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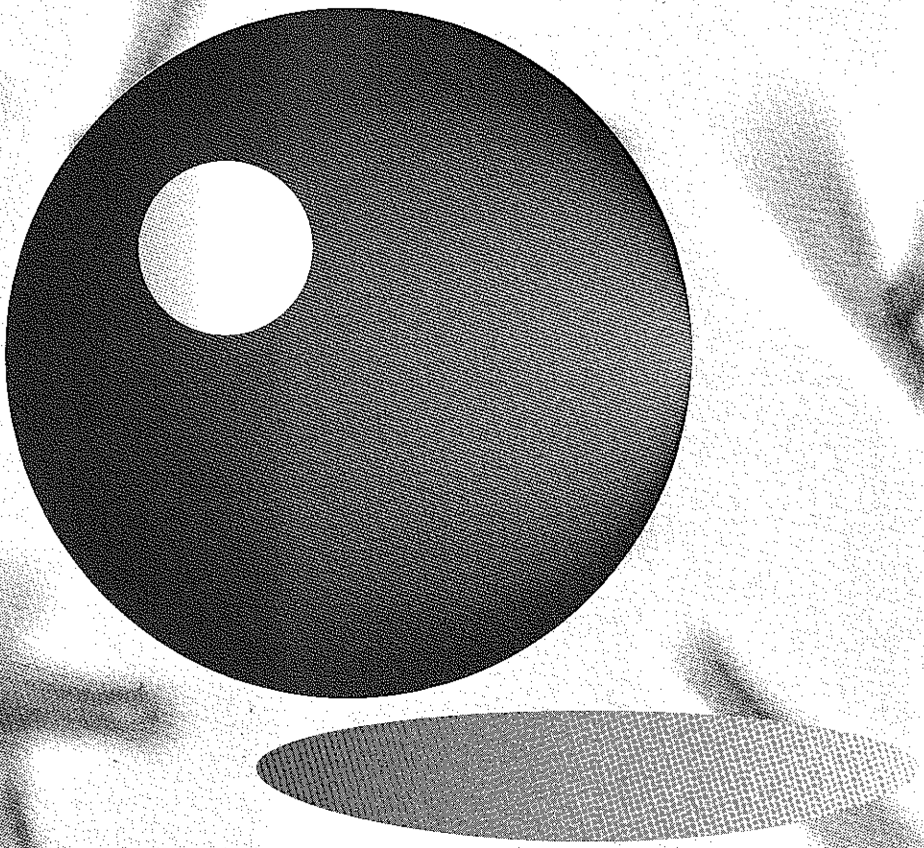

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Electronic data treatment within PIE

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Summary	**Distribution**
Since a couple of years the IFE hot lab at Kjeller has introduced electronic data acquirement, treatment and storage to a number of post irradiation examination (PIE) techniques. Electronic data acquirement and data treatment is a powerful tool within evaluation and graphic presentation of measuring data, documentation of structural/microstructure images with photographic quality, quantitative image analysis, archiving, and quality assurance. In this presentation the benefits of electronic data acquirement and treatment are shown and discussed for dimensional measurements and gamma scanning of irradiated fuel rods.	**Summary:** Directors Project management, Halden Department heads

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Topic I

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Topic I

Electronic data treatment within PIE

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1 Abstract

Since a couple of years the IFE hot lab at Kjeller has introduced electronic data acquirement, treatment and storage to a number of post irradiation examination (PIE) techniques. Electronic data acquirement and data treatment is a powerful tool within evaluation and graphic presentation of measuring data, documentation of structural/microstructure images with photographic quality, quantitative image analysis, archiving, and quality assurance. In this presentation the benefits of electronic data acquirement and treatment are shown and discussed for dimensional measurements and gamma scanning of irradiated fuel rods.

2 Introduction

During the last years high quality personal-computers came on the marked at a reasonable price. State of the art computers can handle large amounts of acquisition data for processing and storing, i.e. several MFLOPS. The combination of effective computers and suitable, commercially available data handling software opens up new possibilities in acquisition and visualisation techniques. With the introduction of modern digital data acquisition equipment well established PIE methods for irradiated fuel rods such as dimensional measurements and γ-scanning can be extended further.

3 Dimensional measurements

Physical parameters such as diameter and bow (profile) of irradiated, experimental fuel rods are measured in profilometry. The measurements are an important experimental control of reactor induced deformations of fuel rods, e.g. pellet cladding interaction that can lead to rod degradation or failure. Up to recently, results from profilometry could only be presented in 2-D graphs. In such graphs diameter values are plotted versus the positions on the rod axis at a given circumferential orientation.

Over the last three years the laboratory has done modifications to the profilometer bench. This includes a new steering control and data acquisition system. The acquisition system in profilometry was upgraded for three-dimensional surface measurements, i.e. fuel rod outer diameter and straightness. Three dimensional measurements (3-D) mean that with each individual measurement three parameters (intensity, circumferential/0 to 180(360) degree and axial position along the rod axis) are logged and used in data evaluation and presentation. With the newly modified profilometer bench at the hot laboratory at Kjeller and suitable software 3-D maps of a fuel rod can be produced. The 3-D maps give a complete picture of the rod.

3.1 Experimental set-up for 3-D profilometry

Description of the profilometer bench: The measurement principle of the profilometer bench is based on linear voltage displacement transducers (LVDT) connected to two measurement knives. The profilometer bench and transducer arrangement are given in Fig. 1.

The knife edge (sapphire) is on a 2 mm diameter polished sapphire rod. Both knives are connected to the diameter LVDT and one of them is also connected to the profile LVDT. One of the transducers measures the outer diameter of the fuel rod and the other one the profile or distance from the rod to the bench structure (steel axle).

Programmable step motors control the movement of the measuring bridge or trolley in the vertical direction (approximately parallel with the fuel rod) and the circumferential direction (rotation) of the rod. The trolley is moved up and down where the minimum step-length corresponds to a displacement of 5 μm. The minimum angular displacement corresponds to 0.9 degrees. This means that the measuring trolley moves upward one step and then the rod rotates 400 steps (max.) until it reaches the zero degree orientation, moves another axial step and so on.

The data acquisition is performed between each rotation step while the rod and trolley is completely at rest (static measurements).

Alignment of the knives: For the overall accuracy of the measurement a correct alignment of the knives is significant, prior to all dimensional measurements. The knives have to be aligned vertically parallel and horizontally tip to tip. When doing profilometry measurements on a slightly bowed fuel rod and the alignment of the two knives is poor, the error in measurements introduced at certain angular orientations of the fuel rod can be quite large (30-50 μm). A procedure for adjusting the alignment of the knives within certain limits is necessary and established to assure a satisfactory overall measurement accuracy.

Steering control, data acquisition, and data storage: The complete measuring programme for calibration rods and fuel rods is performed by a personal computer and a data programme developed at IFE called ROD MASTER. The data programme, with its hardware, generates the pulses to the two step motors to obtain the correct measuring position and reads the signal values from the two transducers. The values are stored together with the generatrices (angular orientation) and axial position on the storing disk. When the dimensional measurements is completed the acquired data set is transferred to a password protected network disk. The axial position along the fuel rod is usually counted relative to the lower end of it, positive upwards. The generatrix values are counted from 1 to 360 and counter-clockwise when viewing the rod from above.

Calibration: The diameter and profile sensor is calibrated by measuring on a calibration rod with two (or more) accurate machined regions (D_1, D_2) that are close to the fuel rod diameter (D), i.e.

$$D(z,\theta) = (\Delta D/\Delta C)\{C(z, \theta) + D_1\},$$

where $\Delta D/\Delta C = (D_1-D_2)/(C_1-C_2) \equiv (\text{sensitivity})^{-1}$, C_1 and C_2 represent the analogue-digital converter (ADC) values acquired from the two calibration steps and $C(z, \theta)$ is the ADC value for the diameter sensor at an arbitrary position. The bow or profile (P) of the rod is given by,

$$P(z,\theta) = 0.5\cdot(\Delta D/\Delta C)\cdot C'(z, \theta) + \text{an arbitrary constant},$$

where $C'(z, \theta)$ is the ADC value for the profile sensor at an arbitrary position.

Data treatment: The presentation software used in visualisation of the measurement values (Z) in a three dimensional (3-D) surface map such as shown in Fig. 5, is called 'Surfer', a standard software package from Golden Software, Inc. (USA). *Surfer* is a grid-based contouring and three dimensional surface plotting/mapping programme that runs under Microsoft Windows, Windows 95 and Windows NT. *Surfer* interpolates irregularly spaced XYZ data on a regular spaced grid, and places the interpolated data in a grid file. The grid files are used to produce contour maps and surface plots. Maps are enhanced with *Surfer* by adding boundary information, posting data points, and combining several maps. With the programme further functions can be done, such as adding of drawings to a map, annotating maps with text, etc.. It is also possible to operate on the grid files made from the data set. *Surfer* has commands for smoothing the surface represented by the grid, performing mathematical transformations on grids, and creating grids that represent mathematical surfaces. It is also possible to slice arbitrary traces out from the actual surface and plot it with a *Grapher* package (two-dimensional).

3.2 Qualification test on calibration rod

The ovality of a fuel rod measured can be visualised with the 3-D technique. To demonstrate the effectiveness of this technique a qualification test is done on a well defined calibration rod.

Calibration rod: The calibration rod was machined after given specifications. The rod was made of stainless steel with an initial diameter of 14 mm. It has three distinct regions with different ovality A, B, C. Significant dimensions of the rod can be easily controlled with a micrometer gauge. The dimensions of the test rod are given in Fig. 2. The ovality regions A, B, and C were produced with a programmable t-slot milling machine and the ovality is 25, 15 and 10 μm at the middle of each calibration region. The calibration rod also contains a zero degree orientation mark and a V-groove. The orientation of the initials measurement point coincides approximately with the angular location of zero degree mark (manual setting). The V-groove is used to control the vertical alignment of the knives.

Experimental: The rod was mounted into the modified profilometer bench and measured. The steps selected in the measurement were in angular direction 7.2 degrees (50 measurements per round) and in axial rod direction 1 mm. Measurements of the rod were done along the angular axis from 0 to 360 degree and along the rod axis from 50 mm to 80 mm. Due to the 180 degrees symmetry of the measuring knives the orientation range of 360 is not strictly necessary, but it is done here for the sake of illustration and completeness. The 180 degrees symmetry means that the two knives will switch location after a rod rotation of 180 degrees. In 360 degree measurements experimental inaccuracies can be proven. Experimental accuracy in terms of perfect alignment of the knives is achieved when the diameters measured between 0 and 180 degree commute with diameters measured between 180 and 360 degree. Electronic data treatment was done to present the measurements in a 3-D map of the rod.

Results: Fig. 4 (contour plot) is a so called 3-D map presenting the result of the dimensional measurement on the calibration rod. The marks A, B, and C in the 3-D map in Fig. 3 coincide with specified regions in the ovality test rod given in Fig. 2. The 3-D map presents each measured rod diameter with a grey value. The colour-scale (grey-scale) next to the 3-D map ranging from 11.970 mm (white) to 12.021 mm (black) represents diameter values in the 3-D map. The 3-D map contains all values for the rod diameter measured along the angular axis from 0 to 360 degree and along the rod axis from 50 mm to 80 mm.

When analysing the 3-D map in Fig. 3 bright parallel lines which vary in intensity, grey background, and dark regions are striking.

The bright lines represent diameter minima (11.970 mm) compared to the darker (grey) surroundings/background (11.994 mm). The numbers in brackets are the diameters values taken from the 3-D map grey-scale. The diameter minima are in fact circumferential tracks/rills on the calibration rod, caused in the machining operation by a non precise T-slot cutter. The T-slot cutter introduced at one end a several micrometer deep rill/spoor (ca. 20 µm) . The brightness variation of the lines in circumferentially direction is noticeable with an intensity minima from 50 to 130 degree and from 230 to 310 degree. The brightness variation of the lines reflect diameters ranging from 11.970mm to 11.982 mm. The intensity minima indicate higher diameter values (11.982 mm). This indicates an interference of the line/rills with the ovality in the rod in the actual areas of some 10 µm.

The dark spots in the 3-D map represent the location of the maximum rod diameter (ovality). In the 3-D map it can be seen that the maximum rod diameter due to ovality is smaller and represented by a brighter dark spots in region B (12.012 mm) than in region A (12.021 mm). The numbers in brackets give the diameter readings from the 3-D maps. Due to ovality the control measured maximum diameter of the rod in about 100 (280) degree in region A is 12.021 mm and in region B 12.014 mm.

If one analyses the diametrical map in Fig. 3 the diametric profile from 0 to 180 degree is along the entire rod axis close to a duplicate image of the diametric profile between 180 and 360 degree. One can see that the maximum ovality is located at approximately 100 (280) degree and the minimum is at 10 (190) degrees which is in agreement with the calibration rod design given in Fig. 2. Minor mismatches can be seen. That is due to a minor aligning error of the knives. Absolutely correct aligning is impossible to achieve with the type of measuring bench used.

Conclusion on measurement of the calibration rod: The results taken from the 3-D map on the maximum diameters in the oval regions A, B, and C and their circumferential and axial location on the rod are in good agreement with the values obtained in direct control measurements with a micrometer on the calibration rod, documented in Fig. 2.

The result obtained with the new concept of dimension measurement and electronic data treatment on the well defined calibration rod is promising. It shows that electronic process controls and electronic data acquirement and treatment in conventional profilometry gives correct results and additionally further and valuable data on the rod. From the 3-D map it is possible to slice arbitary traces out from the actual surface and plot the slice which represents a 2-D graph with a *'Grapher'* package.

3.3 3-D profilometry on irradiated fuel rod

Irradiated fuel rod: The rod used in this example was a conventionally irradiated MOX fuel rod. At IFE it was refabricated and instrumented with a pressure transducer and fuel centre thermocouple in the hot laboratory at IFE, Kjeller for further experiments (ramp testing) in the OECD Halden reactor. After ramp testing the fuel rod diameter was measured in the profilometer bench.

Experimental: The x-axis (along the fuel rod) is measured from 380 to 860 mm (fuel stack region, $\Delta x = 1$ mm) and the φ-axis (circumference, $\Delta\varphi = 7.2$ degrees) from 0 to 180 degrees.

Results: The result of the measurement is presented 3-D maps given in Fig. 4 and Fig. 5. The start and end of the active fuel stack region are indicated in the maps and controlled against the gross gamma scan of the fuel rod.

A number of striking features can be seen in the 3-D map of Fig. 4 and Fig. 5. Firstly, and most dominant are the dark-grey, vertical and parallel lines in a grey background. Secondly, appears a diagonal background pattern looking like sea waves. The background pattern is made up of parallel and diagonal stripes, alternating dark and bright.

The features of interest are more enhanced in Fig. 5 than in Fig. 4. The high-lighting or enhancement is achieved by data treatment, namely by selection of the threshold. The 3-D map in Fig. 4 has more steps in the grey values scale than the one in Fig. 5.

The dark-grey lines (diameter maxima) on a grey background reflect the deformation of the rod due to *pellet-pellet-cladding interactions or ridges* generated in-pile. The 3-D map give with the help of grey-scale directly access to diameter readings (in mm) in the dark-grey, vertical parallel lines, representing ridging. The number of pellets can be calculated from the number of the dark-grey, vertical and parallel lines.

The diagonal background stripes represents most probably a roller pattern generated during the fabrication process of the tube. Fig. 6 illustrates the roller pattern in a transversal slice which is twisted all along the tube with a pitch length (angle) of approximately 200 mm (80 degrees). The diameter difference of minimum and maximum in the roller pattern (30 degrees delay) is estimated to be below 10 µm (secondary ovality).

The ovality of a rod /tube can be described as ($\varnothing D_{max}$) - ($\varnothing D_{min}$), where ($\varnothing D_{max}$) is the average, overall diameter maximum in neighbouring axial and circumferential positions (D_{max} -zone) and ($\varnothing D_{min}$) is the average, overall diameter minimum in neighbouring axial and circumferential positions (D_{min}-zone). The *ovality characteristics of the fuel rod* is easily observed in the 3-D map in Fig. 5. A zone with an overall-minimum diameter (D_{min}) appears in the map as a bright zone. Such a zone is located at 0 (180) degree along the rod axis. A zone with an overall-maximum diameter (D_{max}) appears as a darker zone. D_{max} is located at about 30 to 150 degrees along the rod axis. Data presented in the 3-D map give access to extract 2-D graphs in an arbitrary circumferential orientation. To demonstrate the ovality of the rod and show the ridging two *2-D graphs or so called diameter curves* are extracted/sliced from the grid file for the 3-D map. The diameter curve in 0 degree orientation is given in Fig. 7 and the one for 90 degree in Fig. 8. The main ovality of the fuel rod ($\varnothing D_{max}$ - $\varnothing D_{min}$) is estimated from the 2-D graphs in Fig. 7 and Fig. 8 to be 50 µm (rough estimate).

Concluding remarks: The new concept of dimension measurement and electronic data treatment results in a more complete image of the surface of interest in terms of visualising and measuring features such as ovality, ridging and profiles of the fuel rod.

Future modifications to the knives used in the measurements in the profilometer bench may give access to detect fine defects in fuel rod canning, such as thin cracks etc.

4 Gamma Scanning

Gamma scanning of an irradiated fuel rod provides information on radioactive fission products. Gamma scanning in axial rod direction can additionally reveal major inhomogenites in the fuel and provide information on fuel integrity and fuel relocation. The experimental set-up for gamma scanning at Kjeller allows gamma-scanning on whole rods, called axial gamma scanning, and on transversal cross-sections of the rod, called transversal gamma scanning.

The transversal gamma scanning is normally performed in four different diametrical directions, as shown in Fig. 9. The spectrum is measured at various sample positions, e.g. rim region, mid radius and centre at one diametrical direction. The collimator slit aperture is normally 0.1x1.0 mm^2. An alternative collimator with circular opening (0.7 mm in diameter) can be used if desired. Initial positioning of the transversal sample is normally very time consuming and it is necessary to repeat the procedure for all new directions to be scanned.

Initiated last year, the gamma spectroscopy system for transversal gamma scanning will be upgraded. The prospective modification of the gamma scanning bench is to make three dimensional activity measurements of a complete transversal fuel rod cross-section possible.

4.1 Experimental

Detector and collimator: The isotopic content of irradiated fuel rods is acquired with a Canberra germanium detector (model GC2818) and a lead collimator. A number of different collimators are available, usually a collimator with a slit aperture of 0.3 mm is chosen. The detector is controlled by an IBM personal computer with the actual software installed.

Prior to the scanning, the gamma spectrum is recorded with a 1024 channel analyser. For the scanning, a number of energy windows (max. 6) are selected from the total spectrum. Window no. 1 contains the total gamma spectrum from 200 to 900 keV. Window no. 2 to 6 contain photopeaks corrected for the Compton background. Dependent upon the cooling time of the fuel rod, the following fission products are detectable; Cs134 and 137, Ru103 and 106, Zr95, Nb95, Ce144 and Eu154.

Movement for scanning: During the scanning, the fuel rod (specimen) rests on a horizontal support. The scanning is performed in steps, and for each step, the activity is measured for a pre set time. An IBM computer and control electronics generate the pulses to the step motor. Usually, the step length vary from 0.2 to 0.5 mm and the pre set time from 30 to 200 seconds, dependent upon the length of the fuel rod to be measured. The scanning resolution is about 0.35 mm.

Upgrading of the movement for 3-D scanning (future plans): Upgrading of the gamma spectroscopy system for transversal gamma scanning includes the implementation of a new steering system for two step motors performing the scanning. One of them will be used for the horizontal movements and the other for the vertical movements. This means that a transversal rod sample is capable of performing a meandering trace during the measurements.

Software: The software used in data treatment and plotting of the gamma scanning results is the same as for profilometry.

4.2 3-D transversal gamma scanning of specimen

Experimental: The specimen used to illustrate the principle of three-dimensional gamma scanning is a transversal sample, cut off from an irradiated fuel rod. Prior to the measurements, the sample was placed in a specimen holder, mounted in epoxy resin, ground and polished.

The collimator facing the sample during the 3-D gamma scanning had a circular opening with diameter 0.7 mm. The scanning was performed in steps of 0.4 and 0.5 mm in the horizontal and vertical direction respectively. For each step the activity was measured for a pre-set time of 20 seconds. Due to the relative short count time, the gross is the only energy window of interest. Between each horizontal scan, the sample was manually moved 0.5 mm in the vertical direction.

To verify the 3-D transversal gamma scanning and to allow a comparison of the results obtained with this technique with the results, obtained in 'normal' transversal gamma scanning, measurements with both techniques were performed on the same sample.

In 'normal' transversal gamma scanning measurements were performed in the four principal directions, namely 0 to 180 degree, 45 to 225 degree, 90 to 270 degree and 315 to 135 degree. The scanning was performed in steps of 0.2 mm

Results - gross gamma measurement: The result of the gross gamma measurement of approximately 75 percent of the sample surface is given in a 3-D contour plot/map in Fig. 10.

The same software package was used as for presentation of two-dimensional measurements. The colour scale in the figure represents the total gross gamma count values with a resolution of 3000 counts. The relative distance between the contour lines is proportional with the gradient of the gross gamma measurements, i.e. short distances means large variations in the count values and vice versa. Readings of the activity level in each area of the cross-section can be made directly in the 3-D map. The colour scale next to the 3-D map converts the colours in the map to activity levels in total counts.

From the map it is obvious that the total gross gamma activity and the activity variations are relative low in the centre region of the sample. The gross gamma activity increases when moving towards the sample edge. However, a local gross gamma maximum is found in the sample centre.

The results of the gross gamma measurements performed in the four principal directions, namely 0 to 180 degree, 45 to 225 degree, 90 to 270 degree and 315 to 135 degree are presented in four 2-D plots in Fig. 11. Each of the 2-D plots show the gross gamma activity in counts per second versus the diametrical distance in a given direction.

Concluding remarks - gamma scanning: The modified gamma scanning system allows three dimensional measurements (x and y orientation and intensity) of the transversal fuel rod cross-section.

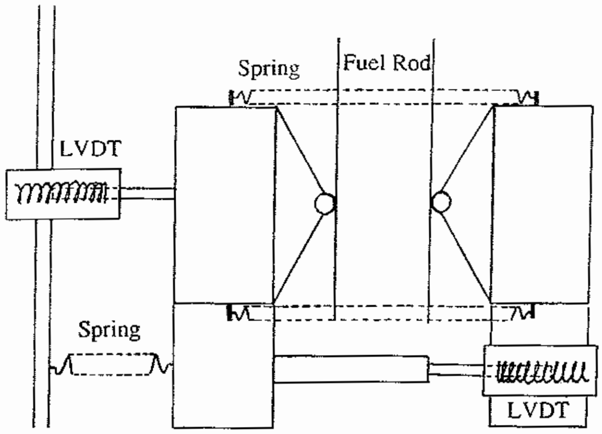
After upgrading the gamma scanning system and doing 3-D measurements with the 'meandering' technique the time consuming initial positioning of the specimen is no longer necessary.

The time needed with the 3-D measurements for data acquisition equals the time normally used during traditional micro gamma scanning in four different directions.

Preliminary measurements of gamma activity with a promising result were performed on transversal cross-section samples cut off from an irradiated reactor fuel rod. Further parameter studies have to be done to establish a 3-D scanning procedure.

5 Conclusion

The last three years upgrading and use of advanced electronic data treatments in PIE have improved the quality of all the project results



Transducer arrangement

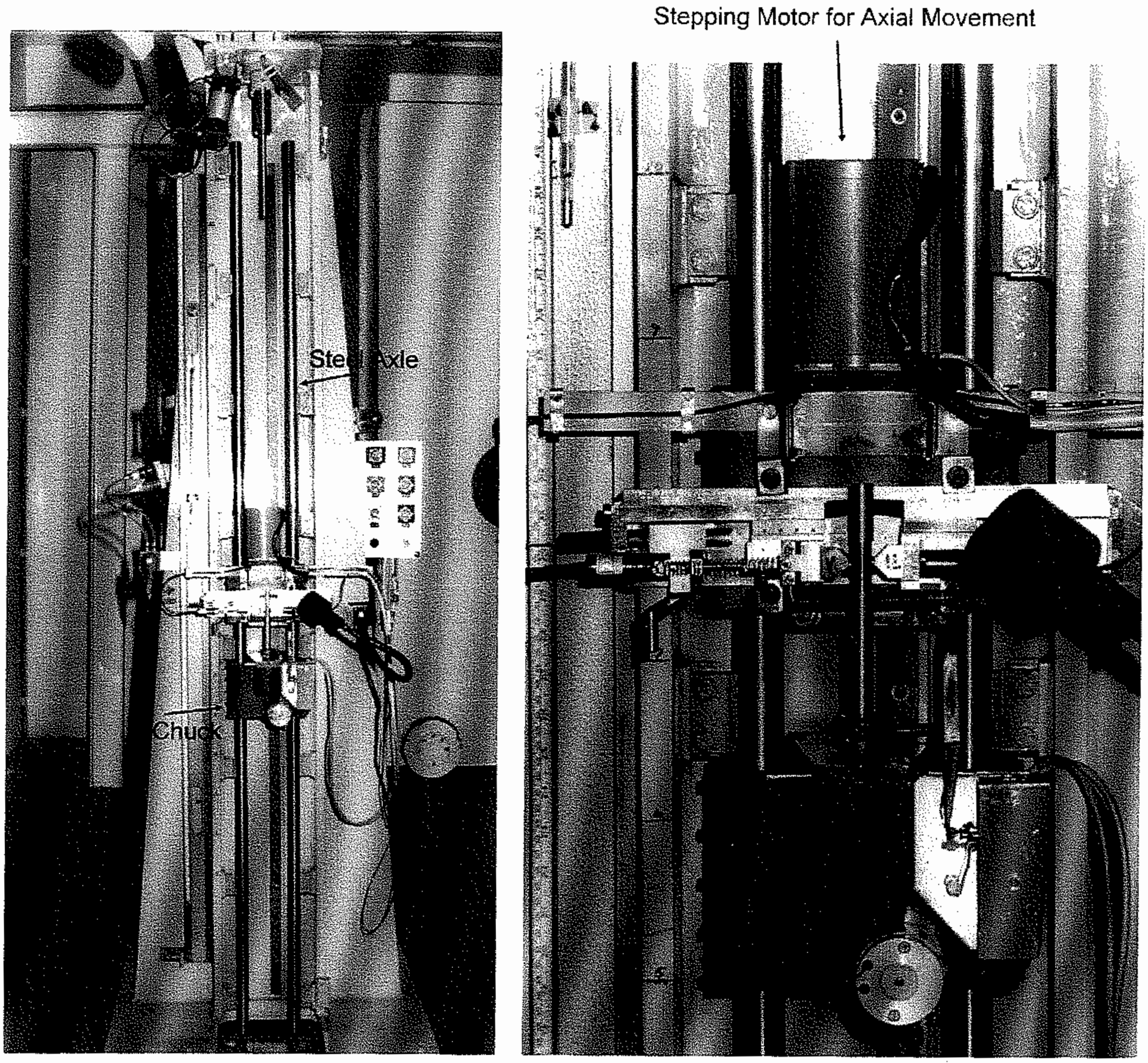


Fig. 1. Profilometer (dimensionale measurement) bench.

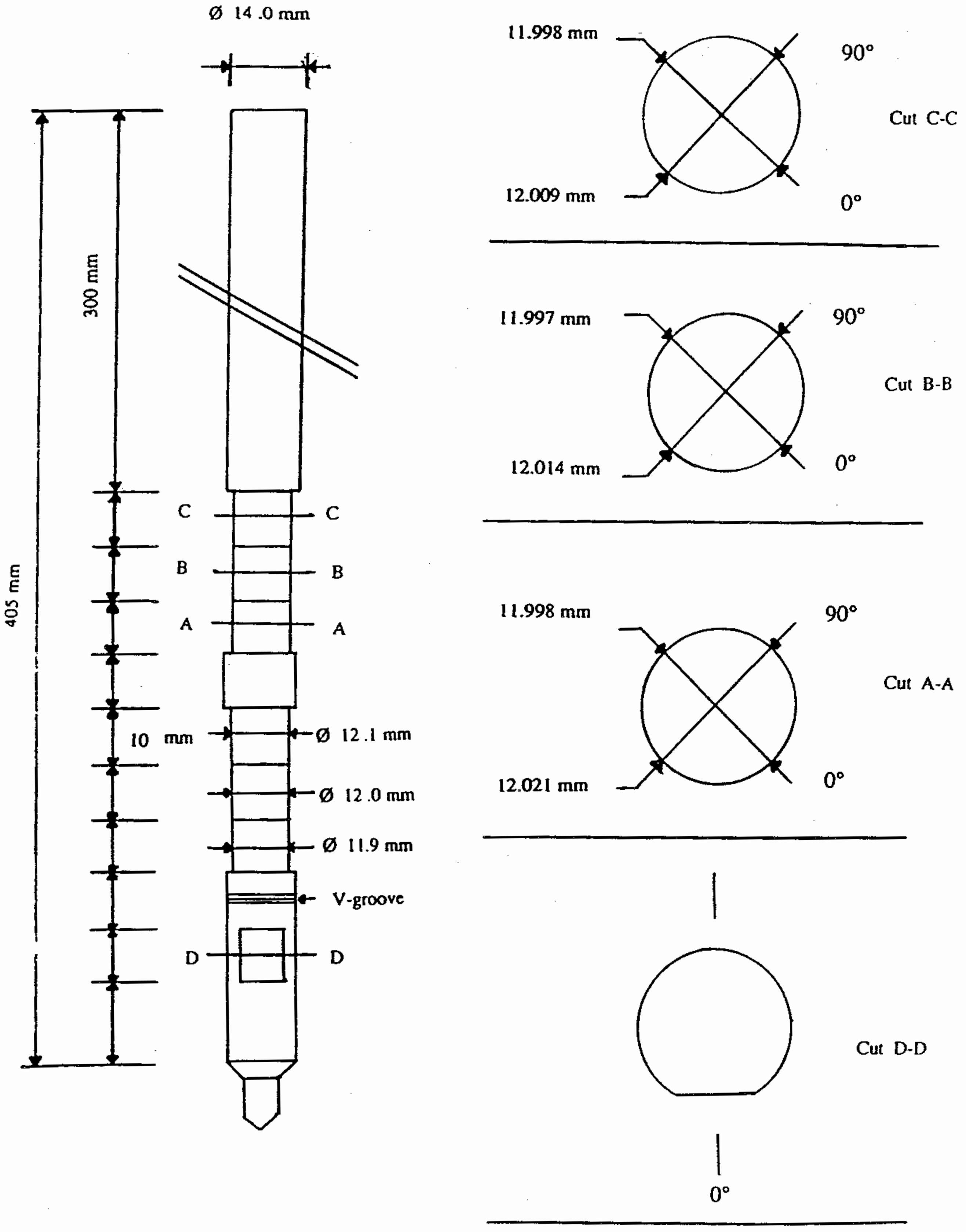


Fig. 2. Specification of ovality test rod.

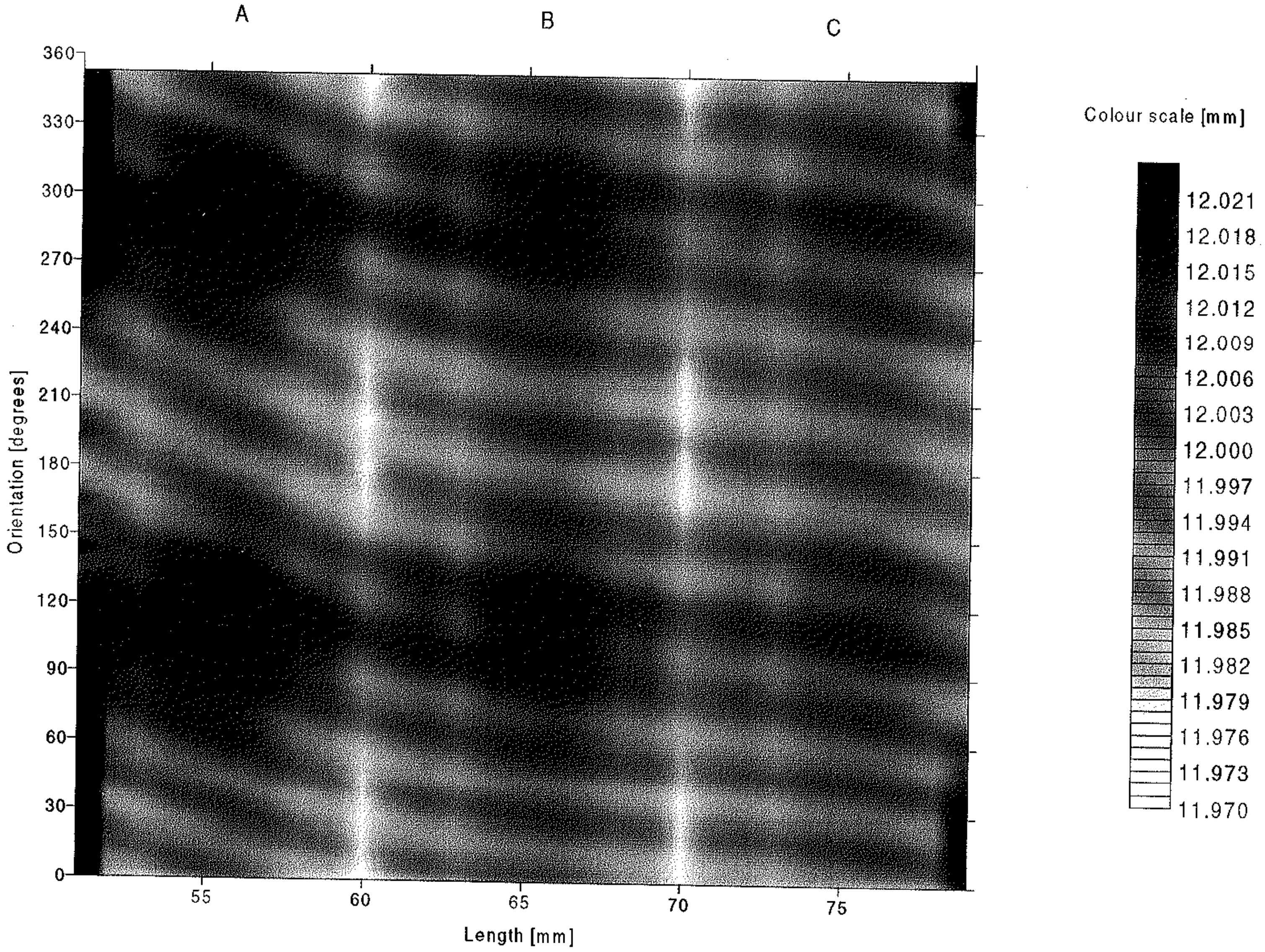


Fig. 3. Contour diameter plot of ovality calibration rod

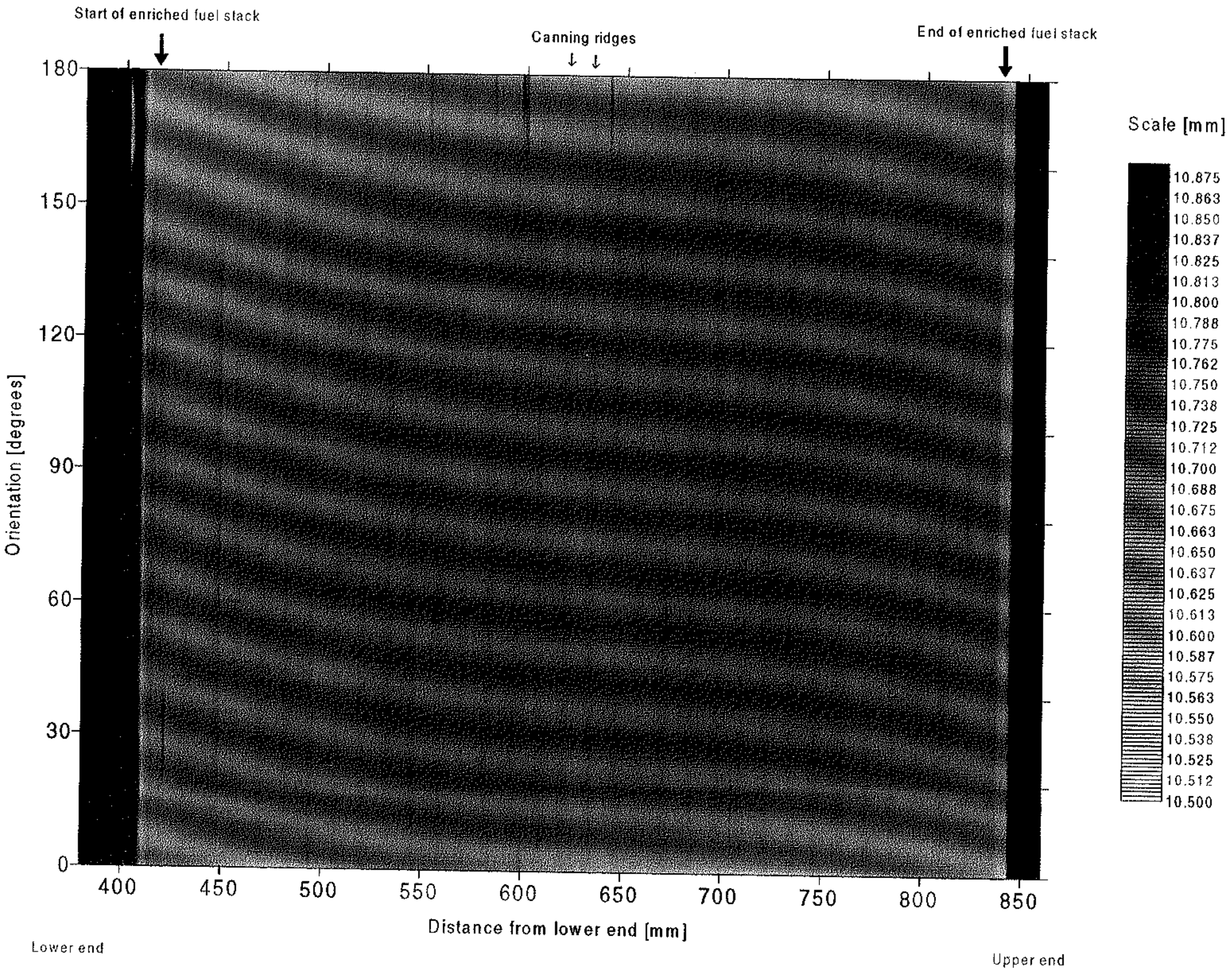


Fig. 4. Diameter surface scan of fuel rod (fuel stack region)

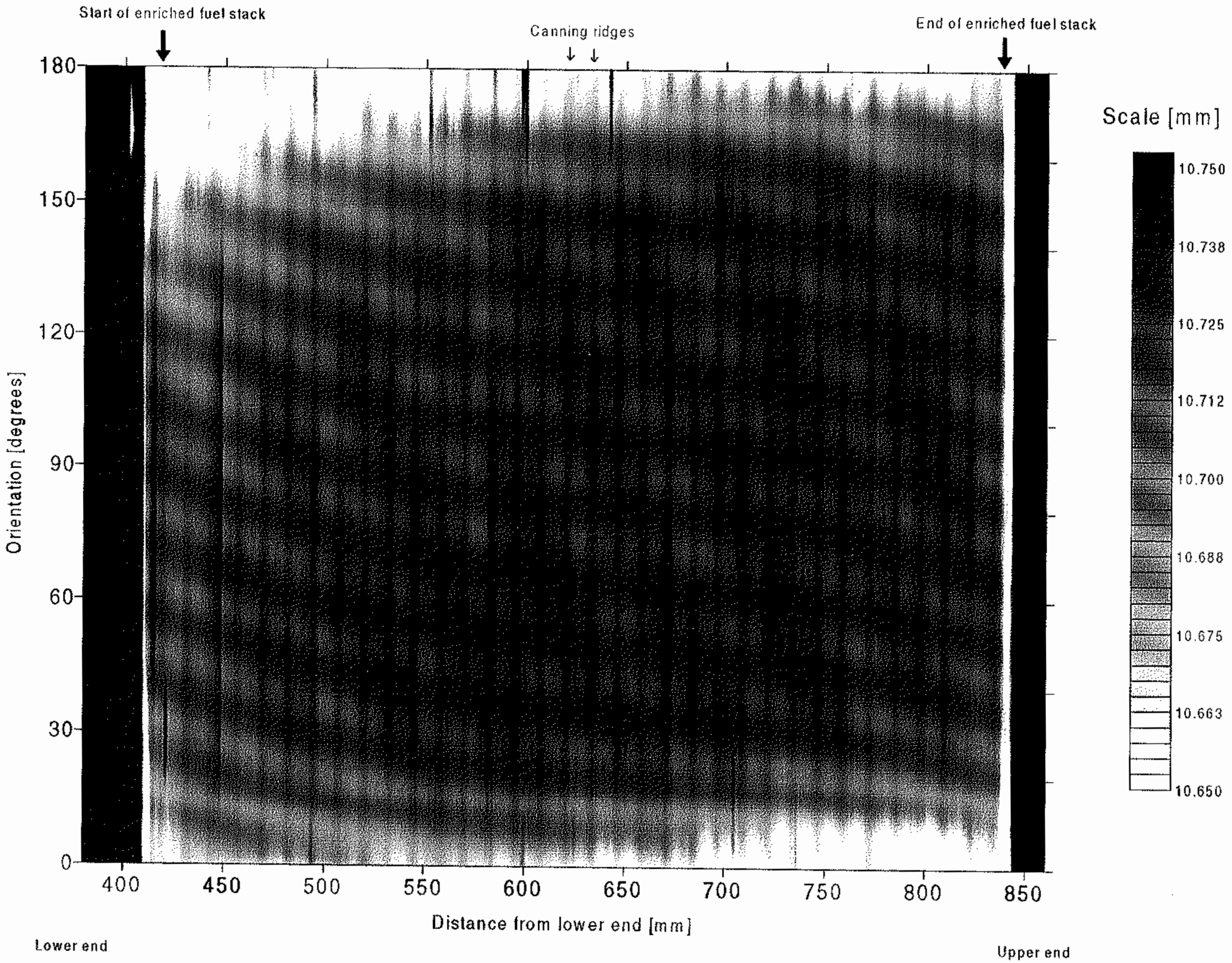


Fig. 5. Diameter surface scan of fuel rod (fuel stack region)

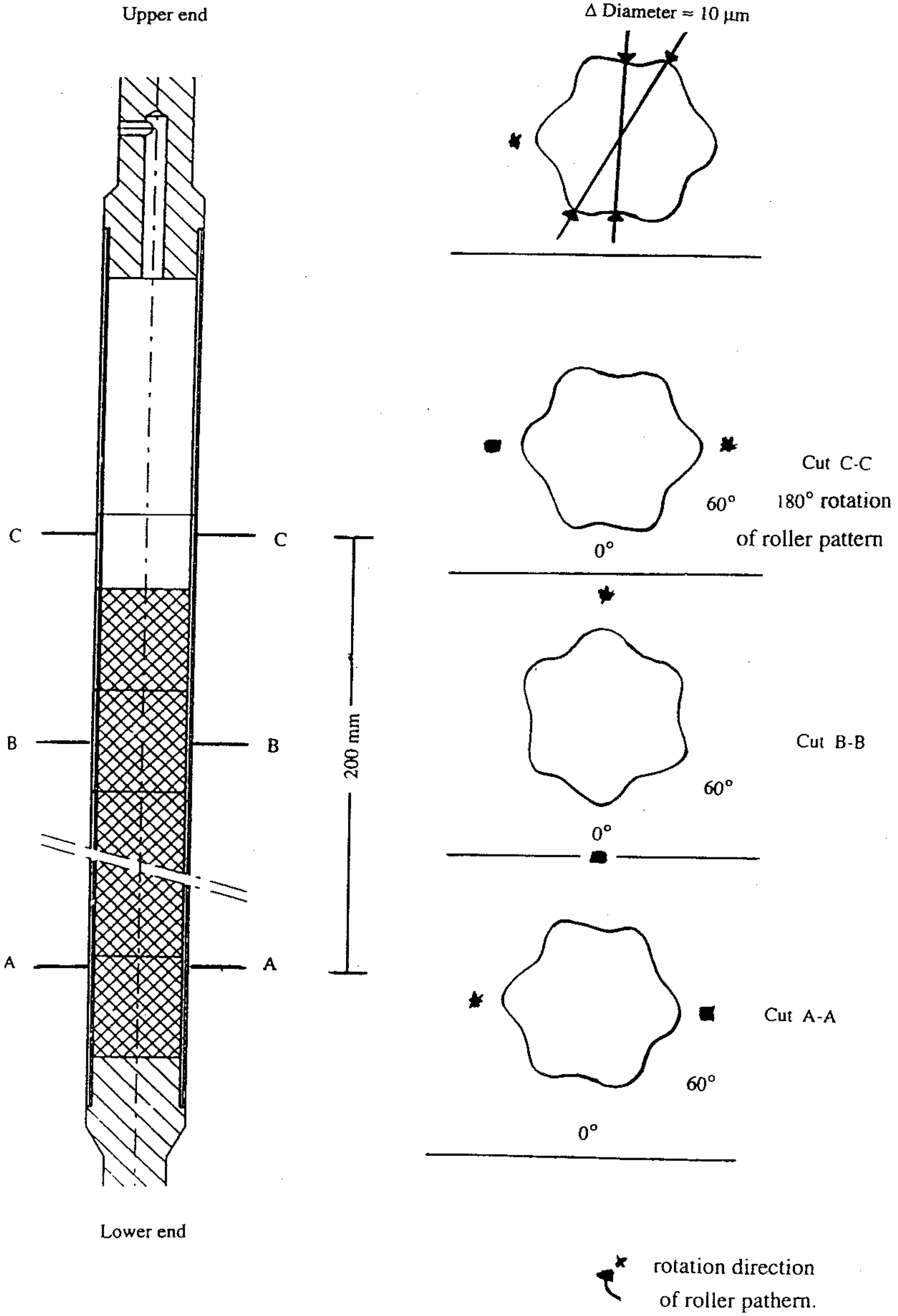


Fig. 6. Illustration of roller pathern.

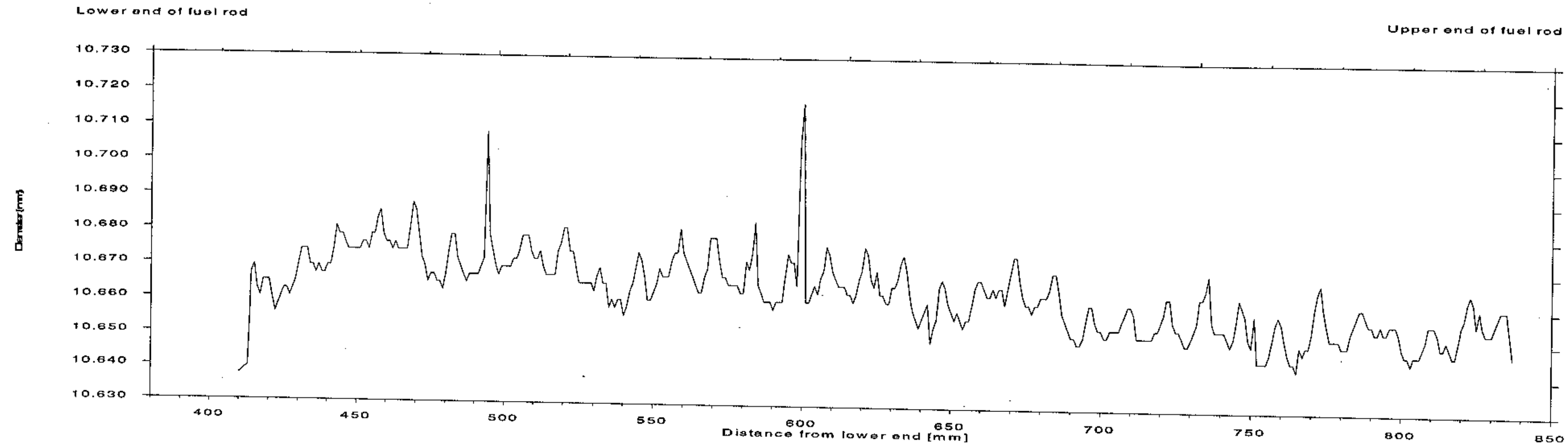


Fig. 7. Diameter scan of fuel rod at 0 degree orientation

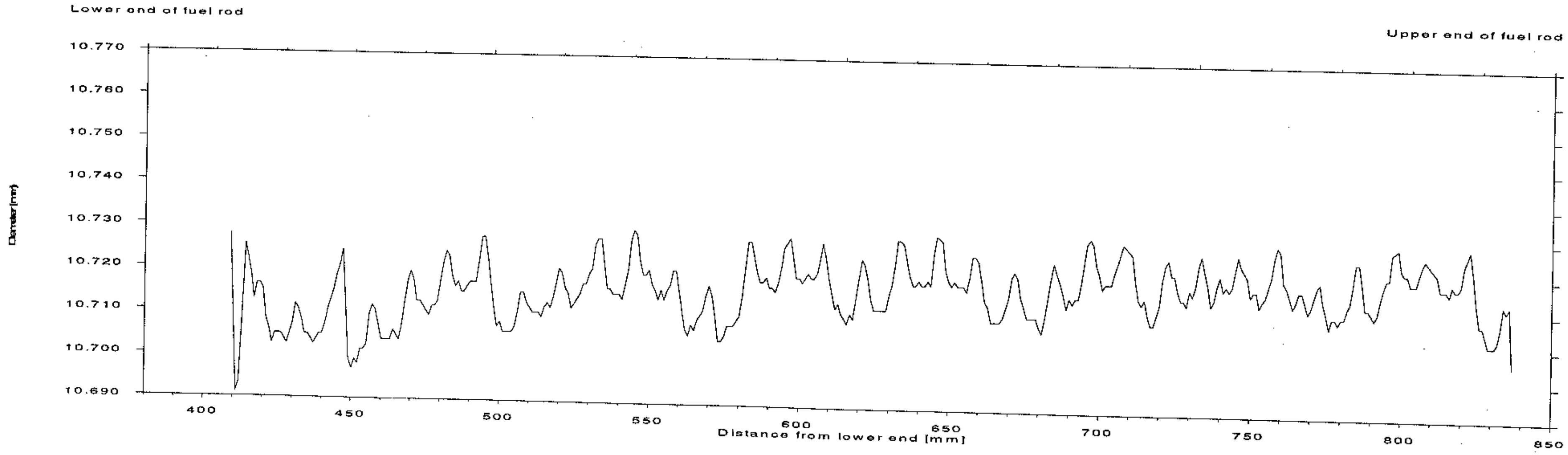


Fig. 8. Diameter scan of fuel rod at 90 degrees orientation

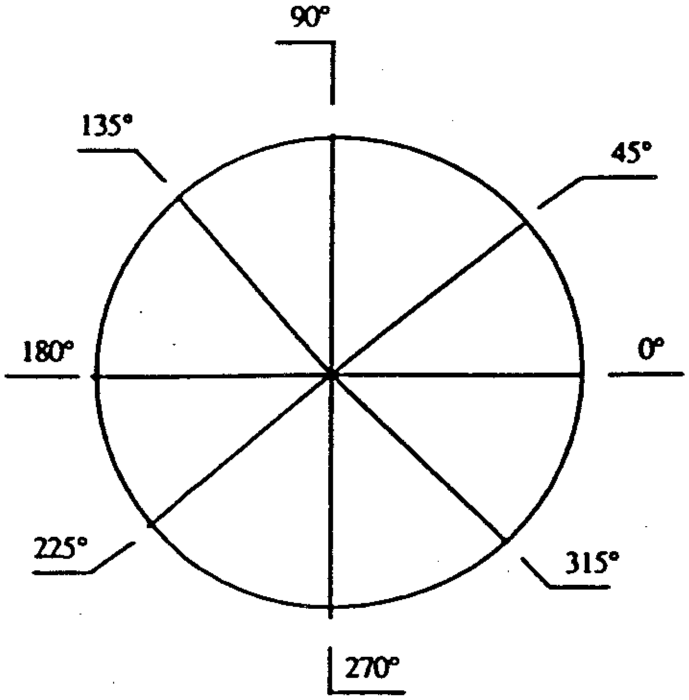


Fig. 9. Angular convention for transversal samples as seen from above.

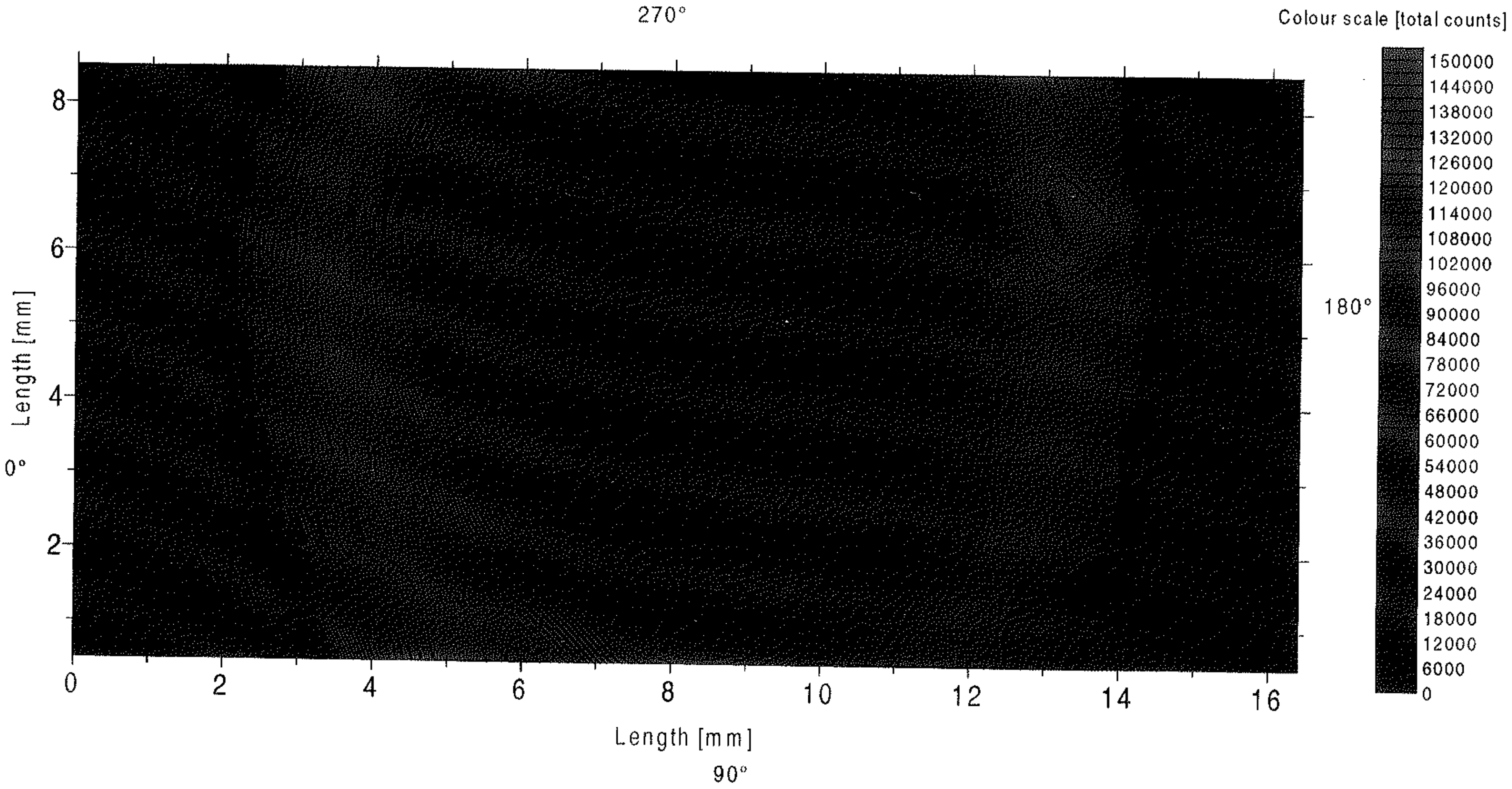
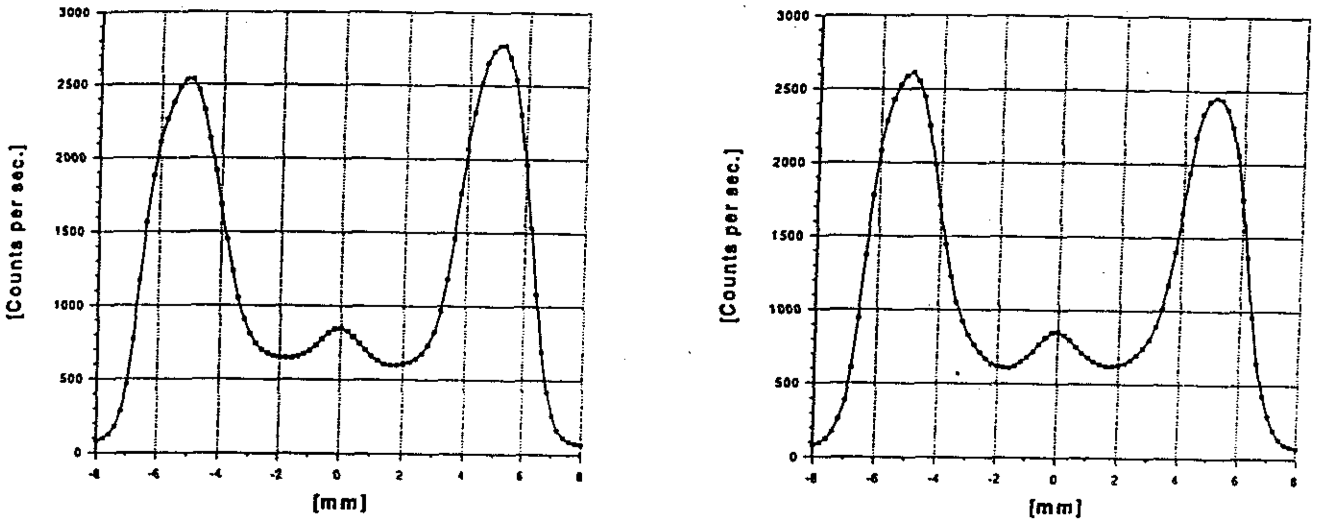
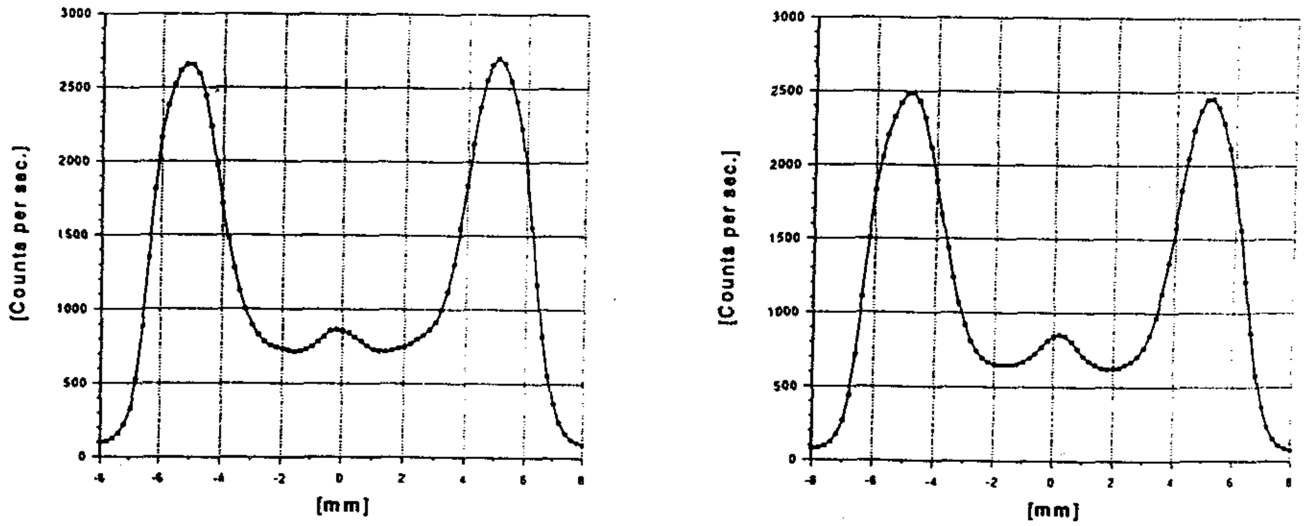


Fig. 10. Countor plot of gross gamma activity on axial fuel rod cross-section.



Direction 0°-180°

Direction 45°-225°



Direction 90°-270°

Direction 315°-135°

Fig. 11. Transversal gross gamma scan