the other geometry parameters. The geometry of the collimator is such that the detector always views the full width of the fuel assemblies. As has been discussed above, it is important that the surfaces of the collimator and, most important, the slit plate, are machined with a high degree of precision. All joint surfaces of the CLAB collimator and slit plate are made with a precision of ± 20 μm. The collimator at TVO has a different geometry as the length is about 147 cm. Otherwise it is constructed in the same way as the CLAB collimator.

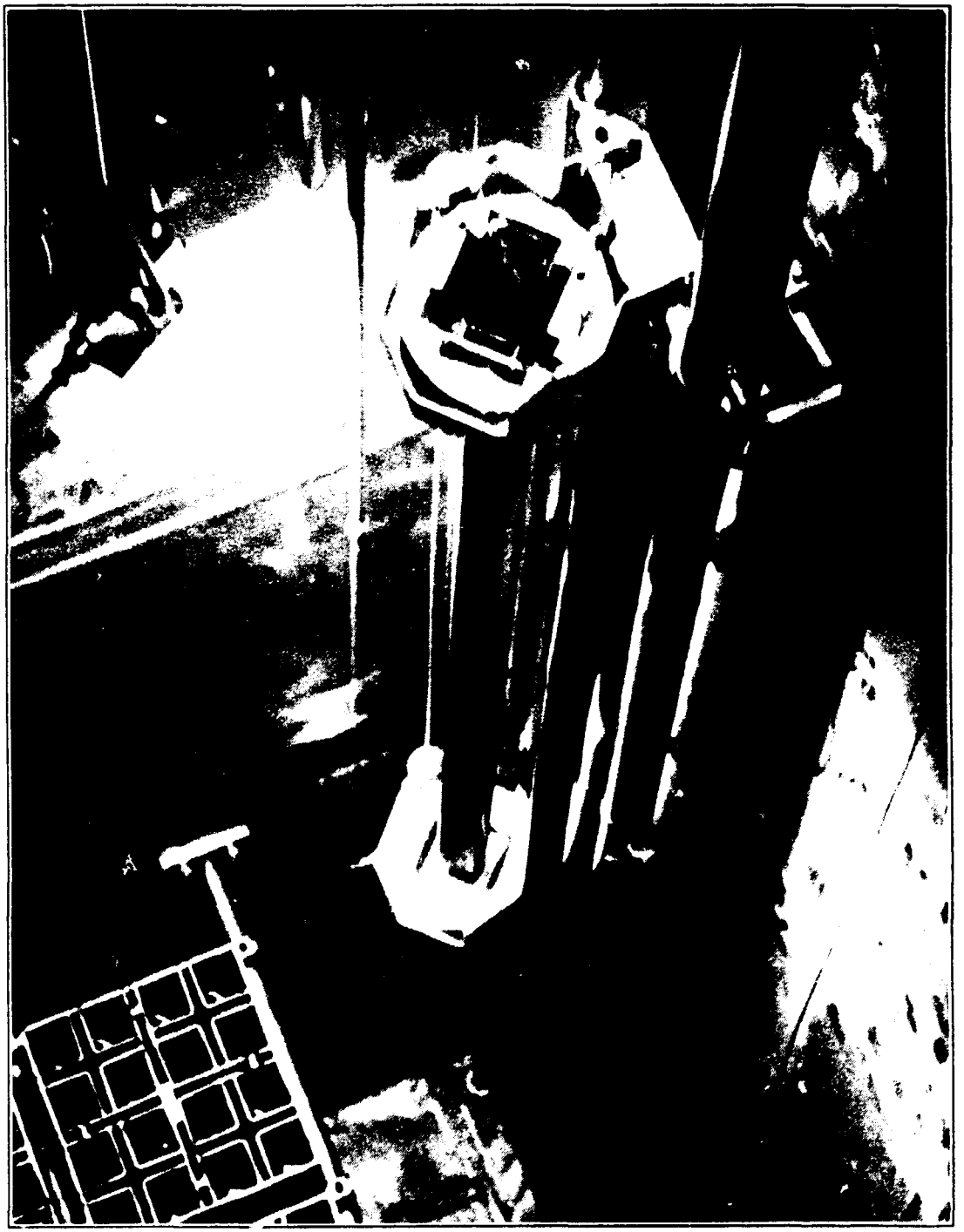

Figure 15. An assembly inside the measurement fixture that is attached to the gamma wagon at CLAB.

3.2.3 Detector system

Hardware

Figure 16 shows a block scheme of the spectrometer system /12/. The detector used was a 40 % HPGe n-type detector equipped with a transistor reset preamplifier which, together with an Ortec 973U gated integrator amplifier, allows a throughput of 100 kcps with an energy resolution less than 3 keV FWHM. In order to optimize the peak shape, the detector is irradiated radially /13/. The ADC is an ND 582 with a fixed conversion time of 1.5 μs and a total busy time of 2.4 μs.

The data were stored and analyzed in a Toshiba 5200 PC via a fast interface card, Gammadata PC16 BIV2.

The dead time was corrected for by using the pulser method (see Fig. 16). The pulser peak was placed at the high-energy end of the spectrum, where the background was negligible. The data taking code automatically evaluated the pulser peak area, calculated the ratio between this area and the actual number of pulser events emitted during the measurement, and corrected the spectrum accordingly.

Software

The gamma-ray scanning of a fuel assembly was performed by sequential measurement of a number of spectra while the assembly was moving vertically at constant speed in front of the collimator. A special code SEDAS, was written in C for sequential measuring and storing of spectra /14/.

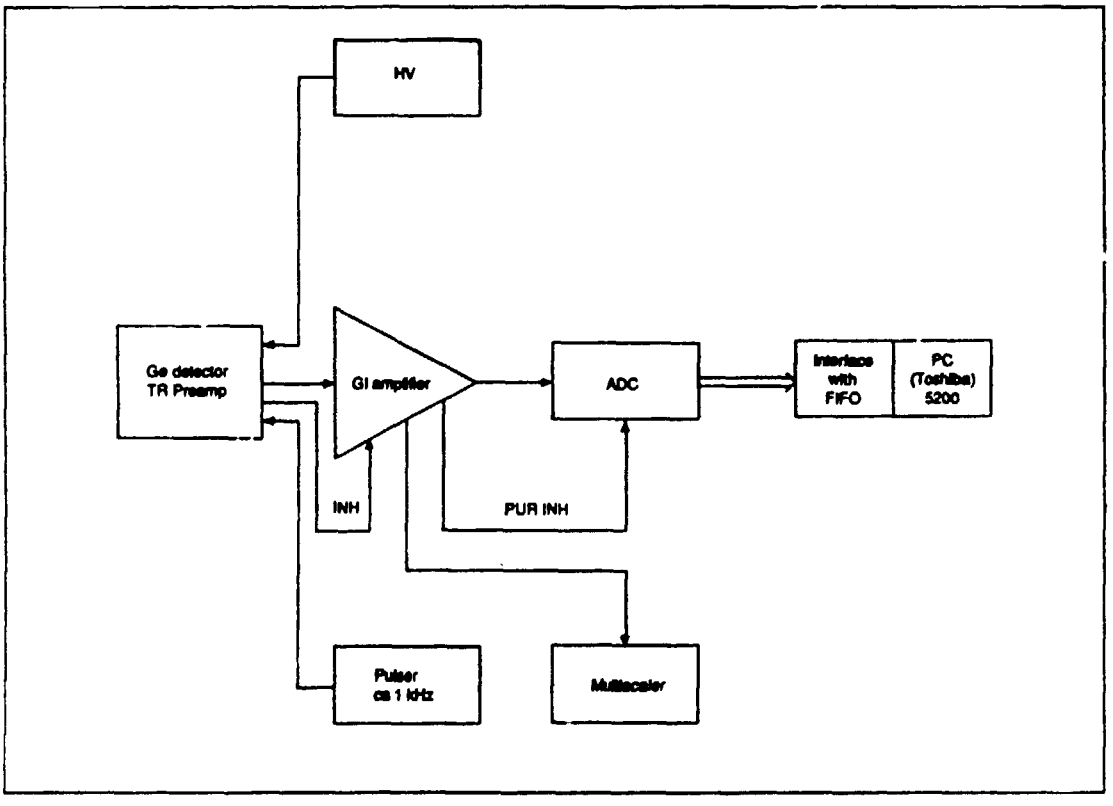

Figure 16. Block scheme of the spectrometer system.

The code works as follows (see also Fig. 17): Before starting, the number of spectra N and the recording time per spectrum T are given together with data on the gamma-ray peaks of interest and the pulser frequency used. The code then sequentially records N spectra and stores them on the hard disc. Three spectrum areas are used and the switching between the areas is performed with no loss of events. For controlling the procedure, two other spectrum areas are used to display the sum of all spectra, and an optional number of histograms showing the intensity of selected gamma-ray peaks as a function of the spectrum number. Figure 18 displays three such histograms showing the intensities of ^{137}Cs, ^{154}Eu and ^{60}Co as the complete length of a fuel assembly was scanned with N = 70 and T = 3 seconds. The sharp peaks in the ^{60}Co histogram originate from the spacer grids.

After completion of a scan, all spectra are automatically corrected for dead time. A dead time corrected summed spectrum is created and stored together with histograms, also corrected for dead time. Finally the energies and intensities of the peaks of interest are evaluated from the corrected summed spectrum and printed.

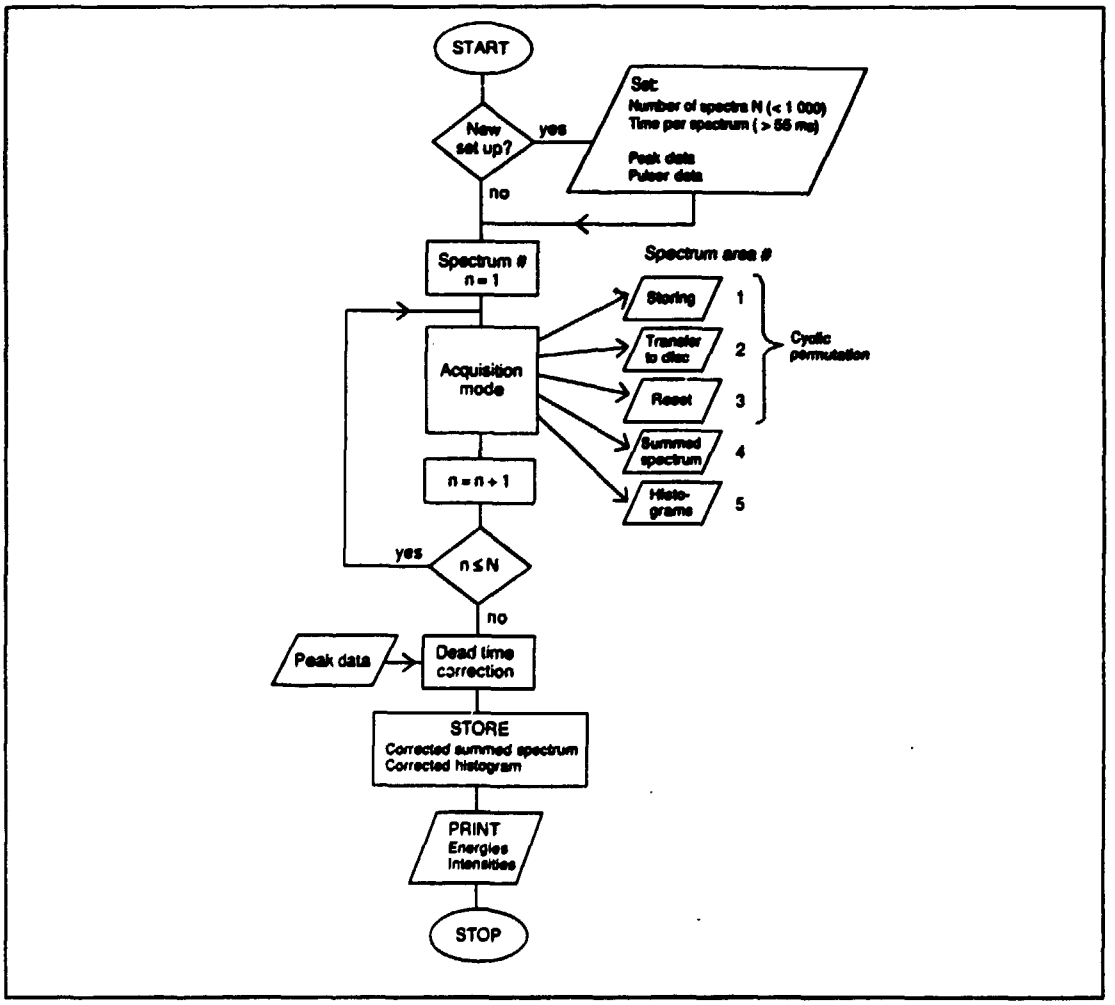

Figure 17. Flow diagram of the SEDAS code.

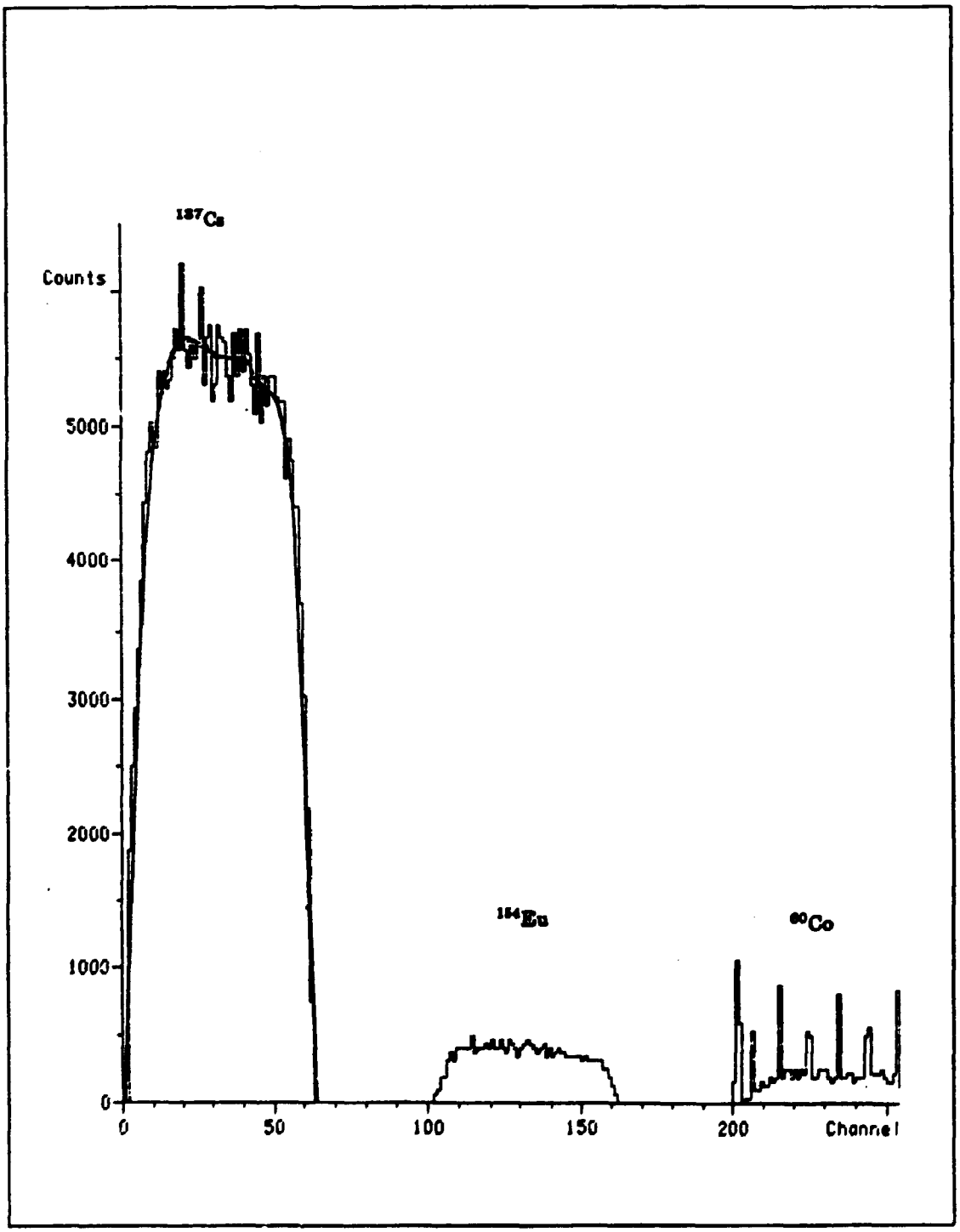

Figure 18. Measured vertical intensity distributions of an assembly with BU = 33 MWd/kgU and CT = 39 months.

3.2.4 Measurements

For the purpose of the cross calibration 9 assemblies were measured at CLAB and 3 assemblies at TVO. All measurements were made by scanning the full length of the assemblies with the corners directed towards the gamma-ray detector /3/. The intensities of all the four corners of each assembly were measured and the average intensity was used.

To check that no changes occurred in the experimental conditions during the measurements, a ^{65}Zn source, emitting 1115 keV gamma rays, was mounted on the detector during the CLAB measurements as well as during the TVO measurements.

A number of 4 mm thick lead plates were placed between the collimator and the detector. This suppressed the intensity of the low energy part of the spectra. To attenuate X-rays from the lead plates, a 2 mm copper plate was placed after the lead filter.

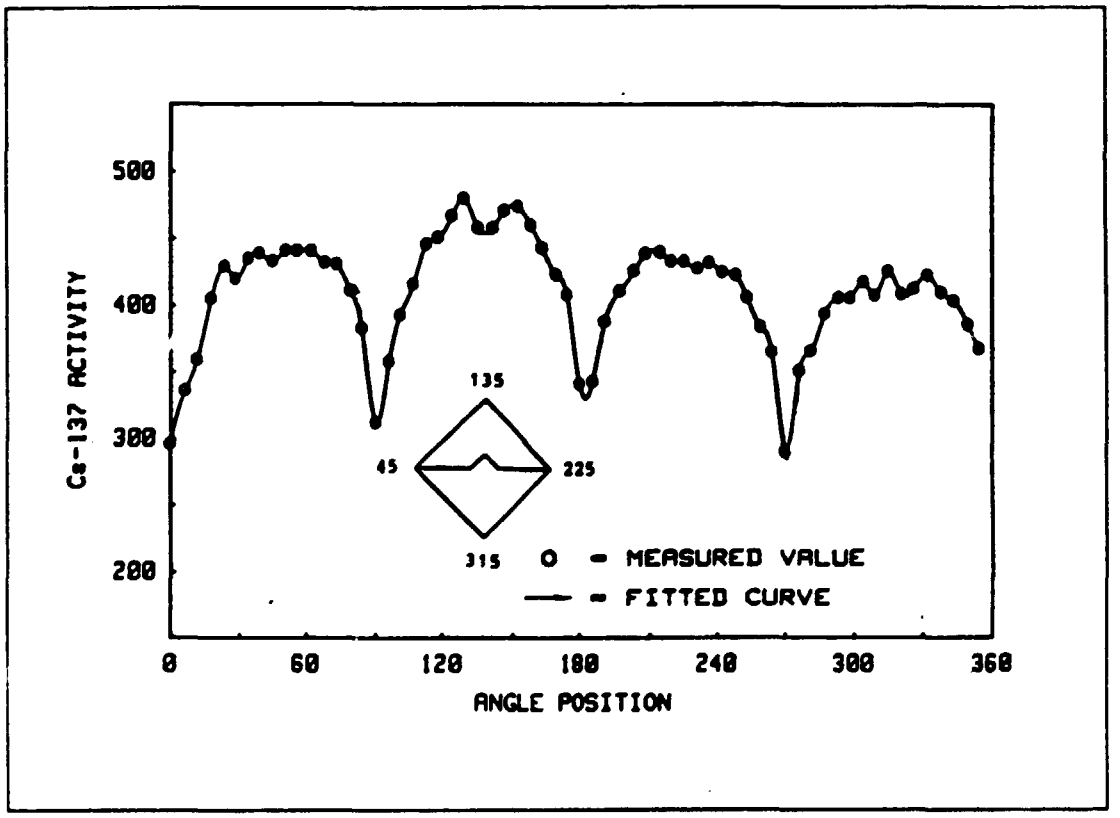

Figure 19. Measured ^{137}Cs count rate versus radial angle for a spent square shaped BWR assembly /3/.

Measurements at CLAB

The assemblies measured at CLAB were loaded while the gamma wagon was in the lower position. The measuring session was started by turning the reference corner of the assembly into measuring position (as seen in Fig. 15). The reason for measuring on the corners of the assemblies is evident from Figure 19. As shown in this figure, the intensity distribution around 45°, is almost flat. Measuring at the corners will therefore minimize the positioning errors, (see Ref. /1/ for further details).

To ensure that the whole length of the cesium distribution was covered, each scan was started and stopped 10 cm outside the fuel region.

The speed of the gamma wagon differed by about 15 %, depending on whether the scanning direction was upwards or downwards. The acquisition time for each spectrum during a scan was adjusted accordingly. Typical value were 3.3 s in the upward direction and 2.8 s in the downward direction, with N = 70 partial spectra. With these values, each partial spectrum covered 5.8 cm of the fuel assembly.

The slit height at CLAB was 5 mm which is the maximum obtainable with this collimator. With a lead filter of 8 mm the maximum event rate of the detector was about 70 kcps with a dead time of about 35 %.

Measurements at TVO

The three assemblies measured at TVO (Table I) are of the same type as those studied at CLAB. The measurements were performed in a similar manner including measurements of the cesium source. The main difference between the geometries at CLAB and at TVO is the collimator. At TVO it is 147 cm long and the slit height was 3 mm during measurements.

Control of the TVO collimator

As stated in section 3.2.1, the accuracy of the comparison between the assemblies measured at different facilities depends on the transmission properties of the collimators. It is important that the transmission of the collimator does not vary with the source position along a horizontal line perpendicular to the collimator axis. A preliminary evaluation of the data showed that the burnup values obtained at the TVO KPA-STORE were all somewhat lower than expected and one could therefore suspect that its transmission might vary with the source position.

The transmission of the TVO collimator was investigated in the following way: A radioactive source of ^{110m}Ag, emitting strong gamma radiation at 685 keV, i.e. almost exactly the energy of the ^{137}Cs radiation used for the burnup measurements, was moved in the horizontal symmetry plane of the collimator at a distance of 44 cm from the collimator's front end and perpendicular to the collimator symmetry axis /15/. The results of this investigation are shown in Figure 20. It can be seen that the transmission of the collimator is highly dependent on the torque applied to the bolts which keep the collimator together. Due to an uncertainty of the torque actually applied on the bolts during the measurements at TVO, the value of the correction factor is afflicted with an error that is difficult to estimate. From this measurement a correction factor of 1.04 for the TVO KPA-STORE ^{137}Cs intensities was regarded as reasonable since hand-held tools were used in assembling the collimator.

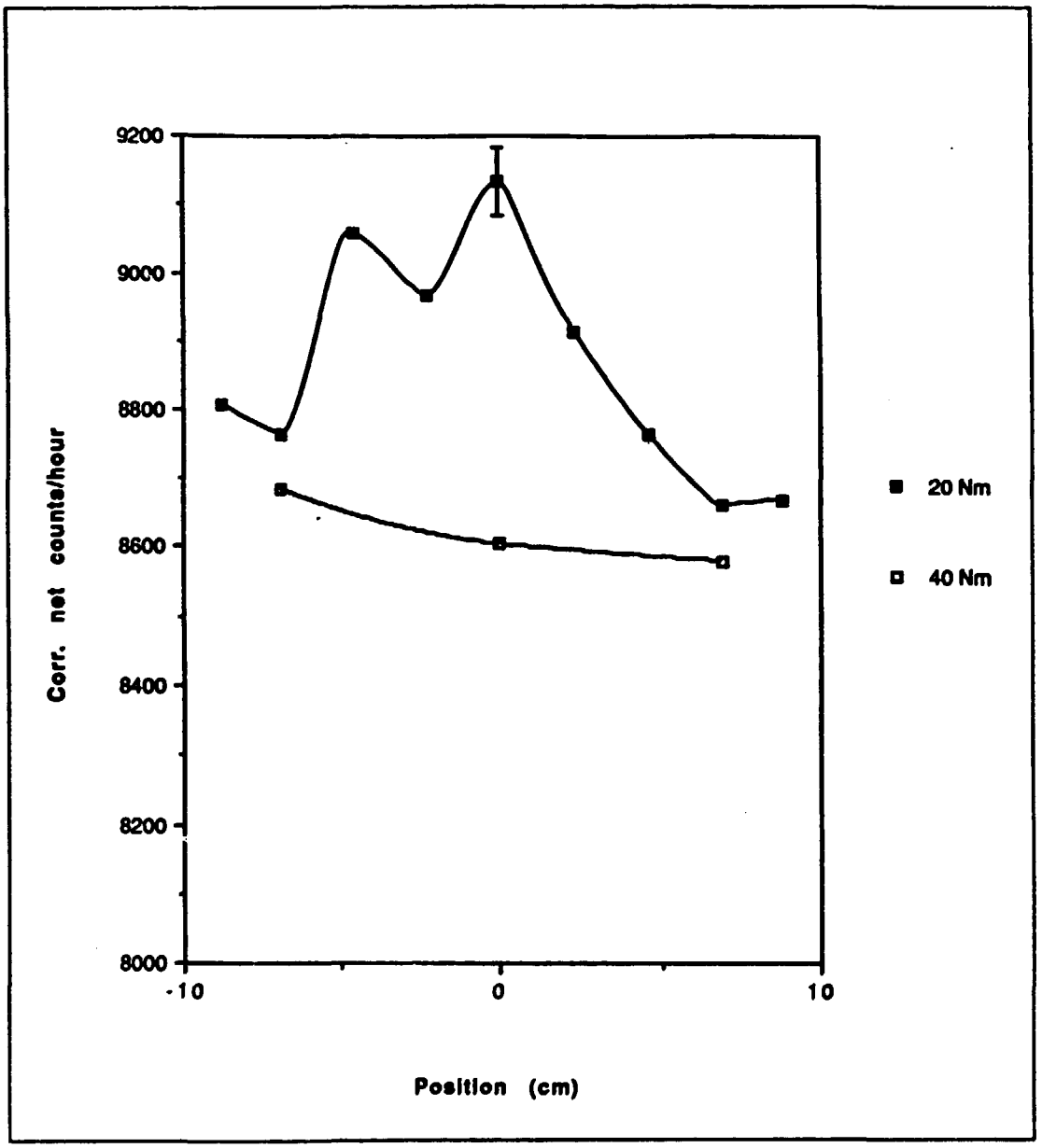

Figure 20. Transmission versus horizontal position for two different compressive forces of the TVO gamma collimator.

3.2.5 Data analysis

Peak evaluation and error analysis

Due to small angle scattering and high count rates, the gamma-ray peaks show an asymmetry around the centroid, which necessitates a careful background subtraction. Figure 21 schematically illustrates the procedure used in this work. The centroid of a peak is determined and the peak region is defined around the centroid. Two regions defining the background are also marked symmetrically at each side of the peak. The code used in this work fits a straight line to the background regions and thereby defines a background for the peak. It is important to define the regions symmetrically around the centroid. An investigation was undertaken which showed that if these regions are placed asymmetrically with respect to the centroid, the variation of the peak areas may be as high as 10–15 %. If the regions are located symmetrically, the peak area obtained is not very sensitive to the position and size of the background regions. It turns out that within reasonable variations of the location of the regions, the variation of a peak area is less than 1 %. This is the dominating contribution to the errors in the spectrum evaluation, since the statistical error in the peak area was about 0.2 % in all spectra.

The limited pulser rate used also introduces an error. For example, for a spectrum recorded during 3 seconds at 50 % dead time and a pulser rate of 2 kHz, the dead time correction factor has a statistical error of 2 %. For a scan with N = 70 partial spectra, this contributes to the final error by about 0.2 %.

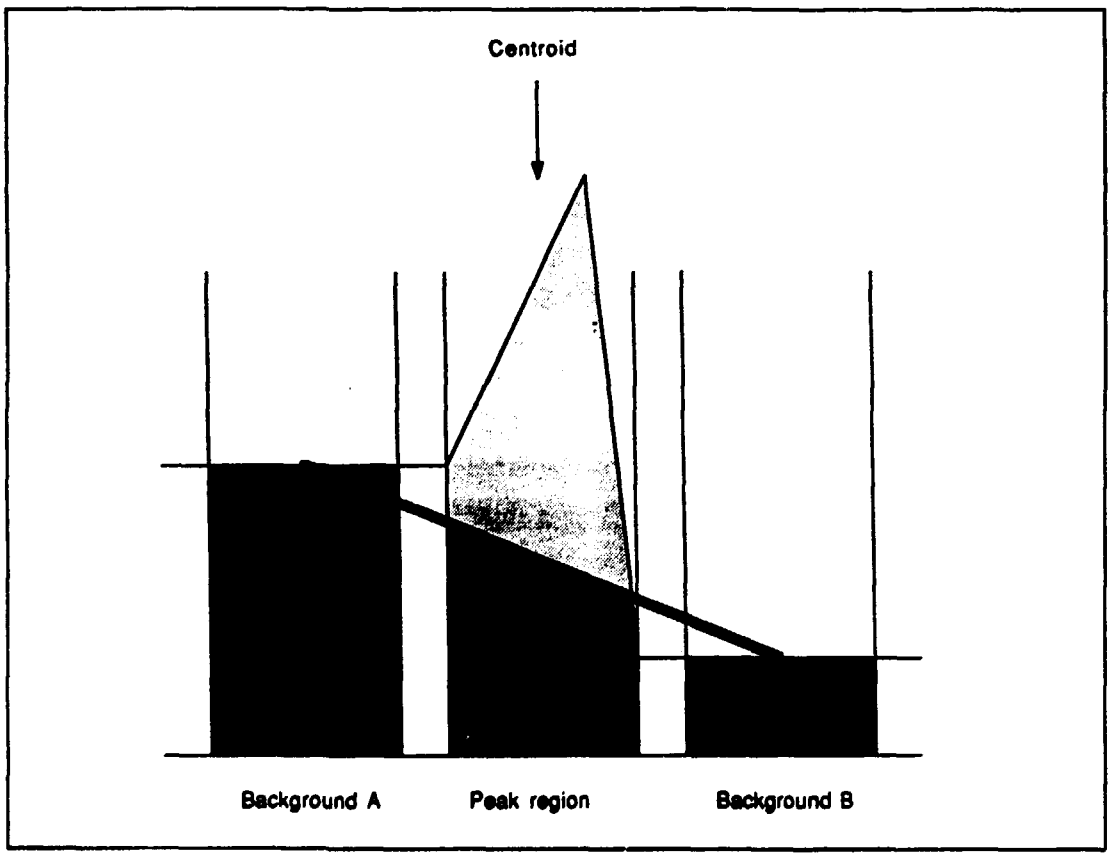

Figure 21. Principle of the background subtraction used.

As has been pointed out in section 3.2.2, the speed of the gamma wagon in each direction is constant within 1 %. This fact introduces an error in the measured intensities of about 0.5 %. The error due to the uncertainty in the positioning of the assemblies into the fixture is of the order of 0.5 %.

The limited number of partial spectra used in a scan introduces a slight uncertainty in the duration of the period of time that the fuel is seen by the detector. This introduces an additional uncertainty in the measured average intensity of about 0.5 %.

With the above errors taken into account, a total relative error of about 1.5 % is obtained for each data point.

Burnup profiles

Using the method described above for peak area evaluation of all partial spectra, histograms were constructed. There are several ways to use these histograms in order to get as much information as possible from a measurement. The on-line sorting of data into histograms makes it possible to check that the measurement is running properly. After correction for dead time these histograms can be used for checking the quality of node level burnup calculations as the histograms give a direct measure of the burnup along the fuel assembly. An example of such a comparison is shown in Figure 22. In this figure, the points represent the measured ^{137}Cs distribution for assembly 5769, while the curve is the declared burnup distribution. In order to facilitate the comparison, the experimental data have been smoothed so that statistical fluctuations are less pronounced. This operation does not change the functional dependence of the distribution.

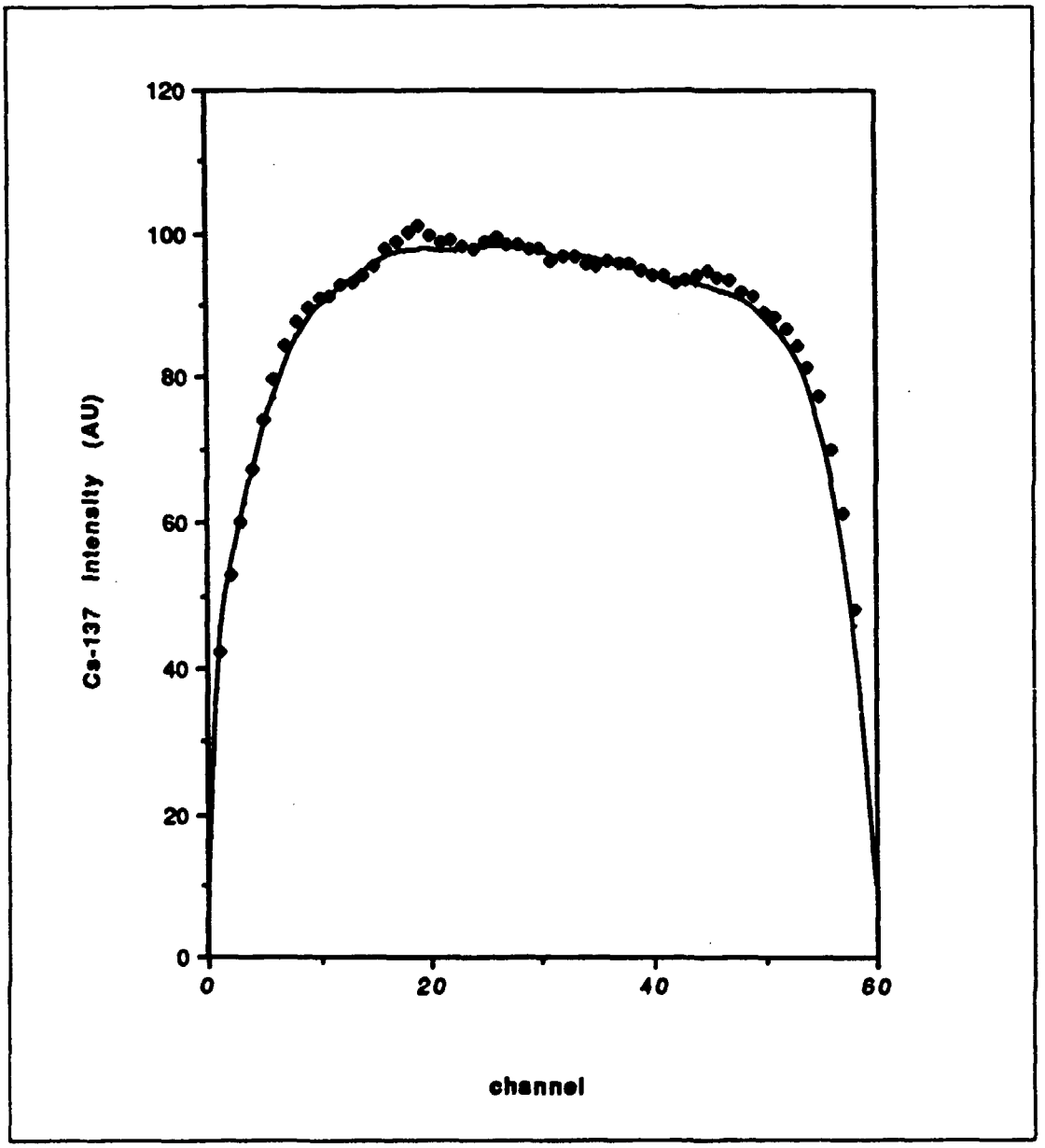

Figure 22. Comparison of the calculated burnup profile (dots) with operator declared burnup profile (line) for assembly 5769.

3.3 Sealing, water analysis and weighing

The gamma collimators at both facilities were opened, checked and closed before starting the measurements. The integrity of the collimators was maintained by sealing them by the standard IAEA metal seals as seen in Figure 14. Both collimators were kept sealed during the whole calibration exercise. Also the ^{137}Cs and the ^{252}Cf calibration sources were sealed before starting the measurements. This guaranteed the normalization between the two facilities to depend only on the facility conditions, not on the sources. Afterwards the seals were checked and verified at IAEA headquarters.

In order to be prepared for any unexpected results of the cross calibration, water samples of the storage ponds of CLAB and the TVO KPA-STORE were taken and analyzed in the IAEA Seibersdorf Laboratory. The measured boron concentrations gave no reason for extra actions in the (neutron) data analysis. This is confirmed also by Figure 23 showing the ratio of the detected neutron rates of Cd and bare fission chambers of the fork detector. The measured ratio seems not to depend on the burnup within the detection limits confirming the findings of Reference /11/.

As an extra check for integrity of the assemblies and presence of the fuel channel, the gross weight of each measured assembly was measured at fixed height using the gauge in the fuel handling machine. The weights, about 260 kg for assemblies with the fuel channel and 230 kg for that without it, were consistent within the precision of the gauge (± 5 kg). This equals roughly the weight of two fuel rods in this type of fuel assembly.

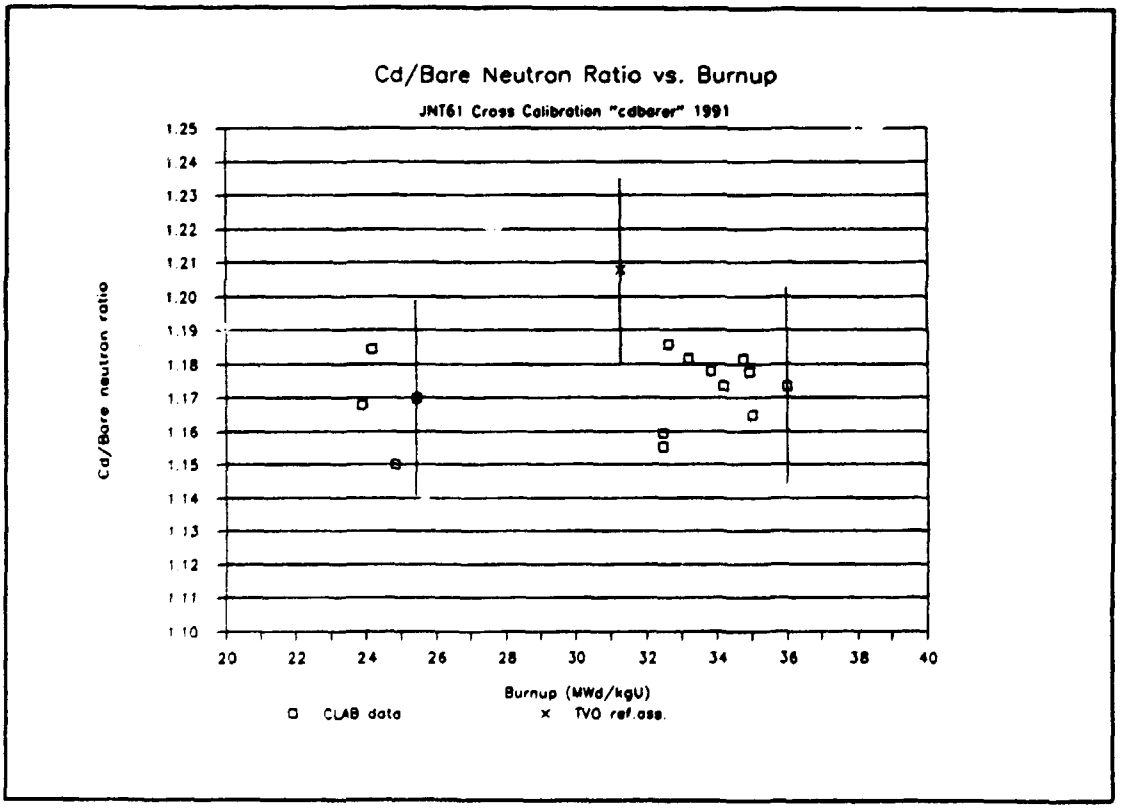

Figure 23. Ratio of the detected Cd and bare neutrons of the fork detector versus burnup.

4 RESULTS

4.1 Neutron calibration curve

Results of the PNA measurements using Cd-wrapped chambers are shown in Figure 24.

The curve was fitted by the Deming code using the data of the 14 CLAB measured assemblies. The calculated fitting parameters and standard deviations (see Eq. 1) have the following values: a = (7.1 ± 3.5) $*10^{-5}$ and b = (4.57 ± 0.14) with CR in counts/s and BU in MWd/kgU. Figure 24 shows also the 95 % confidence intervals /9/. In Figure 24 also the corrected and normalized neutron rate of the TVO reference assembly is shown. This point was not used in fitting the calibration curve. As can be seen, the measured neutron rate of the reference assembly versus declared burnup falls clearly within the 95 % confidence interval of the fitted curve.

Results of the PNA measurements using bare fission chambers are shown in Figure 25.

The fitting parameters and standard deviations, calculated using the 14 CLAB measured assemblies, have the following values: a = (6.4 ± 3.2) * 10^{-5} and b = (4.55 ± 0.15) with CR in counts/s and BU in MWd/kgU. Also Figure 25 shows the 95 % confidence intervals. The corrected and normalized neutron rate of the TVO reference assembly is shown versus declared burnup. The normalized count rate of the reference assembly also for bare fission chambers is consistent with the data measured at CLAB.

4.2 Burnup deduced by PNA

The behavior of the measured neutron rates for both types of fission chambers, Cd-wrapped and bare, is very similar. All CLAB measured rates are consistent, within the confidence limits, with each other as can be seen from Figures 24 and 25. The measured assemblies consist of two burnup groups. The one with higher burnup, around 33 MWd/kgU, and the one with lower burnup, around 24 MWd/kgU, respectively. Due to the relatively large number of points, the fitted curve is representative. The biggest deviations from the fitted curve can be noticed with assemblies in the lower burnup group. The deviations are, however, very small taking into account the sensitivity of the neutron rate to the burnup. One may note that the fit to the assemblies of the higher burnup group, i.e. around the reference assembly, is very good. None of the deviations in the detected fast neutron rate (Cd-wrapped chambers) is bigger than 1 %. This seems to be the case also with the thermal neutron rate (bare chambers).

There are different ways of deducing the burnup of the reference assembly and its uncertainty from a calibration curve with confidence limits. The goal of this task was cross calibration, that means to show whether the declared burnup of the TVO reference assembly is consistent with the trend represented by the calibration curve of CLAB measured assemblies. This is why the calibration curve was used for interpolation and the normalized reference assembly neutron rate was used to deduce the calculated burnup. Tables II and III show the calculated burnups for all measured assemblies.

Using the method mentioned above, the burnup calculated by the Deming code for the TVO reference assembly, using Cd-wrapped chambers, is (31.41 ± 0.62) MWd/kgU. When contribution of all error sources is taken into account, the deduced burnup value of the reference

assembly has an accuracy of 4.2 %, i.e. (31.4 ± 1.3) MWd/kgU. When the neutron rate of bare fission chambers is used with the Deming code, the calculated burnup of the reference assembly is (31.20 ± 0.63) MWd/kgU. Using the overall accuracy of 4.2 %, the deduced burnup of the reference assembly is (31.2 ± 1.3) MWd/kgU.

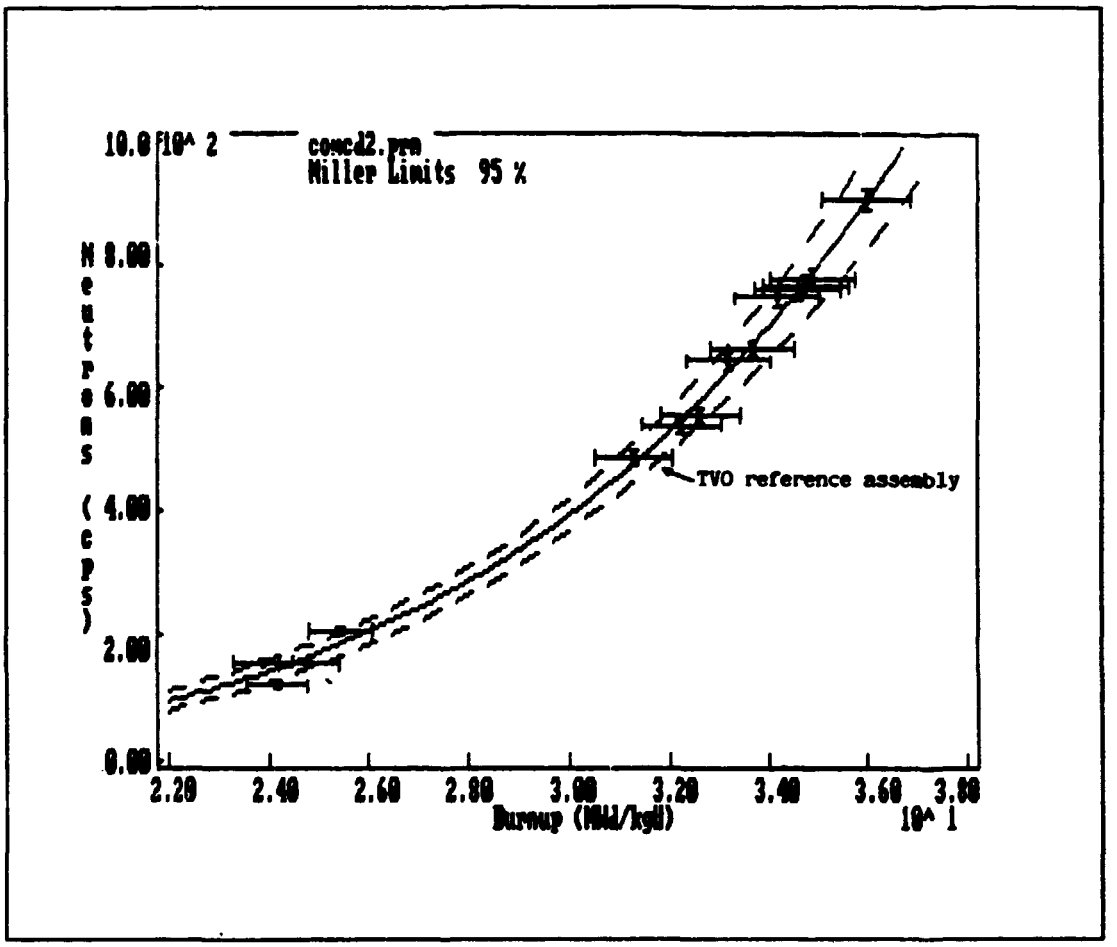

Figure 24. The corrected (Cd-wrapped) neutron rate versus declared burnup for the CLAB measured assemblies and for the TVO reference assembly.

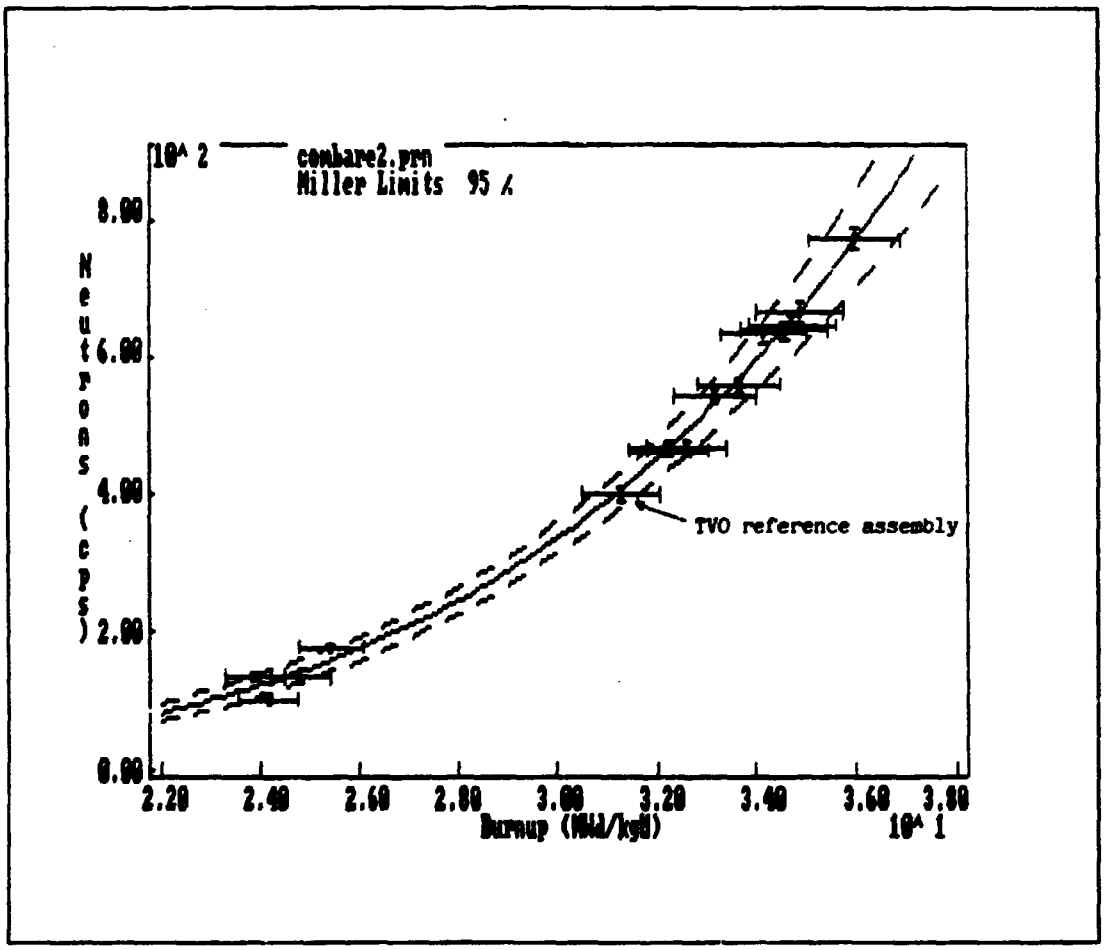

Figure 25. The corrected (bare) neutron rate versus declared burnup for the CLAB measured assemblies and for the TVO reference assembly.

Table II. Compilation of the neutron rates and burnup values for Cd-wrapped fission chambers. The relative difference between calculated and declared burnup is indicated by the diff. value.

Meas. at / No.	ID	Cd neutron rates (cps)			Burnup (MWd/kgU)		
		Detected for side		Corrected average for D & C	De-clared	Calcu-lated	diff. (%)
		D	C				
CLAB							
1	5711	639	636	777 ± 16	34.89	34.81	- 0.2
2	5769	452	457	553 11	32.62	32.32	- 0.9
3	1196	612	611	745 15	34.17	34.50	1.0
4	4922	442	443	539 11	32.24	32.14	- 0.3
5	4921	444	441	539 11	32.24	32.13	- 0.3
6	1179	546	540	661 13	33.68	33.61	- 0.2
7	5808	744	745	907 18	35.99	36.01	0.1
8	5762	529	526	643 13	33.19	33.40	0.6
9	5717	617	628	758 15	34.59	34.63	0.1
10	4855	130	130	158 3	23.89	24.58	2.9
11	4854	128	127	155 3	24.82	24.47	- 1.4
12	4857	98.6	99.2	120 2	24.16	23.15	- 4.2
13	5721	626	628	764 15	34.75	34.68	- 0.2
14	4858	171	171	208 4	25.44	26.09	2.6
TVO							
15	6782	397	400	485 10	31.28	31.41	0.4

Table III. Compilation of the neutron rates and burnup values for bare fission chambers. The relative difference between calculated and declared burnup is indicated by the diff. value.

Meas. at / No.	ID	Bare neutron rates (cps)			Burnup (MWd/kgU)		
		Detected for side		Corrected average for D & C	De-clared	Calcu-lated	diff. (%)
		D	C				
CLAB							
1	5711	548	547	667 ± 13	34.89	34.87	- 0.1
2	5769	389	377	467 9	32.62	32.24	- 1.2
3	1196	526	517	635 13	34.17	34.50	1.0
4	4922	386	377	465 9	32.24	32.21	- 0.1
5	4921	386	379	466 9	32.24	32.24	0.0
6	1179	463	459	561 11	33.68	33.58	- 0.3
7	5808	636	632	773 15	35.99	36.02	0.1
8	5762	449	444	544 11	33.19	33.35	0.5
9	5717	525	528	642 13	34.59	34.58	- 0.0
10	4855	111	112	136 3	23.89	24.58	2.9
11	4854	110	112	135 3	24.82	24.55	- 1.1
12	4857	82.1	84.9	102 2	24.16	23.07	- 4.5
13	5721	530	534	648 13	34.75	34.66	- 0.3
14	4858	146	146	178 4	25.44	26.09	2.6
TVO							
15	6782	335	325	402 8	31.28	31.20	- 0.3

4.3 HRGS calibration line

The measured ^{137}Cs intensities are listed in Table IV. The data represent an average over the whole assembly and over the four corners. By plotting the intensities as a function of declared burnup values, the graph shown in Figure 26 is obtained. The line is a least squares fit to all data points obtained at CLAB, except the one corresponding to assembly 5711, which features an unexpectedly large deviation (see 4.4). The equation of the line is:

$$I_G = K * BU \quad (15)$$

where K = (2.86 ± 0.02) counts/sec/MWd/kgU.

The ^{65}Zn intensities in Table IV for assemblies no. 6 – 8 are somewhat higher. This is due to the fact that the Zn-source was moved and repositioned roughly at the same place again. The significant change of intensities indicates a possibility to use a source of this kind to check if the detector system has been tampered with during the measurement.

Table IV. Measured gamma-ray intensities and the relative difference between the calculated and the declared burnups.

Meas. at / No.	ID	BU (MWd/kgU)	Measured ^{65}Zn rate (cps)	Measured ^{137}Cs rate (cps)	Burnup diff. (%)
CLAB					
1	5711	34.89	19.2 ± 0.3	105.1 ± 1.6	5.3
2	5769	32.62	19.3 0.3	92.0 1.4	- 1.4
3	4922	32.24	19.4 0.3	91.9 1.4	- 0.3
4	4921	32.24	19.1 0.3	90.6 1.4	- 1.7
5	5808	35.99	19.2 0.3	104.4 1.6	1.4
6	5762	33.19	20.2 0.3	96.1 1.4	1.2
7	4855	23.89	20.2 0.3	69.9 1.0	2.3
8	4854	24.82	20.2 0.3	71.3 1.1	0.4
9	1405	19.83	19.1 0.3	57.5 0.9	1.4
TVO					
10 R	6782	31.28	15.1 0.2	88.1 1.3	- 1.5
11	4538	18.03	15.0 0.2	49.6 0.7	- 3.8
12	7501	33.06	15.0 0.2	91.4 1.4	- 3.3

Figure 26 also includes two lines representing ± 5 % deviation from the fitted line. The intensity of assembly 1405 has been corrected with a factor of 0.87 ± 0.01 for the fact that this assembly was not mounted in a fuel channel. The intensity values for the three TVO assemblies given in Table IV are the originally measured intensities multiplied with a normalization factor C_c = 6.58 ± 0.08 obtained from the reference source measurements and Equation (12). The intensities have also been corrected according to the discussion in section 3.2.4.

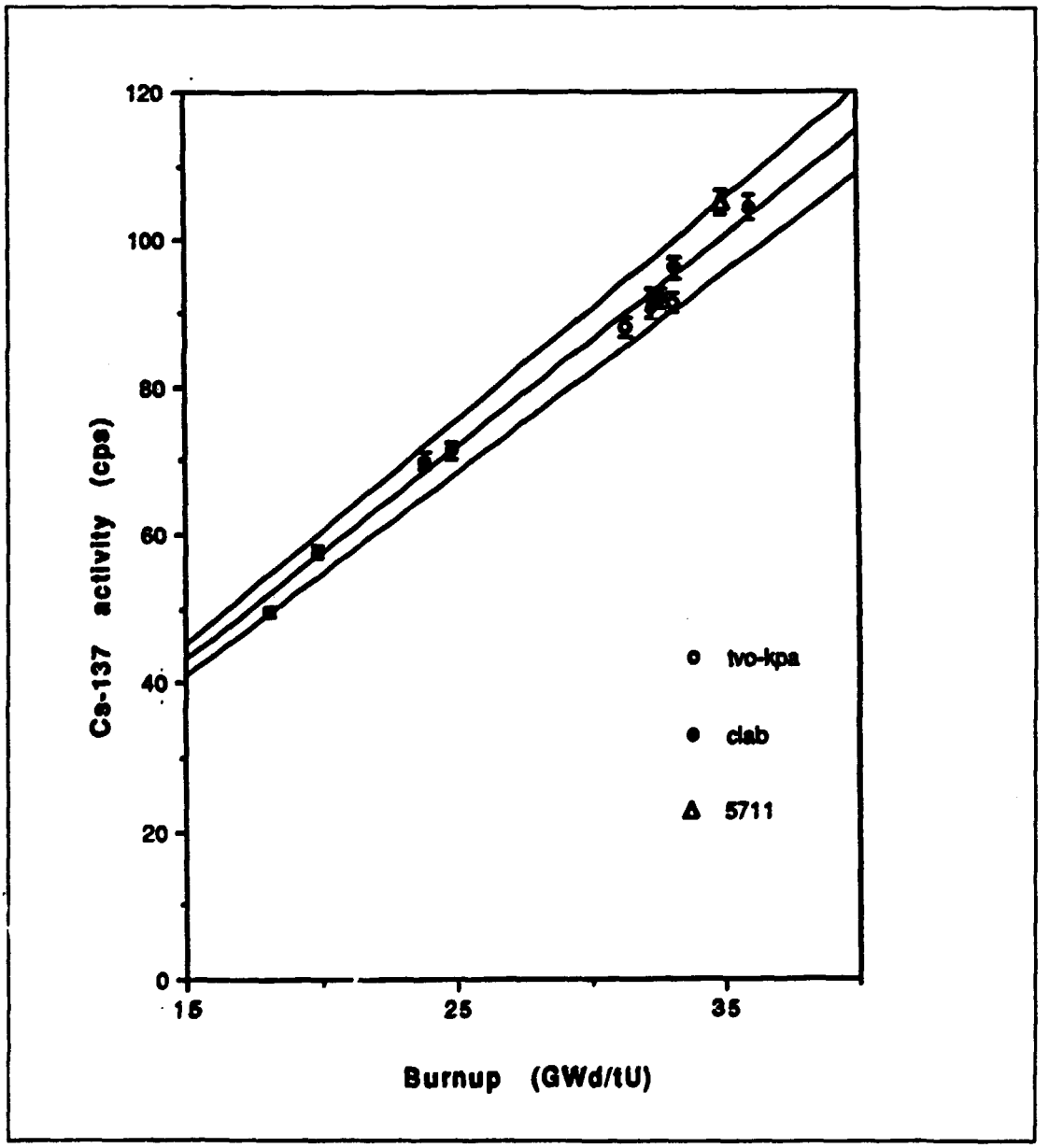

Figure 26. ^{137}Cs calibration line of the CLAB measured assemblies and the TVO measured assemblies.

4.4 Burnup deduced by HRGS

The last column of Table IV displays the relative difference between the burnup values calculated from the fitted line and the measured ones. The CLAB points lie typically within ± 2 % and the standard deviation is 1.5 %. Assembly 5711 is an outsider, as the measured intensity is far from the fitted line. A preliminary analysis of the ^{154}Eu intensities of the CLAB assemblies shows a regular dependence of burnup on all assemblies and gives no clues about the behavior of 5711 in this case. A re-measurement is therefore planned for this assembly in order to reveal the discrepancy.

From Table IV and Figure 26 it is clear that the TVO data lie systematically below the CLAB data. As discussed in section 3.2.4, the discrepancy between CLAB and TVO data was due to a geometrical inconsistency of the TVO KPA-STORE collimator, and the correction factor applied to the TVO data was reasonable according to the results from the test experiment on that collimator. However, the correction factor is afflicted with a large uncertainty that is difficult to estimate and has not been included for the TVO data in Table IV and Figure 26. It should be noted that the discrepancy is not inherently connected to the method as such, but indicates that care should be taken in shaping and assembling the collimators. If this is done, it can be estimated that the HRGS calibration method would yield a precision of ± 1 %.

4.5 Cooling time verification

Gross gamma (GG) measurements performed with the fork detector were used for rough verification of the declared cooling time (CT). No normalization between the different measurement geometries was done. The PNA measurements with the ^{252}Cf source proved to be repeatable within about ± 1.6 % (see 3.1.8). The repeatability of the gross gamma measurements, using the same detector head, can be estimated to be about the same.

The cooling time verification method itself is approximative in nature. This is why a detailed error calculation would not be very useful. It should be kept in mind also that the cooling time is quantized, i.e. only integers of irradiation cycles, each about one year long, are possible.

By fitting the power function of Equation (2) to the 14 CLAB measured points, the following fitting parameters were received: a = (2.6 ± 1.9) x 10^4 and b = (0.915 ± 0.097) with GG given as the GRAND I gamma reading, BU in MWd/kgU and CT in days. Figure 27 shows the cooling time curve, measured gross gamma reading divided by the declared burnup in MWd/kgU versus declared cooling time in days, with fixed ± 15 % limits for the Y-values. The Deming code was used to interpolate the cooling time for each measured GG/BU ratio. These calculated cooling times are compilated with the declared values in Table V. The measured cooling time of the TVO reference assembly is 269 days, about 9 months, shorter than the declared value. The uncertainty of the result is, however, large. Table V shows also the relative differences between the calculated and the declared cooling times.

With the above mentioned limitations in mind, it can be concluded that the declared cooling time of the TVO reference assembly is consistent, within the measurement uncertainty, with the declared cooling times of the CLAB assemblies.

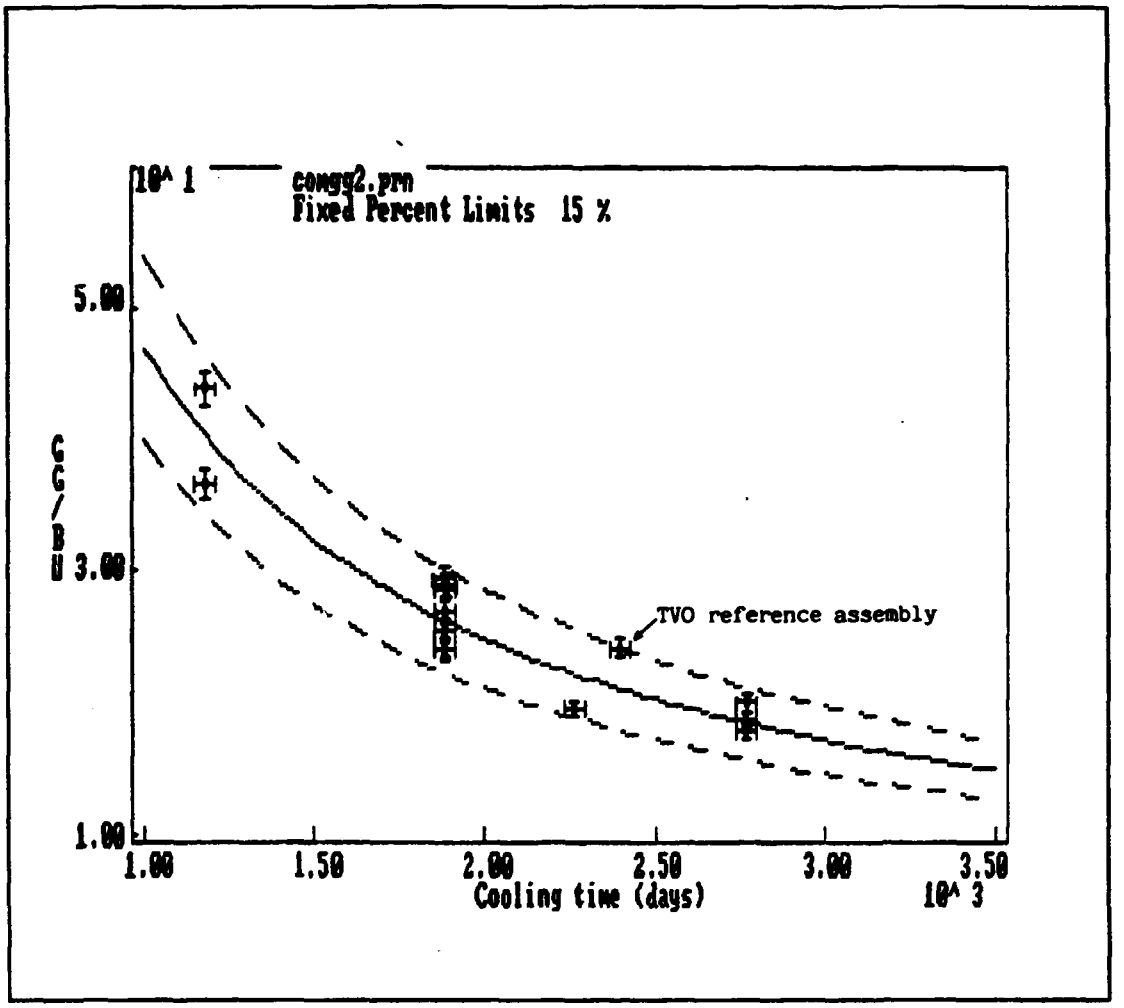

Figure 27. Cooling time curve for the measured assemblies.

Table V. Compilation of the gross gamma (GG) and cooling time (CT) data. The relative difference between the calculated and the declared cooling time is indicated by the diff. value.

Meas. at / No.	ID	Detected GG reading for side		Average GG (D & C) /BU $(MWd/kgU)^{-1}$	Cooling time (days)		
		D	C		De-clared	Calcu-lated	diff. (%)
CLAB							
1	5711	1022	1036	29.4 ± 0.9	1879	1667	- 11
2	5769	1183	1199	36.5 1.1	1176	1315	12
3	1196	916	922	26.9 0.8	1880	1836	- 2.3
4	4922	774	789	24.1 0.7	1880	2071	10
5	4921	777	785	24.0 0.7	1880	2074	10
6	1179	856	872	25.6 0.8	1880	1942	3.3
7	5808	1582	1575	43.9 1.3	1177	1076	- 8.6
8	5762	943	956	28.6 0.9	1881	1716	- 8.8
9	5717	1008	1009	29.0 0.9	1881	1690	- 10
10	4855	450	443	119 4	2766	2734	- 1.2
11	4854	442	440	17.8 0.5	2766	2887	4.4
12	4857	482	463	19.5 1.1	2262	2601	15
13	5721	1004	1009	28.8 0.9	1883	1703	- 9.6
14	4858	513	503	20.0 0.6	2767	2540	- 8.2
TVO							
15	6782	749	757	24.1 0.7	2340	2071	- 12

5 DISCUSSION

The reference assembly of the TVO KPA-STORE is a part of the GBUV verification method developed for LWR spent fuel verification. The GBUV method itself is capable for semi-quantitative verification of spent BWR fuel assemblies supposing all the fissile material is present. Extra assurance of the integrity of the measured assemblies can be received by weighing them during verification.

By measuring several points of each assembly the sensitivity of PNA to positioning and small local changes of burnup was smoothed out. By selecting assemblies which are favorable to PNA measurements, two high quality calibration curves were established. This is especially true for the burnup region above 30 MWd/kgU where the consistency between the measured assemblies was of the order of 1 %. The performance control of the whole measurement chain by the ^{252}Cf source guaranteed tamper proof normalization and operation of the method as well as conclusions of the reference assembly burnup. The results of the PNA calibration are supported independently by the HRGS results. The PNA results of the cross calibration show consistency between declared and measured burnup values that is of the order of ± 1 %. This precision is obtained for the CLAB measurements as well as the measurements performed at TVO.

The combined neutron and gamma calibration measurement has given opportunity to accurately test the Cs reference source method. The measurements show good agreement between declared and measured burnup. The precision is within 2 % in this case. Taking into account that the accuracy of the declared mean burnup is ± 2.5 %, means that the declared burnups of the assemblies irradiated at the four facilities listed in Table I are verified by NDA to be consistent on a confidence level normally only achieved by using destructive assay (DA).

The IAEA Safeguards Criteria for Spent LWR fuel requires partial defect verification to be able to reveal missing of ≥ 50 % of the fissile material. The results of this report indicate that PNA and HRGS methods alone or especially combined can make it possible to lower the detection limit from 50 % by one order of magnitude.

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