A NEW COMPUTED TOMOGRAPHY SYSTEM IN THE ECN HOT CELL LABORATORY

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1.6.

ABSTRACT

The geometrical distribution of a radio-nuclide in some cross-section of a fuel rod can be determined by measuring its gamma-intensity coming from those strips of the cross-section which are visible to a collimator detector system. Moving the rod along the measurement equipment (so as to obtain the intensity of many strips) and repeating this procedure for different rotation angles, provides the necessary information to allow for the computation of the distribution. Reconstructing this image on the basis of measured projections with the aid of a computer algorithm is the objective of what is called Computed Tomography (CT). The form in which it appears at ECN/Hot Cell Laboratory is referred to as Emission CT (ECT).

The adopted approach is to regard it as a least squares problem where the "theoretical" projections (arising from a "hypothetical" distribution) should fit to the measured projections as closely as possible. A hypothetical distribution follows after some appropriate discretization of the problem. The least squares problem is then solved through an iterative technique. As such a variant of the Preconditioned Conjugate Gradients method is applied. The CT-software provides for graphical output (surface views, contours) of the resulting - optionally smoothed - distribution. Usage is interactive, command-driven.

1. INTRODUCTION

The section "Non-destructive examination" of the ECN Hot Cell Laboratory performs gamma scanning of various types of fuel rods. This method was introduced and used to measure the radial distribution of fission products in both LWR and LMFBR-type fuel rods.

In the beginning of 1989 the development of a completely new model was started with emphasis on the resolution of the calculated radial isotope distribution and the ability to deal with irregularities such as rod bow. This model is based on the least squares principle in combination with the conjugate gradient method. In addition a sophisticated system has been developed on the basis of the UNIRAS graphics software, for visualizing the calculated distribution patterns.

In this report a description is given of the principles of both the hardware and software of the CT-system, together with examples of experimental results.

2. THE PRINCIPLE OF ECT

Application of Emission Computer Tomography (ECT) enables the non-destructive evaluation of the distribution of a gamma-emitting isotope in a crosssection (more precisely: a thin radial slice) of a fuel rod [1]. The feasibility of this approach has been clearly demonstrated by e.g. Müllauer [2] in a study of the diffusion kinetics of ^{137}Cs in LWR-fuel. The first stage in the method is the actual gamma scanning: the gamma emission coming from a narrow strip of the fuel rod, focussed by a small collimator system, is measured for selected gamma energy bands. After the rod has been translated, the emission (of a new strip) is measured again and this procedure is repeated until the complete crosssection or slice is scanned. The number of counts obtained after a certain displacement of the rod constitutes one projection value. A set of such projection values, all measured at one rotational orientation of the rod, defines one projection. This measurement is then repeated for different rotation angles. (For an illustration of the terms introduced so far, see Fig. 1). The raw data are corrected for possible excentricity of the rod and for the decay of the isotope during the period of measurement.

The problem is to reconstruct an image (i.c. the isotope distribution over the cross-section) from a given set of projections as described above.

3. MATHEMATICAL APPROACH

A suitable method to solve an ECT-problem mathematically is to regard it as a least squares problem. Quite generally such a problem has to do with the matching between measurements and some model underlying the measured phenomenon. The model in question has a known or hypothesized form containing a number of unknown parameters. It is the presence of the measurement data which allows these parameters to be determined. In principle they should be such that deviations between measurements and model values -arising from the substitution of parameter values- are small in some sense. A least squares method uses as a measure of smallness the sum of the squared deviations (or residuals). There is a sound mathematical basis for this criterion, the so-called least squares principle, and the resulting parameter values possess certain optimal properties.

The measurements consist of projection values obtained at different rotation angles and displacement values for the fuel rod. What is needed in addition is a model to provide us with theoretical projections for the given combinations of projection angles and displacements.

To arrive at a least squares problem with a finite number of unknowns, we first have to discretize the distribution of the isotope over the cross-section of the fuel rod. First the area of the cross-section is subdivided in a number of square cells or pixels. We assume the hypothetical distribution being constant throughout the pixel area. Notice that as a consequence we have as many unknowns (the pixel values, also referred to as concentrations) as there are pixels. Then, for a given set of pixel values we must be able to calculate the corresponding theoretical projection values. In ECT-problems these calculations typically have to account for attenuation caused by the rod material. The effect of attenuation is such that the intensity of the emission decreases exponentially with the traversed distance in the material. In our model attenuation is included as a weight factor preceding the pixel values. Any available a priori knowledge, e.g. on the shape of the perimeter of cross-section (concentration becomes 0 outside) or the presence of certain internal holes (with no attenuation) is incorporated in the weights before the least squares step is taken.

We can describe this approach as follows. We have m measured projections P_i and n unknown concentrations c_k. The least squares problem to be solved is to find a set of values for c_k such that

$$\sum_{i=1}^{m} (P_i - \hat{P}_i)^2$$

is minimal. The theoretical projections $\hat{P}_i$ are weighted sums of the concentrations, i.e.

$$\hat{P}_i = \sum_{k=1}^{n} w_{i,k} c_k$$

Explicitly we have for the weight factors.

$$w_{i,k} = g_{i,k} a_{i,k}$$

where $g_{i,k}$ accounts for the geometrical correction (that is: the area of the k-th pixel in the i-th ray) and $a_{i,k}$ accounts for the attenuation.

For the numerical solution of the least squares problem several methods are in existence. Since the matrix of the weight factors is sparse (has many zero elements) an iterative technique is preferred to reduce both the solution time and the amount of main memory required. This is the more appealing if the model is to be extended, e.g. to become fully 3 dimensional. The iterative technique chosen is a variant of the Preconditioned Conjugate Gradient method [3].

We end up this description of our approach by pointing out that in order to find a unique solution for the least squares problem the number of unknown parameters should not exceed the number of measurements. Hence, there is a limitation for the achievable resolution of the result, namely the number of pixels should not exceed the number of given projection values.

The CT-software developed at the Service Unit Informatics of ECN is based on the outlined principles and provides options for high-quality graphical output to visualize the resulting (possibly smoothed) distribution. The user-interface is interactive and command-driven.

4. GAMMA SCAN MEASURING SYSTEM

The gamma scan measuring system consists of:
- Tulip 386/25 MHz personal computer system;
- scan device with motion control;
- adjustable slit collimator
- germanium (high purity) coaxial detector system.

The gamma scan system is composed of units, which are presented in figure 2 and 3. The key part of the entire system is the Tulip 386/25 MHz personal computer. This computer system, with an internal S100 Canberra multi channel analyzer interface, is working under MS-Windows, with software expansion to MS-Excel. Various measuring methodes are available and pre-programmed with macros in MS-Excel.

The gamma scan device has an axial travel of 770 mm, a cross travel of 120 mm and offers the possibility for continuous rotation of the fuel rod. The accuracy of each increment amounts to 0.01 mm for X and Y, whereas the rotation (Z) has an accuracy of 0.1 degrees. The scan direction, the step size and the position parameters are controlled by an external controller interface, type MPM 68008. An error logging system file can be readout during the measurement, indicating parameters like e.g. position deviation and peak shift. This enables a continuous control of the measurement procedure.

In the rear cell wall a 1400 mm long slit collimator system is installed. This collimator slit has a fixed height of 15 mm, whereas the width can be adjusted from 0.0 through 8.0 mm, the accuracy of the adjustment amounts to 0.025 mm. The entire collimator system can be rotated 90 degrees, if so required for specific measurements or object conditions.

To measure the gamma intensities a high purity germanium (coaxial one open end) detector system is used. The specifications of this detector system are:
- resolution Full Width Half Maximum (FWHM) is 1.73 keV;
- Relative Efficiency amounts to 20.2%;
- the Peak/Compton ratio is 56.2 : 1.

The quality of movement system and collimator is of prime importance for the tomographic results. For this reason we have designed and constructed bench and collimator in our own house. A two side adjustable slit collimator of 1400 mm length is now under construction.

5. EXPERIMENTAL PERFORMANCE

The CT-system described in the previous chapters, consisting of the measurement devices, the mathematical model and the visualization software, became operational in the first half of 1990. The first experimental phase is mainly being devoted to refinement of the system. A major point is the attainable resolution. Possiblities seem, in principle, to be promising. When the two side adjustable collimator, under construction now, will become available, a systematic approach including fuel slice thickness as a parameter will be possible.

The subject has an economic aspect as well. It will be necessary to select at a given gamma source strength the collimator opening and translational step size that give the best compromise in terms of resolution and measurement costs.

In figure 4 through 6 three examples are given of results obtained so far. Figure 4 shows the ^{140}La distribution in an LMFBR-type fuel rod that has been base irradiated and subsequently subjected to a high power transient test. The cut-away view clearly shows the central minimum, which is related to fuel melting during the transient. Figure 5 shows the ^{137}Cs distribution in an LWR-type fuel rod with a burnup of 16.8 GWd/T(U). The almost homogeneous radial distribution of ^{95}Zr in the same fuel rod is shown in figure 6.

A detailed benchmark programme is now being set up with emphasis on maximum resolution and on the ability to identify irregularities such as holes in the fuel pellet or possible clusters in mixed-oxide fuel.

6. REFERENCES

[1] HERMAN, G.T. (ed), "Image Reconstruction from Projections", Springer-Verslag, Berlin (1979).

[2] MÜLLAUER, J, Untersuchungen zum Transportverhalten des Spaltproduktes Cäsium im UO_2-Kernbrenstoff unter Anwendung der Gamma-Computertomographie, GKSS 86/R/17, GKSS-Forschungszentrum Geesthacht (1986).

[3] VAN DER SLUIS, A., VAN DER VORST, H.A., The rate of convergence of conjugate gradients, Numer.Math. 48 (1986) 543-560.

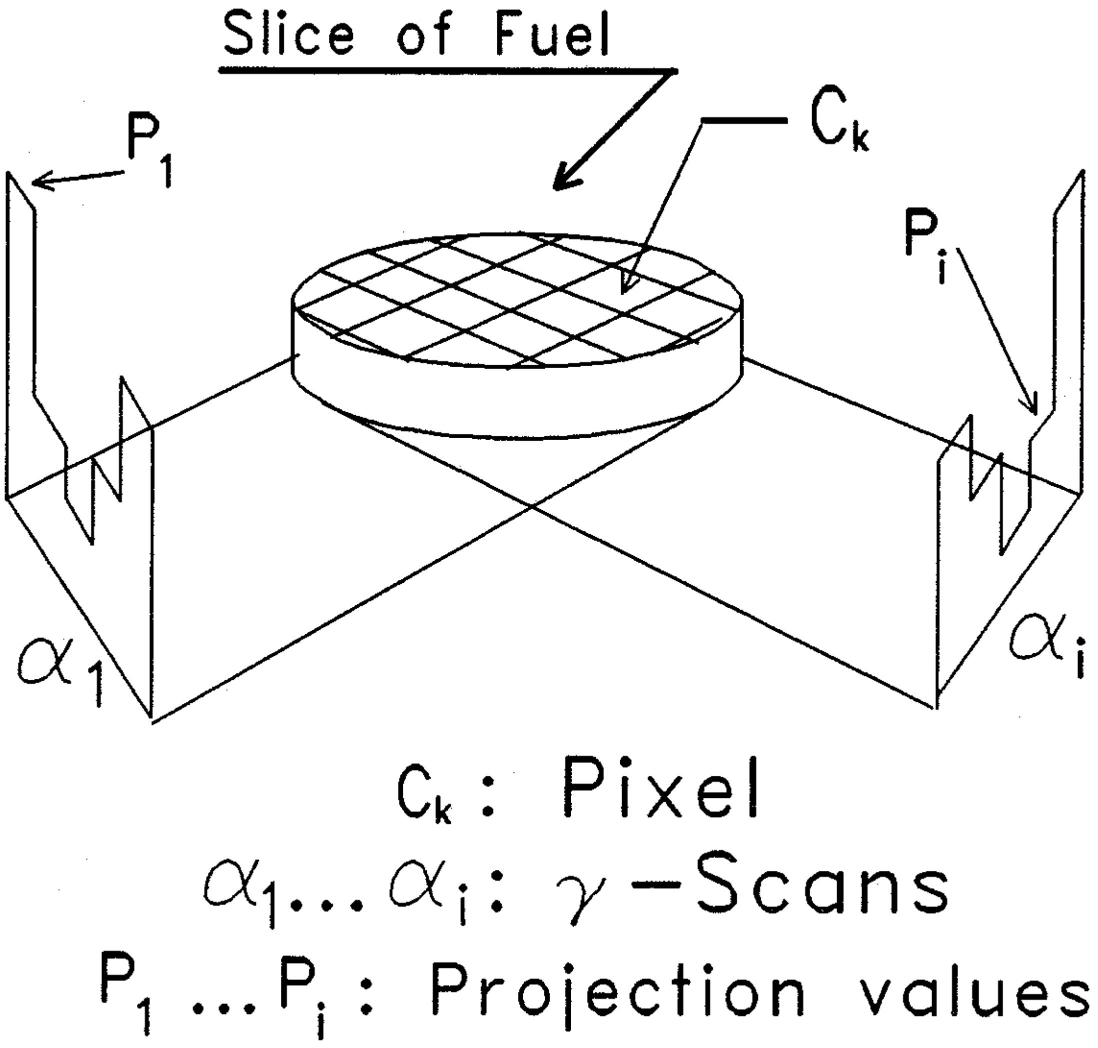


Figure 1. Basic principle of γ-CT

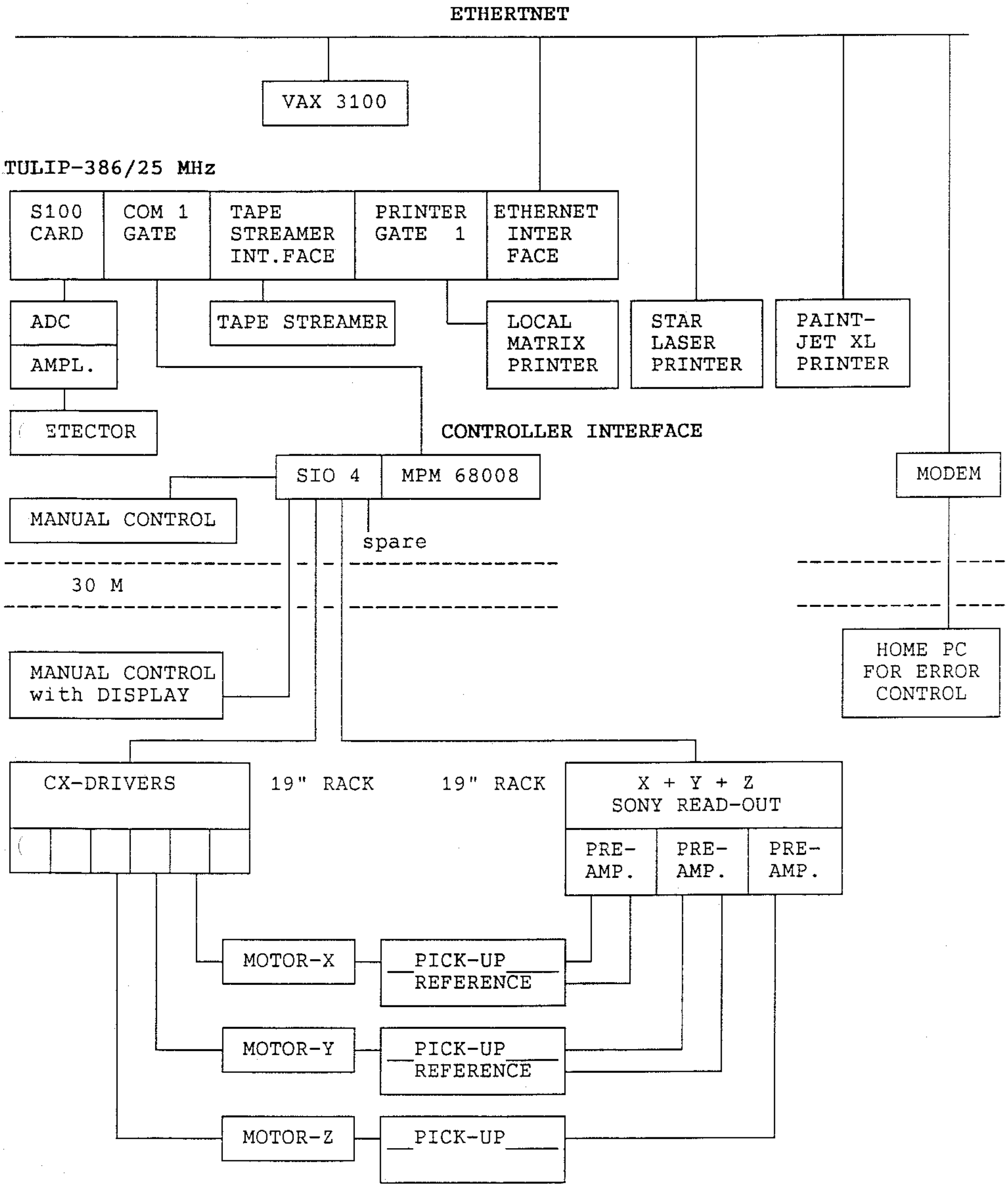


Figure 2. System architecture

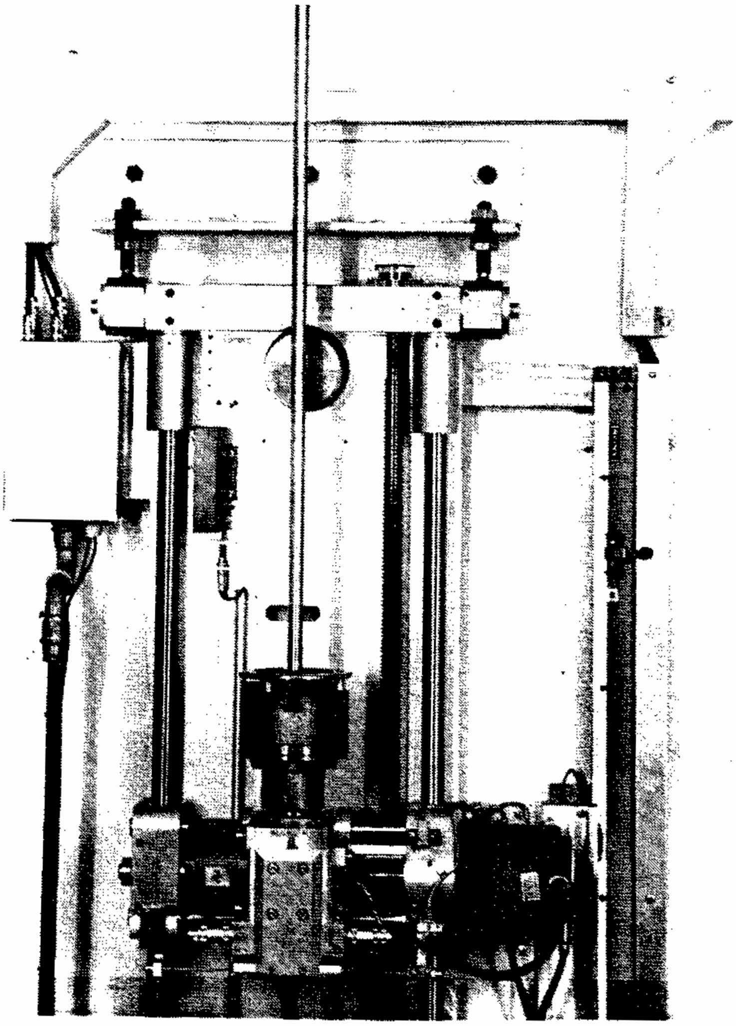
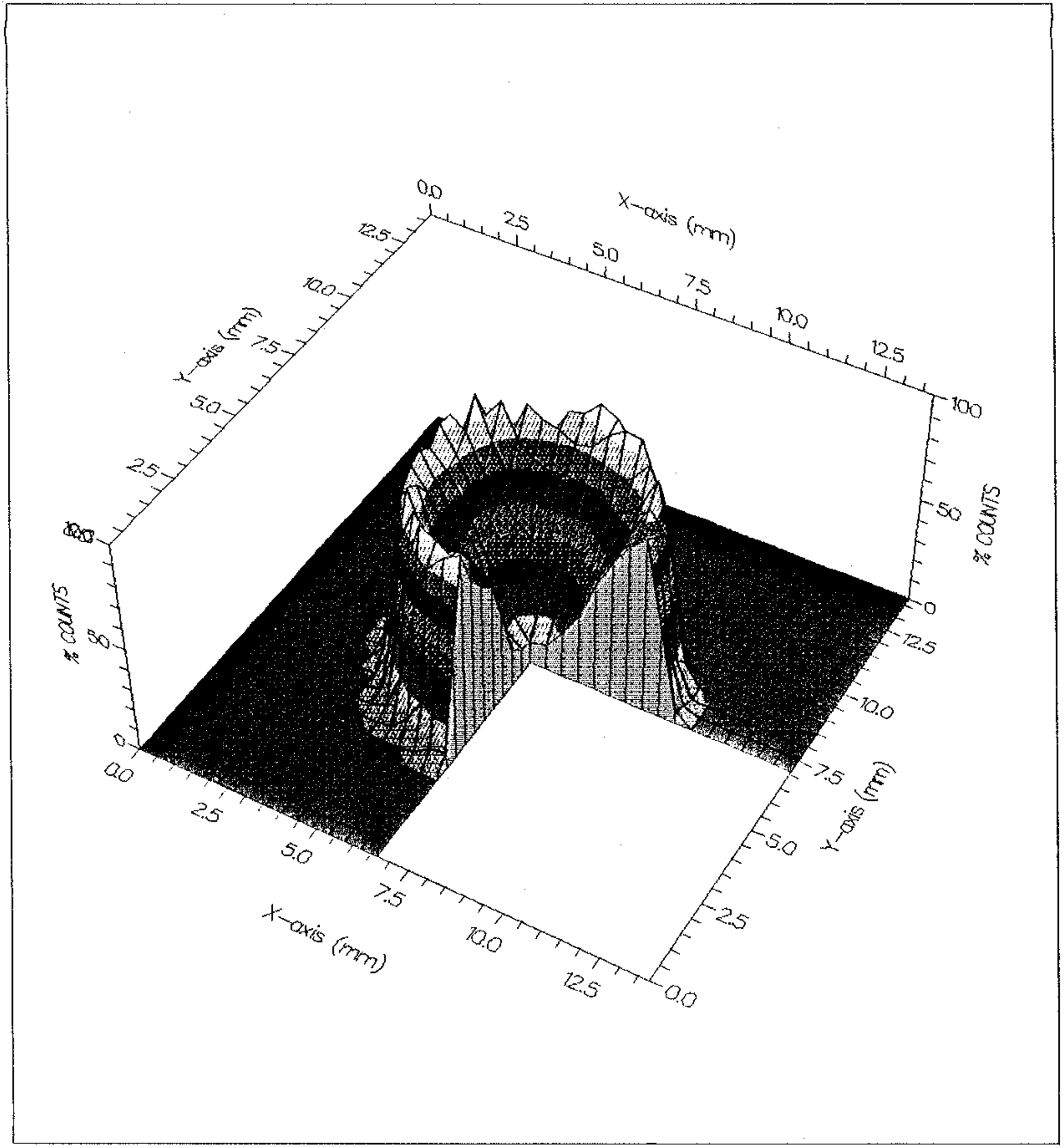


Figure 3. Gamma scan device with fuel rod



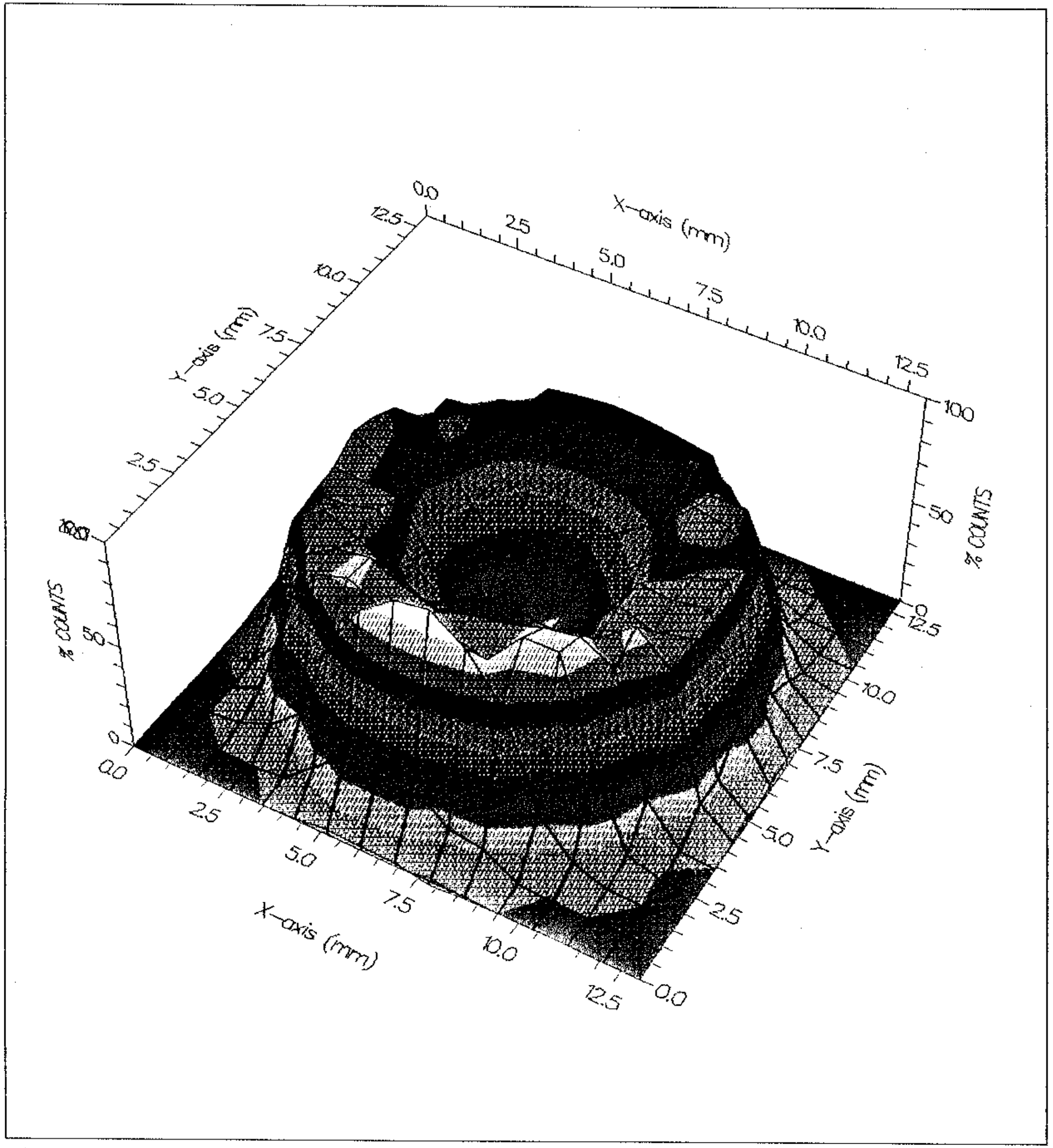
ECN/HCL – tomography

Calculated cross-section

Experiment : LMFBR
HCL-scan : D08001
Date : 07-12-87
Nuclide : LA-140
Energy : 1596.6 KEV
Half-life time : 12.80 DAYS
Maximum : 19854 counts
#lines : 18
#points : 71
Resolution : 32x32
Diameter : 6.40 mm
Hole : 0.00 mm
Mu : .55 cm^{-1}
Iterations : 10

□ 90 – 100
▨ 80 – 90
▨ 70 – 80
■ 60 – 70
▨ 50 – 60
▨ 40 – 50
■ 30 – 40
■ 20 – 30
▨ 10 – 20
▨ 0 – 10

Figure 4. LMFBR type fuel rod



ECN/HCL – tomography

Calculated cross-section

Experiment : Test-example
Identification : P1234
HCL-scan : D32001
Date : 06-01-89
Nuclide : CS-137
Energy : 661.6 KEV
Half-life time : 11140.13 DAYS
Maximum : 94.39 counts
#lines : 20
#points : 46
Resolution : 16x16
Diameter : 10.50 mm
Hole : 0.00 mm
Mu : 1.12 cm^{-1}
Iterations : 10

□ 90 – 100
▨ 80 – 90
▨ 70 – 80
■ 60 – 70
▨ 50 – 60
▨ 40 – 50
■ 30 – 40
■ 20 – 30
▨ 10 – 20
▨ 0 – 10

Figure 5. LWR type fuel rod

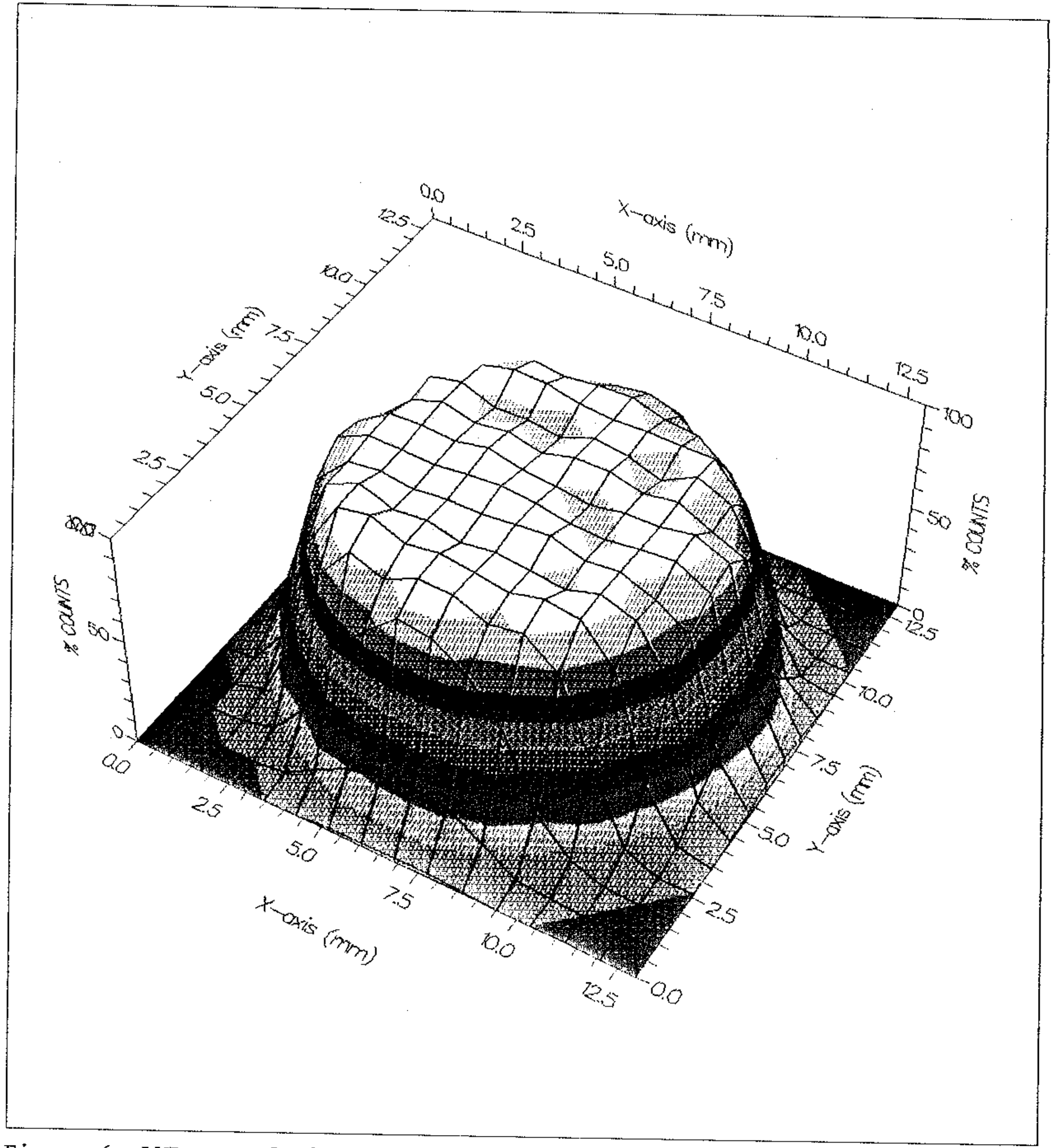


Figure 6. LWR type fuel rod

ECN/HCL – tomography

Calculated cross-section

Experiment	:	Test-example
HCL-scan	:	D32001
Date	:	06-01-89
Nuclide	:	ZR-95
Energy	:	724.2 KEV
Half-life time	:	63.98 DAYS
Maximum	:	3140 counts
#lines	:	20
#points	:	46
Resolution	:	16x16
Diameter	:	10.50 mm
Hole	:	0.00 mm
Mu	:	1.12 cm^{-1}
Iterations	:	10

□	90 – 100
▨	80 – 90
▨	70 – 80
■	60 – 70
▨	50 – 60
▨	40 – 50
■	30 – 40
■	20 – 30
▨	10 – 20
▨	0 – 10