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Optimisation of Gamma Assay Techniques for Characterisation of Radioactive Waste Packages

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Foreword

The work described in this report was part of a R&D project carried out by the following partner organisations:

SCK.CEN,	Belgium
NRG,	Netherlands
NNC/WQCL,	England
CIEMAT,	Spain
ANPA.	Italy
University 'La Sapienza' of Rome,	Italy
TUM/RCM,	Germany
FZJ/ISR,	Germany

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The results described in the following report have been mainly achieved by FZJ, Institute for Safety Research and Reactor Technology, if not indicated otherwise in the text.

Abstract

Conditioned radioactive waste has to meet the specifications and acceptance criteria defined by national regulatory and management authorities. Gamma scanning is one of the most widely used non-destructive assay techniques for routine quality checking of radioactive waste drums. The result of gamma scanning measurements is strongly influenced by the gamma attenuation in the waste matrix.

Standard correction procedures for gamma-ray attenuation are often performed by drum weighing or calculation of corrective factors based on 'simple' assumptions regarding the distribution of density and activity in the waste. In the case of heterogeneous activity and/or matrix distribution uncertainties will be introduced when applying standard correction procedures that can lead to significant errors in the activity determination especially for medium and high density waste combined with low and medium gamma-ray energies (below ca. 500 keV).

The main objective of the R&D project was to develop and test methods that will decrease systematic uncertainties and bias, caused by a lack of information on the activity and matrix distribution, by *taking into account the relevant characteristics of the waste package under inspection*. For the applicability of the improved gamma assay techniques in routine operation two important requirements were defined: *The methods should keep the inspection time in an acceptable range* and *the implementation into existing systems should be possible without extensive hardware modifications and at reasonable costs.*

A modelling software (SOLIDANG, /SCK-1/) was used to calculate the detection efficiency of 'standard' gamma scanning systems which helped to design, evaluate and optimise new scanning techniques. Validation of the simulation software has proven that SOLIDANG can be used as an efficient tool for performance evaluation and optimisation of gamma assay techniques. With this software the quantitative influence of relevant parameters on the assay result was investigated with reduced experimental effort. The results lead to a better understanding of possible sources of bias.

Within the R&D project several advanced NDA-methods have been developed, tested and implemented into prototype assay systems. These techniques involve *multi-energy transmission* measurements of the drum and *special scanning modes* which reveal more information about the density and activity distribution inside the drum.

Performance assessment was carried out on well-defined and specially designed mock-up configurations and on selected drums under routine 'field' conditions. The results showed significant improved accuracy for the new developed assay techniques compared to 'conventional' state-of-the-art gamma scanning procedures.

Zusammenfassung

Radioaktiver Abfall muss die jeweils gültigen Spezifiaktionen und Annahmebedingungen erfüllen, die von den zuständigen nationalen Aufsichtsbehörden für die Zwischen- und Endlagerung festgelegt werden. Das Verfahren des 'Gamma-Scanning' gehört zu den am häufigsten eingesetzten zerstörungsfreien Nachweismethoden zur Qualitätskontrolle an Abfallgebinden. Das Ergebnis dieses Meßverfahrens wird in erheblichem Umfang von den Abschwächungseigenschaften der Gebindematrix für Gammastrahlung beeinflußt.

Etablierte Verfahren zur Korrektur der Abschwächungseffekte von Gammastrahlung basieren z. B. auf der Berechnung von Korrekturfaktoren aufgrund von vereinfachenden Annahmen über die Zusammensetzung und den Aufbau der Matrix. Zu den Simplifizierungen zählt z. B. die Annahme einer homogenen Dichte- und Aktivitätsverteilung im Gebinde. Hieraus resultieren bei der Inventarbestimmung systematische Abweichungen zwischen der gemessenen und der tatsächlichen Aktivität im Gebinde, die im Einzelfall nur schwer zu erfassen oder zu korrigieren sind. Diese 'Nachweisunsicherheit' kann vor allem bei niedrigen Gammaenergien und mittleren bis hohen Dichten im Abfall zu erheblichen Fehlern führen.

Wesentliche Zielsetzung des durchgeführten F+E-Vorhabens war es, verbesserte Korrekturverfahren zur Berücksichtigung von inhomogenen Dichte- und Akivitätsverteilungen für das Gamma-Scanning zu entwicklen, zu validieren und unter praxistauglichen Bedingungen zu implementieren. Ausgangspunkt der Entwicklung waren Methoden, die die individuellen Eigenschaften eines Abfallgebindes zu erfassen gestatten, welche für das Meßergebnis wesentlich sind. Außerdem sollten die entwickelten Verfahren die notwendige Meßzeit pro Gebinde nicht deutlich erhöhen sowie in existierende Meßsysteme durch Erweiterung implementiert werden können.

Zur Konzeption und Auslegung geeigneter Korrekturverfahren wurde ein spezielles Simulationsprogramm (SOLIDANG, /SCK-1/) zur Modellierung von Gamma-Scans verwendet. Im Rahmen von Validierungstests wurde die Eignung der Software zur Simulation von Messungen verifiziert.

Innerhalb des Projektes wurden verschiedene Korrekturverfahren entwickelt und getestet. Diese basieren auf Techniken zur *Transmissionsmessung mittels einer externen Durchstrahlungsquelle* sowie auf *speziellen Scan-Prozeduren*, die detailliertere Informationen über die Verteilung von Aktivität und Dichte in einem Gebinde liefern.

Die entwickelten Korrekturverfahren wurden anhand spezieller Testkonfigurationen validiert und unter Routinebedingungen erprobt. Als Ergebnis der durchgeführten Untersuchungen konnten deutliche Verbesserungen der Nachweisgenauigkeit gegenüber den derzeit angewandten Standardverfahren erzielt werden.

Key Words

nondestructive assay (NDA), characterisation, radioactive waste package, conditioned radioactive waste, gamma scanning, swivel scanning, angular scanning, gamma-ray attenuation, attenuation correction, self-attenuation correction, transmission measurement, multi-energy transmission

List of abbreviations

AS	Angular Scanning
SWS	Swivel Scanning
SGS	Segmented Gamma Scanner/Scanning
TC-SGS	Transmission corrected SGS
DR	Digital Radiography
TCT	Transmission Computerized Tomography
ECT	Emission Computerized Tomography
MCNP	Monte Carlo Neutron Photon code
PLC	Programmed Logical Controller
QA/QC	Quality Assurance, Quality Control
SRWGA	SEA Radioactive Waste Gamma Analyser
WPRS	Waste Package Reference Standard
NDA	Non destructive assay
CF	Correction factor

CONTENTS

From this experience it is evident that one of the major problems of waste characterisation by nondestructive means in practice is related to the unknown distribution of the matrix material and the radioactive substances in the drum.

To optimise conventional gamma scanning it is therefore necessary to estimate and to reduce these sources of bias as far as possible.

1.2 Objectives: Improvement of 'conventional' gamma scanning

The scope of the work programme was focused on the optimisation of nondestructive gamma scanning techniques applied to the quality checking of radioactive waste packages. The improvement of the performance is based on the following two methods:

- *Attenuation correction by transmission measurements*
  ('transmission corrected segmented gamma scanning' – TC-SGS).
- *Correction for non homogeneous distribution of activity by appropriate scanning techniques*
  (swivel scanning and angular scanning).

The method of attenuation correction is based on simple and fast transmission measurements through the object at selected heights with an 'external transmission source'. This correction technique has been already developed for fissile material in raw waste. It has been proved that the method leads to significantly improved accuracy for the determination of activity inventories in heterogeneous waste matrices of low density /PAR77/. The research work included all necessary steps to extend the application of attenuation correction techniques for the characterisation of *intermediate and medium density waste (0.4 to 2.2 g/cm^3).*

The developed methods will help to decrease systematic uncertainties and bias, caused by unknown variations of the activity and matrix distributions. The results of the work programme are of interest for nearly all applications where nondestructive gamma assay systems are used to measure volumetric radioactive waste packages.

2 BASIC GAMMA SCANNING TECHNIQUES

2.1 Determination of activity inventories by conventional gamma scanning ('volumetric scanning')

One standard procedure[1] which is used routinely for the determination of radioactive inventories is conventional gamma scanning of waste drums.

Measurement of the activity of certain key-nuclides in a waste drum can be achieved by the method of gamma-scanning /PAR84/. This method usually involves a collimated HPGe-detector moving along the drum axis, while the drum itself rotates on a turn table (Fig. 2.1). For some specific applications even simpler versions exist where no detector movement takes place and no collimator is used. The standard measurement time is 30-120 minutes for one scan.

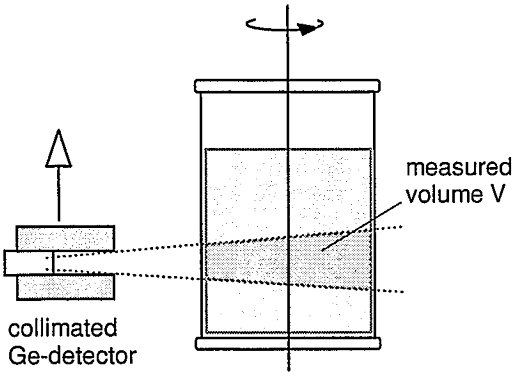


Fig. 2.1: Sketch of one 'standard' method of gamma-scanning

The activity inventory can be calculated for all detected nuclides from the evaluation of the integral gamma-spectrum with sufficient accuracy if the activity and the waste are distributed uniformly throughout the drum. For homogeneous fillings the following relation between the measured net peak count rate Z and the activity concentration a = A/m of a volumetric source holds /FIL89-1/:

$$Z = const \cdot (1-T) \cdot \left(\frac{\mu}{\rho}\right)^{-1} \cdot \frac{A}{m} \qquad (2.1)$$

with
Z: measured count rate
A: activity of one nuclide
T : gamma transmission
$T = \exp(-\mu \cdot d)$
m : mass of the matrix
μ/ρ: mass attenuation coefficient

[1] In the following those scanning techniques, where the attenuation correction for gamma rays is based primarily on 'a priori' assumptions on the distribution of matrix and/or activity in the waste package (in many cases homogeneity of matrix and activity distribution is assumed) will be called **'conventional or standard'** techniques.

Usually the factors µ/ρ and T are estimated on the basis of weighing the drum and making assumptions about (or knowing) the composition of the matrix.

Problems associated with standard nondestructive gamma scanning

For real waste packages the above conditions (homogeneous distribution of activity and matrix inside the drum) are only fulfilled in rare cases (see table 1.1). As a consequence, the results obtained by gamma scanning can be affected by large, in general unknown and possibly non-conservative, errors due to the following effects or difficulties:

- non-uniform activity distribution,
- inhomogeneous matrix composition and distribution,
- internal shielding structures of unknown design.

Figure 2.2 illustrates one of the simple effects which occur in standard volumetric gamma scanning of a drum with unknown filling height, if only the overall spectrum is analysed under the assumption of homogeneity of matrix and activity distribution.

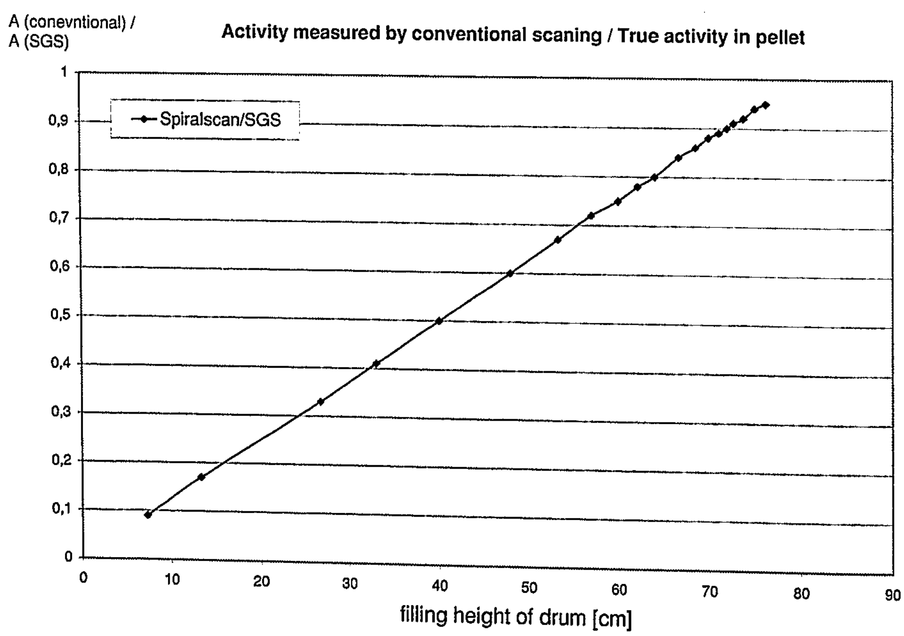


Fig. 2.2: Influence of filling height on Performance of Standard Volume Scanning (μ/ρ=0,12 cm^2/g, M=200 kg)

A more systematic and detailed presentation of the influence of varying distributions of activity and density is shown in figure 2.3 for a 'two pellet drum' configuration. The following parameters have been fixed for this example:

Volume [l]	200 l
diameter	56 cm
height	80 cm
µ/rho	0,12 g/cm^3
mass	200 kg
CPS (tot)	100 s^{-1}

Table 2.1 Fixed values for simulation of the influence of varying density and activity distribution on the performance of standard scanning

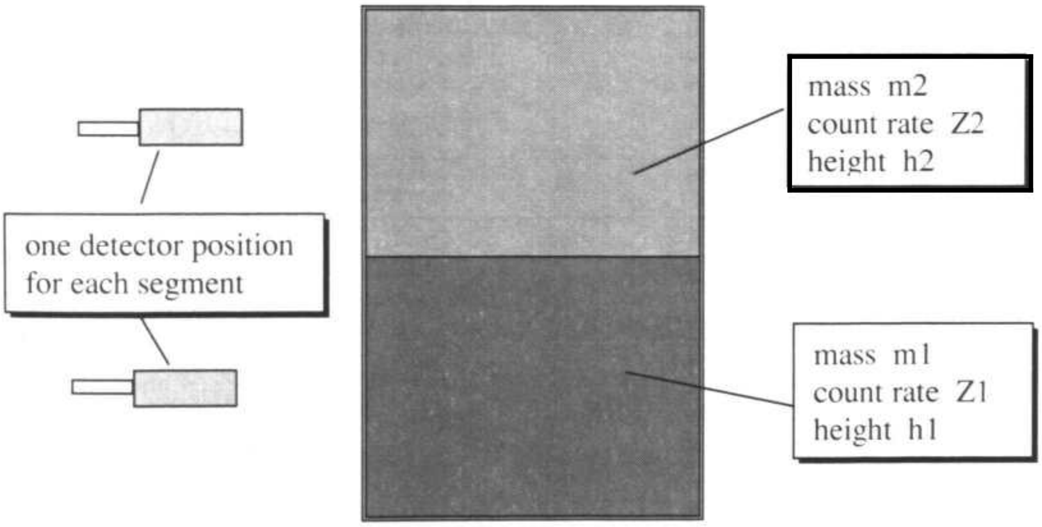


Fig. 2.3 Sketch of a simple simulation geometry model to demonstrate the effects of varying density and activity distribution on the performance of standard scanning

Figure 2.4 shows the results of the calculated ratios of the response functions (activity measured) of segmented and standard scanning. In segmented scanning it was assumed that the two detector positions are always located at the centre line of each segment while in standard scanning there is only one overall spectrum for both segments.

Looking at figure 2.4 it becomes evident that for equal masses m1 = m2 (i.e. equal densities) there is no difference between a 'two segment scan' and a volume scan of the above configuration. But if density changes from segment 1 to segment 2 then the difference between segmented scanning and standard scanning increases significantly if the activity concentration is also different between the upper and lower segment. As a 'rule of thumb' it may be concluded from this example *that the error in standard scanning increases if the activity concentration in the lower dense part of the drum increases and vice versa.*

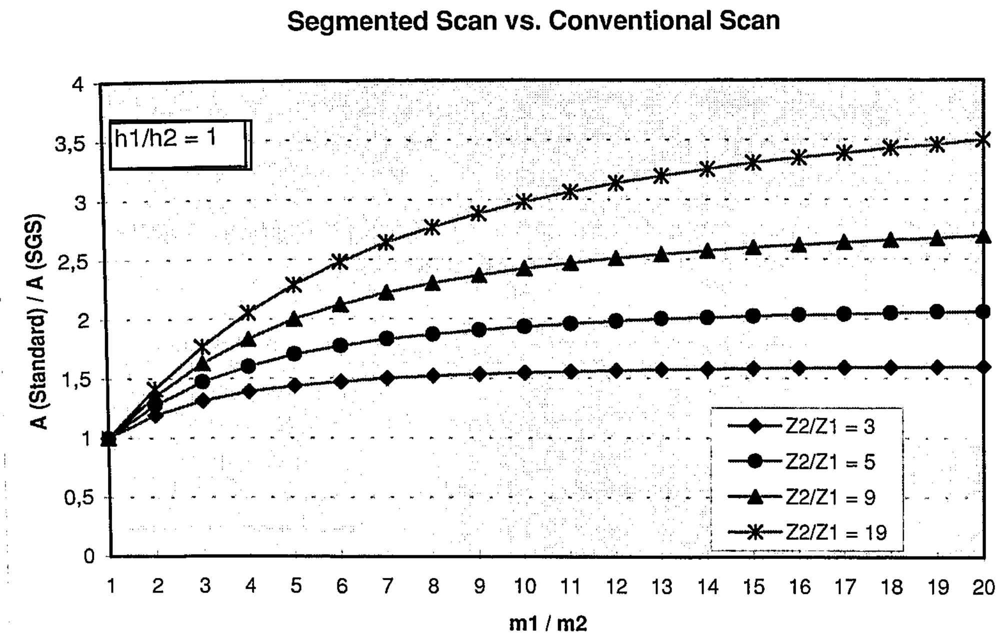


Fig. 2.4 Effects of varying density and activity distribution on the performance of standard scanning (equal heights of segment: h1 = h2).

2.2 Attenuation correction by transmission measurements

Looking at the simple formula 2.1 it is evident that one of the main problems of gamma scanning is the lack of information on the gamma absorption characteristics of the drum filling, i.e. not knowing the transmission factor T and the mass attenuation factor μ/ρ:

$$S_{absorption} = (1-T)/(\mu \cdot d) = \frac{1-T}{-\ln(T)} = \frac{1-T}{(\mu/\rho)\cdot \rho \cdot d} \qquad (2.2)$$

This lack of information can lead to significant errors especially in cases where low energetic γ-lines and high densities of the waste are involved.

Improvement of gamma assay of heterogeneous waste can be achieved by experimental determination of the factors T and μ for the object under investigation (drum or segment of a drum). With this information a valid correction for 'self absorption' in the matrix is achievable. This can be done by simple and fast transmission measurements with an external radioactive source (Fig. 2.5).

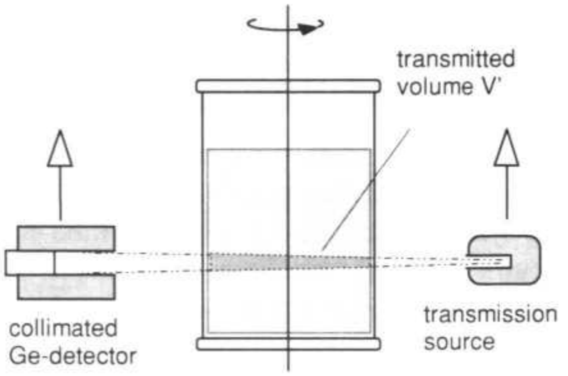


Fig. 2:5: Sketch of the method of gamma-scanning with transmission correction

The method of attenuation correction by transmission measurements is already used for the activity determination of fissile isotopes in low density waste (up to 0.5 g/cm^3). The intention of the work programme is to make use of this technique within the field of quality checking of intermediate and high density waste (0.4 to 2.2 g/cm^3).

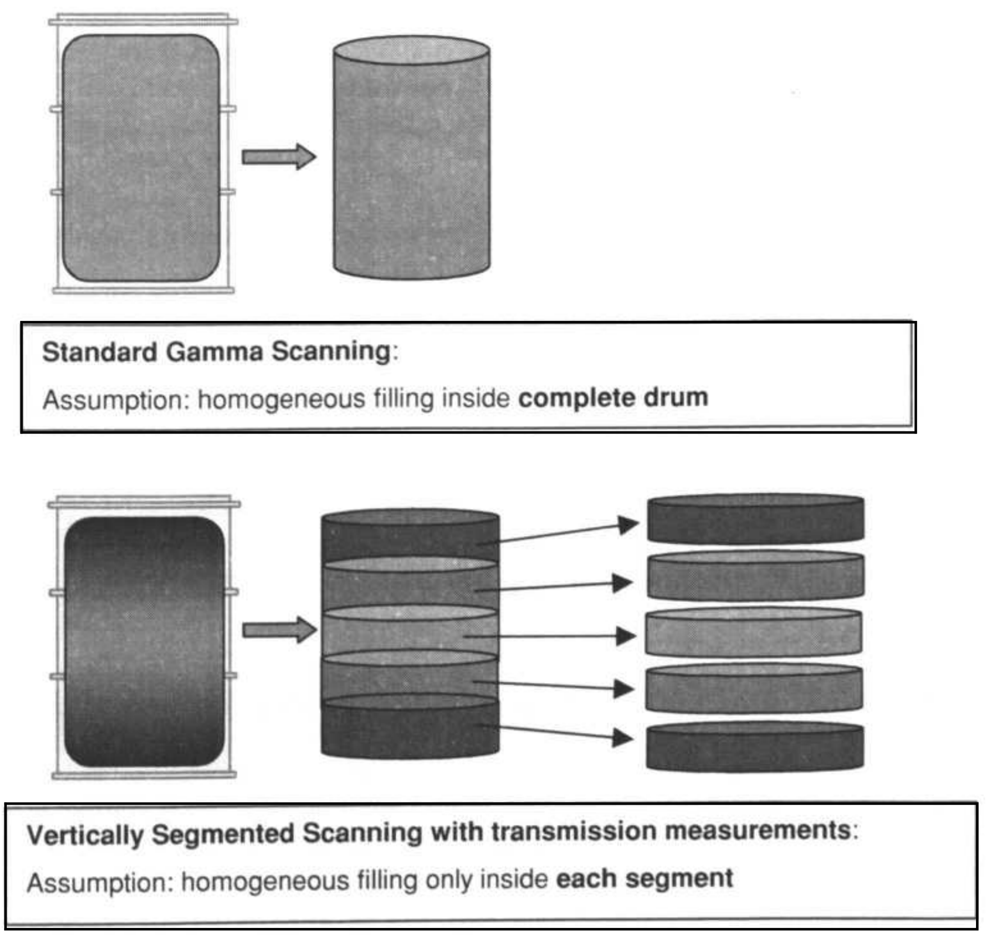


Fig. 2.6: Illustration of the difference between 'Conventional/Volume Scanning' and 'Segmented Gamma Scanning'

The main difference between standard gamma scanning with drum rotation and vertically segmented gamma scanning with transmission measurements is illustrated in figure 2.6. The segmentation process makes it possible to specify certain characteristics of the drum filling with respect to well defined horizontal slices (here called segments). These segments *are assumed to have* fairly homogeneous density and activity distribution.

The segmentation is carried out with some 'overlap' to assure that the drum is measured completely. The problem associated with this method originates from the fact that the response recorded by the measurement system at a certain vertical position is thus normally made up from contributions of the 'main' segment and its neighbours. This effect, called 'crosstalk', is a result of the geometrical configuration of object and detector.

Therefore, one of the problems which have to be solved in SGS is to define a consistent way of 'summing up' the activity values from each individual segment.

Competitive techniques

To account for inhomogeneity of activity or matrix distribution more advanced nondestructive testing methods like computer tomography and digital radiography have been developed and can be used in addition to gamma scanning. These advanced methods may be regarded as 'highly sophisticated' assay techniques and they involve much more complex system design and data evaluation than the standard procedure. In addition the time and cost spent for such extended measurements is usually too high to be within the scope of routine quality checking inspections.

Degree of innovation

The innovative features of the performed research programme are mainly related to the following scientific and technical aspects:

- development of transmission correction techniques for gamma assay of *intermediate and high density* waste packages,
- application of *multi-energy* transmission sources to correct for attenuation at *arbitrary energies* (ca. 200 keV to 1500 keV),
- development and implementation of correction algorithms to account for *variations of activity and density distribution* in gamma scanning systems.

2.3 Determination of activity inventories by the method of 'Swivel Scanning'

The basic assumption of calibration procedures of conventional (integral) gamma scanning is the homogeneity of the matrix and the activity distribution. In practice, these conditions are often not fulfilled (see table 1.1).

The TC-SGS method aims at correcting for vertical variations in a waste package by splitting up the matrix inside the drum into a number of cylindrical slices, called vertical segments. For each segment the density and activity is determined individually. This method is capable of taking into account vertical inhomogeneities of the matrix and the activity distribution under the premises that *at least each segment can be regarded to be filled homogeneously*.

The vertical response profile measured by transmission works as a useful indicator for the fulfilment of these premises which can be checked in routine gamma assay. In situations where the activity may be spatially concentrated (see fig. 2.7) additional scanning methods must be employed to improve the assay result.

Figure 2.7: Transition from homogenous to spatially concentrated activity distributions.

The following options for 'hot spot' detection and characterisation have been considered during the design phase of the project:

- Moving the detector along the detector-drum-axis (distance scanning),
- Moving the detector horizontally (horizontal scanning).
- Rotating along the detector's vertical symmetry axis, i.e. changing the orientation of the detector opening cone in a horizontal plane ('Swivel-Scanning').
- Scanning the drum at different angular positions with medium/high resolution ('Angular Scanning').
- Combination of 'Horizontal' and 'Angular Scanning' ('Tomography').

The choice of an appropriate method for routine operation has to meet two requirements: First it should be fast enough to avoid excessive delays in the routine operation and second it should be implemented without extensive change in the existing systems. For this reason FZJ decided to focus on the 'Swivel-Scanning' (SWS) because no additional hardware installations were required for the GERNOD systems.

Furthermore, the number of additional measurements required when applying SWS is limited to an acceptable amount, which makes it attractive for routine operation. From a mathematical point of view 'swivel scanning' yields approximately the same information as 'horizontal scanning', but it does not need too much hardware modifications.

Basic description of the 'Swivel Scanning Method'

If only multiple rotational scans are performed it is obvious *that a rotating point source can be replaced by an equivalent ring source* (see figure 2.8a) with respect to the mean detected response. Thus a rotating waste package may be regarded to have pure cylindrical symmetry, i.e. having an 'onion-like' structure of 'rings' (see figure 2.8b). The basic idea of the 'swivel scanning method' is to perform measurements in such a way that the activity within these concentric rings is 'reconstructed'. Each ring is regarded to have a fraction A_j of the total activity. If the detector is now 'swivelled' around its vertical symmetry axis the measured response in a swivel position (angle) is different for the individual rings in the plane. This effect makes the method sensitive to radial variations of the activity within a horizontal plane.

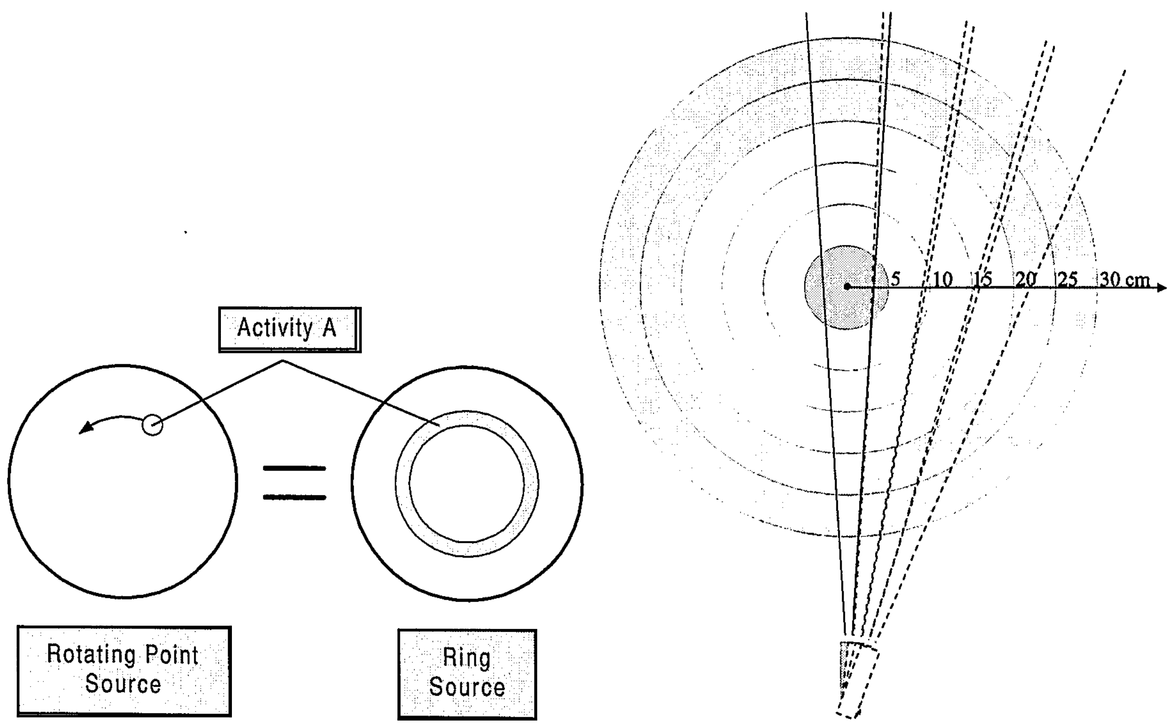


Fig. 2.8: a) (left) Illustration of a model which replaces a rotating point source by an equivalent ring source
b) (right) Illustration of a simple model of replacing a complete drum segment by a number of concentric homogeneous ring sources

Mathematically the activity distribution inside the 'ring model' can be represented by a m-dimensional vector $\underline{A}$, if m rings are chosen to subdivide a segment. Similarly the measured response for n different swivel positions can be represented by a n-dimensional vector $\underline{Z}$. The relation between $\underline{Z}$ and $\underline{A}$ may be represented by a (n x m)-matrix $\underline{\underline{G}}$, which is frequently called 'transfer matrix' in the following simple form:

$$\underline{Z} = \underline{\underline{G}} \cdot \underline{A} \qquad (2.3)$$

The elements of the matrix g_{ij} represent the contribution of the j^{th} ring to the i^{th} swivel position. The transfer matrix includes all relevant response parameters, like the geometrical dimensions of the detector system, the absorption properties of the waste material and the intrinsic efficiency of the detector for the respective energy of the observed radionuclide. To reconstruct the activity distribution this matrix equation has to be solved. The total activity can be calculated by summing up all components of the activity vector.

The procedure described does not increase the overall measuring time (additional time needed is ca. 10-20 min) compared to conventional gamma scanning (ca. 30-40 min) as drastically as emission computerised tomography does (ca. 1-2 hours), especially if the method is limited to the 'hot spot zone' of the waste package under inspection. The vertical region of interest may be identified by a standard multiple rotational scan which is often performed in routine assay.

3 Working Programme Planned at FZJ

This chapter describes briefly the overall structure of the R&D project and gives detailed information on the planned work programme at FZJ.

Within the research programme three main work areas were identified and labelled A, B and C :

- AREA A: System design, modelling and performance calculations,
- AREA B: System set-up for transmission correction measurements and swivel scanning on intermediate and high density waste,
- AREA C: Testing and performance assessment of the transmission correction method and the swivel scanning method.

A 'definition phase' at the beginning of the project was used to define the detailed work programme and the distribution of work packages among all partners of the project.

Within work area A, the major uncertainties and sources of errors of conventional gamma scanning measurements were determined and simulated by appropriate computer modelling. The results of the calculations were then used to develop concepts for improved gamma scanning techniques by modification and upgrading of existing systems.

After the design phase an improved system was set-up and tested for intermediate and high density waste (GERNOD-II system). With the upgraded prototype system the performance of the improved scanning techniques was assessed by measurements on 'mock-up' drums and on selected real waste packages. The performance was compared to results of 'conventional' gamma scanning.

The main work areas A, B and C and the performance assessment part of the project are described in the following.

3.1 System design, modelling and performance calculations (Area A)

Computer calculations were foreseen to calculate the influence of major uncertainties and possible sources of error for conventional gamma scanning measurements. Design studies were performed to define appropriate hardware and software configurations for the implementation of correction techniques for inhomogeneity effects of matrix and activity distribution in intermediate and high density waste packages.

The following activities had been planned at FZJ:

- computer modelling of the system response of conventional gamma assay systems with respect to the following parameters:

    density of waste,

    range of energies for transmission measurement,

    type of waste material, type of containers, characteristics of the matrix distribution,

characteristics of the activity distribution,

material composition of the matrix

- development and/or adaptation of algorithms for attenuation correction
- theoretical assessment of the performance of improved gamma assay procedures under various conditions (by computer calculations):

  composition and density of the matrix,

  energies of transmission,

  practical lower limit of transmission values,

  influence of statistics.

3.2 System set-up for transmission correction on intermediate and high density waste (work area B)

It was intended to modify and upgrade existing scanners to be able to implement the developed correction procedures. The work of FZJ within area B was aimed at implementing transmission measurement capabilities into the existing GERNOD system.

The following activities had been planned at FZJ:

- system design for improved gamma scanning:

  mechanical and electrical set-up of combined gamma scanning and transmission scanning procedures,

  design of appropriate 'filters/absorbers' for the attenuation of the transmission source,
- definition of appropriate measurement procedures for the application of improved scanning and attenuation correction techniques,
- evaluation and procurement of useful transmission sources (Eu-152, Ir-192),
- installation of multi-energy transmission sources and adaptation to the existing assay equipment at FZJ/ISR3,
- upgrading of existing NDA systems and implementation of the correction methods at the respective testing facilities.

3.3 Testing and performance assessment of the transmission correction method (Area C)

After implementation of the hardware and software the systems had to undergo extensive testing on mock-up drums with known matrix structure and activity content. These investigations were used to benchmark the computer models and to assess the correction algorithms that have been developed within work area A. Finally measurements were planned on real waste drums to demonstrate the performance of the optimised gamma scanning techniques for routine quality checking on raw and conditioned waste packages.

The following activities had been planned at FZJ:

- benchmark testing on drums of known composition and content,
- assessment of the performance of the developed algorithms to account for non-homogeneous density and activity distribution,
- measurements on selected real waste drums and performance assessment,
- inter-comparison of conventional and transmission corrected gamma scanning,
- assessment of errors, uncertainties and detection limits.

As a result of the project, recommendations have been formulated on how to perform gamma scanning more accurately for a certain range of applications. These guidelines will help the respective people who perform gamma measurements to select those techniques which are best suited for a specific quality inspection task, to identify and quantify possible errors and to select appropriate measures to reduce uncertainties.

3.4 Overview of Work packages scheduled at FZJ

The working program as described in paragraphs 3.1 – 3.3 is subdivided into several tasks. The following main activities have been carried out by FZJ:

Number Description

Area A: *System Design, Modelling and Performance Calculations*

Development of correction procedures:

- Swivel-scanning (co-operation with: TUM)
- Transmission corrected gamma scanning

Area B: *System-Layout, Procedures and Set-Up of Prototype*

- System Layout (hardware & software)
- Prototype Installation
- Prototype Testing

Area C: *Measurements on 'mock-up' drums and real waste packages*

- Test measurements on 'mock-up' drums
- Evaluation of benchmark tests
- Selection and characterisation of real waste drums
- Field measurements on selected waste packages
- Data evaluation and performance assessment of the developed new methods

Table 2: Overview of work packages carried out by FZJ within the R&D project

In the following chapter the experimental and theoretical work performed at FZJ is described.

4 WORK PERFORMED BY FZJ/ISR3

This chapter summarises the work actually performed and the results achieved within the project referring to the work packages described in chapter 3. Additional and more detailed information may be found in the official final report written for the European Commission. A list of all available topical and final reports on the project is given in the annex.

4.1 Development of correction procedures

The main objective was to improve the performance of gamma scanning by making use of the following three correction techniques to account for heterogeneities in activity and matrix distribution:

- Activity determination by swivel scanning .
- Attenuation correction by transmission measurements.

General description

Correction procedures are being developed to minimise the influence of attenuation effects and inhomogeneities on gamma scanning results. The fundamental technique used to reveal more information about the structure of the sample is based on transmission measurements. Enhanced scanning techniques like 'swivel scanning' have been developed to compensate for non-homogeneous activity distributions.

The following concepts have been defined for correction algorithms:

- *multi-energy transmission measurements for attenuation correction (TC-SGS)*

  Multi-energy transmission measurements are used to 'estimate' the mean attenuation of gamma-rays in a vertical segment of the drum. This information can be used to approximate the average density at a certain height of the object and to correct for gamma attenuation within each segment. A respective correction algorithm has been developed by FZJ based on this method.

- *correction for source inhomogeneities by swivel-scanning - or horizontal-scanning - with continuous drum rotation (SWS)*

  The basic idea is to record within a vertical segment the count rates at different angles of the detector relative to the drum axis (swivelling) - or at different horizontal positions of the detector relative to the drum (horizontal movement) - while the drum is continuously rotated. The recorded data are used to 'reconstruct' the distribution of the activity of prominent γ-emitters in a cross-sectional plane of the drum (low spatial resolution). The respective correction algorithms have been developed by FZJ in co-operation with TUM/RCM.

4.1.1 Swivel scanning

General description

A central problem of conventional and transmission corrected segmented gamma scanning is the determination of the activity of spatially concentrated radioactive sources in a waste package. The main purpose of this task is to develop an additional procedure which can deal with non homogeneous activity distributions. The swivel scanning was selected from a variety of different methods mainly because it is easy to implement in existing gamma scanners without extensive hardware modifications. Furthermore, the number of additional measurements is limited to an acceptable amount, which makes it attractive for routine operation.

Work performed

The main attention during the developing process of the swivel scanning procedure was focused on the simulation of the efficiency matrix. The real measurement situation should be reproduced in the simulation as precise as possible. The software code 'Solidang' produced for efficiency calculation of gamma scanners was used for this purpose /SCK-2/. It was adapted to the real situation of the GERNOD gamma scanner of FZJ by setting up the geometrical parameters and fitting the measured collimator profile by the collimator function used in the Solidang code.

The absorption data included in the simulations were calculated by 'Photocoeff' which is used in the SOLIDANG software. This procedure was later replaced by using the measured transmission data of the TC-SGS, which is more straight forward because in practise the material composition and density of a specific segment under observation is not know with sufficient accuracy.

An alternative simulation code using a different collimator model was developed and implemented in the reconstruction procedure. Due to a reduction of features (especially concentrating on homogenous absorbers) and a different sampling technique this code works faster than SOLIDANG. Therefore, it can calculate the efficiency matrix 'on-line' during the reconstruction. It was especially used to analyse different ways of data treatment.

For the solution of the transfer equation two algorithms were developed and tested. For a quadratic transfer matrix the most obvious way to calculate $\underline{A}$ from (*) is a simple inversion. This was performed by calculating the inverse matrix by a standard algorithm and an iterative method. For a (n x m)-transfer matrix a algorithm named radial variation method was developed. It compares the normalised measured count rate vector with the normalised columns of the transfer matrix and determines the minimum deviation. The position of the minimum corresponds to the radial position of the source. The activity is calculated by a division of the count rate of minimal uncertainty by the corresponding transfer matrix element. This method is only applicable for one source.

Results & Achievements

The fundamental theoretical background of a swivel scanning method has been investigated. For the simulation of efficiency matrices the Solidang code has been adapted to the real measurement situation and a more simple but fast code has been developed. All available data can be used to improve the accuracy of the simulation.

For the reconstruction of the total activity two procedures are implemented in a software code. The comparison of the results can be used for an estimation of systematic errors.

Work performed at TUM

In one segment a predefined number of rotational scans is performed, each differing by the swivelling angle of the detector system. Due to the detector collimation, the investigated segment of the waste package is subdivided into a number of rings which may overlap (figure 4.1). Each measured count-rate is then correlated with the activity of the regions „seen" by the detector, i.e. the outer swivelling position is correlated to the outer ring, for the succeeding swivelling angle to the two outer rings, etc. until for the swivelling angle of 0° contributions from the complete segment are „seen". Due to the rotation of the waste package inhomogeneities of the actual activity distribution within each ring are levelled out to some extent and therefore the activity distribution within each ring can be regarded as having approximately cylindrical symmetry. The mathematical model for the evaluation of swivel scanning measurements correlates the measured count-rates Z_i for the different swivel positions with the corresponding activities of the individual rings, defined by the swivel angle and the collimator aperture, via an energy and matrix dependent transfer matrix $\underline{G}$.

$$\vec{Z} = \frac{Q}{p_\gamma} \cdot \underline{G} \cdot \vec{A} \qquad (4.1)$$

with Q being an energy dependent calibration constant and p_γ the transition probability of the evaluated gamma-line.

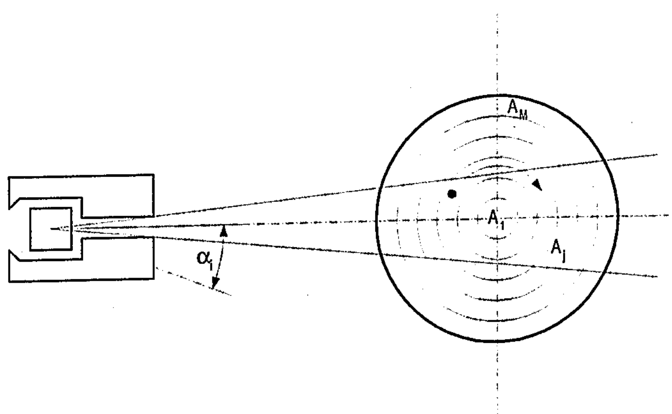


Fig. 4.1: Sketch of the swivel scanning measurement procedure

Extensive investigations were performed concerning the determination of the elements of the transfer matrix. The elements g_{ij} of the transfer-matrix $\underline{G}$ are weighting factors defining the influence of different regions of the waste matrix on the measured count rates. The weighting factors are given by the volume integral:

$$g_{ij} = \iiint \frac{\exp\left(-\sum_k \mu_k \cdot x_k\right)}{y^2} \cdot dV \qquad (4.2)$$

with y: distance between detector and volume element dV,
μ_k: linear attenuation coefficient of ring k and
x_k: path-length within ring k.

The integration is performed for the complete volume seen by the detector and the sum considers all rings intersected by the path from x_k to the detector. It is assumed that the activities and densities are homogeneous within the individual rings.

Investigations were performed to solve the volume integral using mathematical software tools (e.g. /MAT94/) as well as the software SOLIDANG 2.1 and by analytical calculations for special simple situations. As an example table 4.1 shows the results for the inner ring of a peat matrix for a swivelling angle of 0° and three different energies. The value for the transfer-matrix element derived from measurement was determined by using the "Filß"-method /FIL89-2/ and rearranging the corresponding formula to solve the volume integration. Based on the results shown in table 4.1 and achieved by additional evaluations for other swivelling angles, the simulation code SOLIDANG 2.1 was verified.

energy [keV]	SOLIDANG Vers. 2.1	numerical calculation	derived from measurement
100	0.0642	0.064	0.0647
1000	0.3846	0.3845	0.3872
1430	0.4485	0.4484	0.4516

Tab. 4.1: Comparison of the results for determination of transfer-matrix elements using different methods

Different techniques for solving equation 4.7 were investigated:

- matrix inversion,
- direct recursive solution of the system of equations and
- iterative method.

The methods of matrix inversion and of direct recursive solution of the system of equation developed within the project are applicable for a quadratic transfer matrix. The latter has the additional limitation of requiring a triangular matrix. To overcome all these limitation an iterative method was investigated.

Matrix inversion method

The most obvious method for solving the matrix equation (4.1) is to calculate the inverse matrix $\underline{G}^{-1}$. Then the activity vector is given by

$$\vec{A} = \frac{p_\gamma}{Q} \cdot \underline{G}^{-1} \cdot \vec{Z} \tag{4.3}$$

The total activity is the sum of the activity vector components which represent the ring activities.

Direct recursive solution of the system of equations

For the direct recursive solution of the system of equations the transfer-matrix must be first transformed into the triangular form, which is necessary if the collimator cones of neighbouring swivel angles overlap. The matrix equation can be written as a system of equations for n measured count rates and swivelling angles respectively for m = n rings.

$$\begin{aligned} Z_n &= \frac{Q}{p_\gamma} \cdot g_{n,n} \cdot A_n \\ Z_{n-1} &= \frac{Q}{p_\gamma} \cdot \left(g_{n-1,n-1} \cdot A_{n-1} + g_{n-1,n} \cdot A_n\right) \\ Z_{n-2} &= \cdots \end{aligned} \tag{4.4}$$

The first equation to be solved is for the most outer ring (index n) corresponding to the largest swivelling angle (index $n = m$). This result is then used for the calculation of the activity within the next ring, repeating this procedure until the activity for the inner ring is calculated. In practice, the count rate for the most outer measuring position very often has a large statistical error especially for centre source positions because only the outer part of the drum is „seen“ by the detector. Furthermore, The accuracy of the matrix elements for large swivelling angles is strongly affected by the geometrical arrangement (e. g. position of the detector, central position of drum on the turntable, etc.). Both „effects“ may lead to a bias of the accuracy of the calculated activity within the outer rings. Since for the evaluation of the subsequent equations (i.e. for the activities in the inner rings) the previous results are used, the uncertainty of the results may increase.

Iterative method

For the iterative method a modified version of the algebraic reconstruction technique (ART), which is used in computer tomography /HER80/, is applied for solving the matrix equation. The algorithm is defined by the relation:

$$A_j^{(n)} = A_j^{(n-1)} + r \cdot \sum_i \frac{w_{ij}}{a_i} \cdot \left(Z_i^{meas} - Z_i\right) \tag{4.5}$$

with

$A_j^{(n)}$: activity of the j^{th} ring after the n^{th} iteration
r: relaxation factor
w_{ij}: weighting factor $w_{ij} = g_{ij} / \Sigma g_{ij}$

a_i: average factor for the ith swivelling position $\mathbf{a}_i = 1/M \sum g_{ij}$
Z_i^{meas}: measured count-rate for the i^{th} swivelling position
Z_i: calculated count-rate (equ. 4.9), using the activities of the $(n-1)^{th}$ iteration.

Starting with an initial guess for the activity vector $A^{(0)}$ the „true" activity vector A is determined by iteration. If the difference between measured and calculated count rates is below a predefined threshold the iteration stops. The resulting ring activities can finally be summed up to the overall activity within the investigated segment of the waste package.

Results & Achievements

The fundamental theoretical background of the swivel scanning method was investigated. For the simulation of the transfer-matrix-elements the SOLIDANG 2.1 code proved to be suitable.

The three data analysis techniques investigated, matrix inversion, direct solution of the system of equations and iterative method, proved their applicability for the evaluation of swivel scanning measurements.

Discussion of results and conclusions

It was noted, that for the resulting individual ring activities sometimes negative values occur, which is a well known fact in reconstruction theory /HER80/. Nevertheless the summed ring activities were in good agreement with the total activity in the investigated waste package.

Work performed by FZJ

The main attention during the developing process of the swivel scanning procedure was focused on the simulation of the efficiency matrix. The real measurement situation should be reproduced in the simulation as precise as possible. The software SOLIDANG produced for efficiency calculation of gamma scanners was used for this purpose. It was adapted to the real situation of the GERNOD gamma scanner of FZJ by setting up the geometrical parameters and fitting the measured collimator profile by the collimator function used in the SOLIDANG code.

The absorption data included in the simulations were calculated by 'Photocoeff' which is used in the SOLIDANG software. This procedure was later replaced by using the measured transmission data of the TC-SGS, which is more straight forward because in practise the material composition and density of a specific segment under observation is not known with sufficient accuracy.

An alternative simulation code using a different collimator model was developed and implemented in the reconstruction procedure. Due to a reduction of features (especially concentrating on homogenous absorbers) and a different sampling technique this code works faster than SOLIDANG. Therefore, it can calculate the efficiency matrix 'on-line' during the reconstruction. It was especially used to analyse different ways of data treatment.

For the solution of the transfer equation two algorithms were developed and tested. For a quadratic transfer matrix the most obvious way to calculate $\underline{\mathbf{A}}$ is simple matrix inversion. This was performed by calculating the inverse matrix by a standard algorithm or an iterative method. For a (n x m)-transfer matrix an algorithm named 'radial variation method' was developed. It compares the normalised measured count rate vector with the normalised columns of the transfer matrix and determines the minimum deviation. The position of the minimum corresponds to the radial position of the source. The activity is calculated by a division of the count rate of minimal uncertainty by the corresponding transfer matrix element. This method is only applicable for one source.

Results & Achievements

The fundamental theoretical background of a swivel scanning method has been investigated. For the simulation of efficiency matrices the SOLIDANG code has been adapted to the real measurement situation and a more simple but fast code has been developed. All available data can be used to improve the accuracy of the simulation.

For the reconstruction of the total activity two procedures are implemented in a software code. The comparison of the results can be used for an estimation of systematic errors.

4.1.2 Transmission corrected segmented gamma scanning (TC-SGS)

General description

The main purpose of this task was to develop a correction procedure for gamma attenuation based on multi-energy transmission measurements. The task involves the solution of two problems:

- Fitting of multi-energy transmission data T = f (E)
- Definition of a correction function CF = f (T)

Development of a fitting program for multi-energy transmission

The drums are measured over a number (usually ten to twenty) of vertical segments. A transmission measurement is performed with an Ir-192 source for each segment. The software evaluates the recorded spectra to determine how many 'full energy peaks' for Ir-192 gamma rays have been detected properly. For all those peaks detected it determines the net count rate with its measurement uncertainty. The net count rate N_i is used together with the respective net count rate N_{i0} of the reference measurement of an empty drum to calculate the relative attenuation effect along the diameter of the matrix for all detected energies $\mathbf{E_i}$ in the particular segment:

$$T(E_i) = N_i / N_{i0} \tag{4.6}$$

The transmission values $T(E)_i$ are fitted as a function of energy by the implemented fitting routine 'TRANSFIT'. The implemented function calculates the attenuation properties of the particular segment in terms of the product of diameter D and density ρ if the type of matrix (effective atomic number Z) is given:

$$X = D \cdot \rho \tag{4.7}$$

The result of the fitting procedure thus yields a value **X** which can be used to assess the vertical density profile of the drum ρ (h). This value is also used in the calculation of the attenuation correction factor C_{self}.

The program TRANSFIT can be used:

- to analyse measured data in an off-line mode,
- to simulate energy dependent transmission values,
- as integrated fitting routine within the system software for on-line data evaluation.

A description of the user program 'TRANSFIT.EXE' including some test examples can be found in a separate topical report written by FZJ /FZJ-2/. An example of the graphical presentation of a fit result calculated by TRANSFIT is shown in figure 4.2.

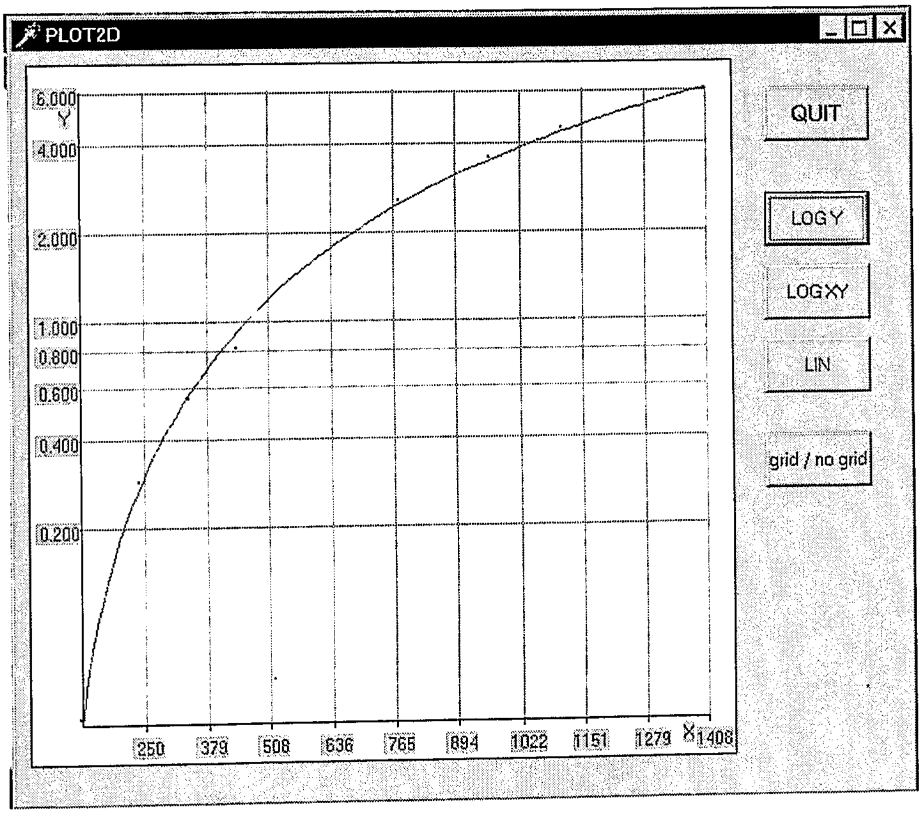


Fig. 4.2: **Graphical presentation of fit result for transmission data from Eu-152 measurement calculated by TRANSFIT (Rev. 3.1)**

Correction Algorithm based on Multi-Energy Transmission

A transmission measurement is performed in every segment and data are fitted by the programme TRANSFIT included as DLL into the data analysis software of the GERNOD system.

In order to interpret the data from transmission measurements in terms of physically significant parameters a simple model of the attenuation process which takes place in transmission measurements with an external source has been defined. This model describes two attenuation processes, one in the wall of a drum ('external attenuation') and the other one in a homogeneous filled segment of the drum itself (referred to as 'internal attenuation' or 'self attenuation'). Figure 4.3 illustrates this model which is used to characterise the matrix inside the drum in terms of geometry (diameter) and physics (mean attenuation coefficient).

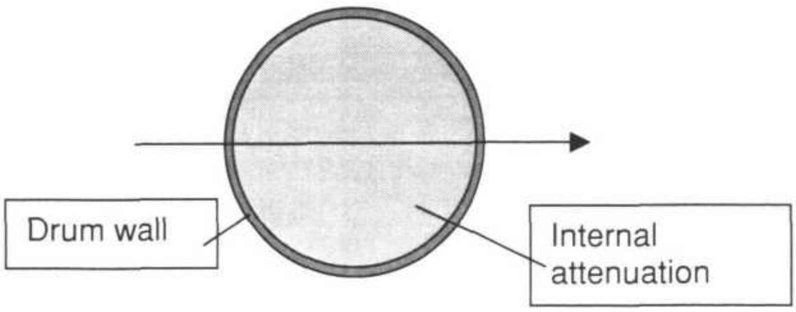


Fig. 4.3: Simple geometrical model to describe the attenuation process which takes place in transmission measurements with narrow beam geometry

According to this model the overall corrective function 'COR(E)' takes the form:

$$COR_{object}(E) = C_{ext}(E) \cdot C_{self}(E) \tag{4.8}$$

$$C_{ext}(E) = \exp\{\mu_w(E) \cdot d_w\} \tag{4.9}$$

By choosing input parameters the model can be adapted to different geometries, like diameter of the drum or even with no drum wall present. An additional internal shielding may also be included into the matrix representation data base.

The geometrical model to calculate the correction factor $\mathbf{C_{self}}$ for an internal attenuation in a vertical segment is based on the 'far field' model proposed by Parker and Reilly /PAR84/ ('The use of calibration standards and the correction for sample self attenuation in gamma ray assay', LA-10045, Revision, Los Alamos National Laboratory 1984). This paper derives a correction factor to be applied to far- and near- field, two and three dimensional, cylindrical sources. The formula for the correction factor $\mathbf{C_{self}}$ as function of the measured transmission **T**(E) at energy **E** is approximately given by:

$$C_{self} = \frac{k \cdot \ln(T)}{(1 - T^k)} \tag{4.10}$$

This model does not fit perfectly for gamma assay in a 'near field' assay configuration applied to a cylindrical object. In general 'far field' applies to geometries which fulfil the relation:

$$D > 5 \cdot R \tag{4.11}$$

with R : radius of the cylinder
D : distance from centre of cylinder to detector

For the FZJ system the ratio of D/R is ~3 which indicates a 'near field' geometry is more likely to be expected. It is possible to choose the geometrical 'scaling parameter k' in such a way that the model fits to standard assay configurations where the detector is not too far away from the drum surface. It could be shown by modelling with SOLIDANG and MCNP calculations performed by NNC/WQCL that for low to medium matrix densities (up to 2.1 g/cm^3) and energies above 300 keV the deviation of the above formula is lower than 10 % if the k-factor is chosen to be k=0.823. This value for 'k' is also defined for far field geometry correction in 'Standard test method for non-destructive assay of special nuclear material in low density scrap and waste by segmented passive gamma ray scanning', ASTM C1133 1996'.

For the data analysis performed at FZJ the value of k used lies between:

$$\pi / 4 < k < 0.823 \tag{4.12}$$

The best value for k should be calculated according to the measurement geometry taking especially into account the collimator profile of the detection system. For non homogeneous activity distributions more complex equations may be applied to calculate the self attenuation correction factor C_{self}. But this involves sufficient knowledge about the distribution of the matrix.

Inter-comparison of calculated and measured transmission data

A comparison was carried out between fitted transmission determined by TRANSFIT and measured data. Transmission measurements at the ten specified Eu-152 gamma ray energies were determined by measurement through real waste packages. This data was input into the TRANSFIT algorithm. A number of cases were compared and in each case the comparison was very good. An example of one such comparison is:

Energy (keV)	Measured Transmission (%)	TRANSFIT Fit Values (%)
244	62.07	62.33
344	62.21	63.1
444	64.42	63.65
779	65.4	64.81
867	65.48	65.03
964	63.05	65.21
1112	65.05	65.48
1408	65.38	65.89

Table 4.1: Inter-comparison measured and calculated transmission values for TRANSFIT

Results & Achievements

A fitting procedure for multi-energy transmission has been developed by FZJ. The resulting program 'TRANSFIT' written by FZJ can be used to describe the measured transmission on the basis of physical significant parameters like 'average density' and 'mean effective atomic number of the attenuating matrix'.

FZJ has set-up a correction procedure for gamma attenuation which can be applied in the case of homogeneous filled vertical segments of a drum measured in a 'near field' geometry. The method is based on one integral transmission measurement made through the centre of the drum in each vertical segment.

4.2 Concept and System Design for Enhanced Gamma Scanning

Work Performed

The main purpose of this task was to develop a procedure for TC-SGS based on transmission measurements with an external Ir-192 source. The task was devoted to the development of an appropriate design for the hardware and software to upgrade the measurement capabilities of the existing GERNOD scanner at Jülich. The following work items have been addressed:

- Set-up of appropriate hardware design for transmission measurements,
- Definition of automated measurement procedures to perform TC-SGS,
- Implementation of data handling and analysis procedures into the SCANNER software.

System set-up and upgrading was performed at the installation 'Chemie-Zellen (CZ)' in the institute ISR. Regarding the system characteristics a set of possible enhanced techniques and procedures was identified and detailed. These techniques are:

I. Techniques to improve the system characteristics with respect to non homogeneous matrix distributions:

- transmission measurements to perform attenuation corrections for a certain segment,
- transmission measurements to assess the vertical density profile of the drum.

II. Techniques to improve the system characteristics with respect to non homogeneous activity distributions:

- vertical segmented scanning to account for vertical inhomogeneities by analysing the count rate distribution,

- sectorized scanning to assess the degree of radial and azimuthal activity variations and to determine source position characteristics,
- horizontal and/or swivel scanning to reconstruct spatial characteristics of the activity distribution within a segment and to calculate the overall activity (preferably in combination with transmission measurements).

The application of the aforementioned techniques involves the following system capabilities to be realised in an upgraded gamma scanning system:

- vertical movement of detector (or drum) along drum axis,
- drum rotation,
- implementation of a transmission source for central drum transmission measurements (incl. exchangeable collimator apertures),
- for the swivel scanning option: A turntable for the detector-collimator subsystem with reproducible angle positioning capabilities,
- for the horizontal scanning option: A translational positioning system for the detector-collimator subsystem (or the drum-turntable subsystem),
- a flexible and adaptable software for handling data coming from different scanning modes and the capability to perform data analysis procedures due to different implemented algorithms.

The existing gamma scanning system at FZJ/ISR was upgraded to perform multi-energy transmission and swivel-scanning. The necessary techniques and the respective hardware/software implementations have been realised in the prototype system set-up during the project. A detailed description is given below for the GERNOD-II system. The system is operated at the waste storage facility TIA-DE.

Concept for TC-SGS realised in the GERNOD II system

The main difference between standard gamma scanning with drum rotation and vertically segmented gamma scanning with transmission measurements is illustrated in figure 4.4. The segmentation process makes it possible to characterise the material inside cylindrical slices of the drum which are assumed to have fairly homogeneous density and activity distribution.

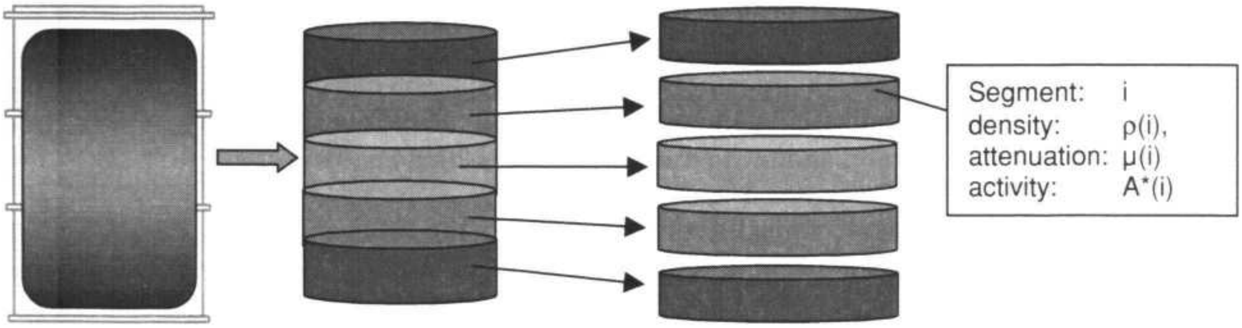


Fig 4.4: Scheme of segmentation in multi-rotational segmented scanning

The segmentation process makes it possible to characterise the material inside cylindrical slices of the drum which are assumed to have fairly homogeneous density and activity distribution. The segmentation is carried out with some 'overlap' (that means that the aperture of the system is larger than the spacing between the vertical detector positions) to ensure that the drum is measured completely. The activity within a single segment for a nuclide with energy j is calculated according to the following equation:

$$A^{*}_{i,j}[Bq] = \frac{Z_{i,j}}{\varepsilon_{cyl} \cdot p_{j}} \cdot C_{ij}(T) \cdot C_{w} \cdot V_{i} \quad (4.13)$$

with:

$Z_{i,j}$: Net count rate in segment i for energy j
ε_{cyl}: Efficiency for empty cylinder
p_j: Transission probability
$C_{i,j}$ Self absorption correction
C_w Container wall correction
V_i: Intersection volume between drum and collimator cone

The overall activity for a specific nuclide is calculated according to the flow scheme shown in figure 4.5. The problem associated with this method originates from the fact that the response recorded by the measurement system at a certain vertical position (segment) is normally made up from contributions of the 'main' segment and its neighbours. This effect, called 'cross talk', is a result of the geometrical configuration of object and detector.

By summing up the calculated activities $\{A^{*}_{i}\}_{i=1,n}$ from all individual segments it is therefore necessary to treat the contributions from the segments by some mathematical procedure, which may be called 'deconvolution'. The deconvolution process F^{-1}:

$$A'_{i} = F^{-1}(A^{*}_{i}) = \sum_{i=1}^{n} A^{*}_{i} - a_{i} \cdot A^{*}_{i-1} - b_{i} \cdot A^{*}_{i+1} \quad (4.14)$$

yields a set of activities $\{A_i'\}_{i=1,n}$ for each individual segment S_i without contribution from neighbouring segments. The deconvolution factors a(i), b(i) for an empty drum (all segments have density zero) are listed in the following table for the standard vertical scan with 40 mm collimator and 10 slices per drum. The values have been calculated by using SOLIDANG and some additional computer modelling for the segmentation geometry.

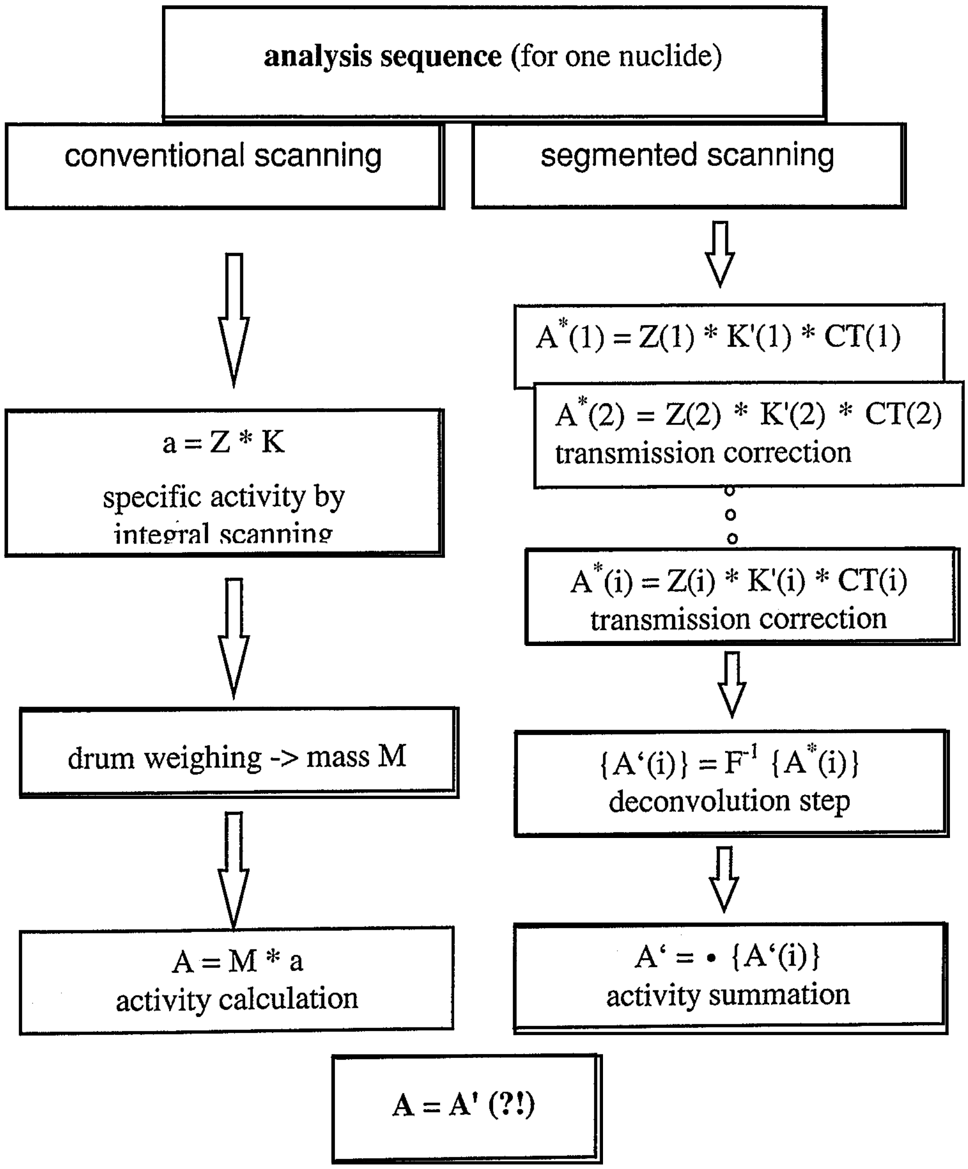


Fig. 4.5: Analysis flow chart to calculate the overall activity for one nuclide in conventional gamma scanning A and in the ‘segmented mode’ A’

It should be emphasised that the factors a(i) and b(i) depend strongly on density (and energy), which makes it necessary to calculate those factors depending on the actual object measured. The deconvolution procedure implemented in the GERNOD II system calculates a(i) and b(i) as function of the measured transmission T in each segment:

$$a(i) = f\{T_{i-1}(E)\} \qquad b(i) = g\{T_{i+1}(E)\} \qquad (4.15\ a, b)$$

Height [mm]	Volume measured [ccm]	a(i)	b(i)
20	7273	0,000	0,307
104	11493	0,194	0,194
188	11493	0,194	0,194
272	11493	0,194	0,194
356	11493	0,194	0,194
440	11493	0,194	0,194
524	11493	0,194	0,194
608	11493	0,194	0,194
692	11493	0,194	0,194
776	7732	0,289	0,000

Table 4.3: Calculated deconvolution factors a(i), b(i) for a 40 mm cylindrical collimator and 84 mm segment spacing (density = 0.0 g/cm^3). The volume measured refers to the intersection between the collimator opening (space angle) and the drum.

The dependence of the deconvolution factors on the measured transmission was to a first extent analytically fitted to simulated values for the 'cross talk' between neighbouring segments using SOLIDANG. The comparison of fitted and simulated values as function of density is plotted in fig. 4.6.

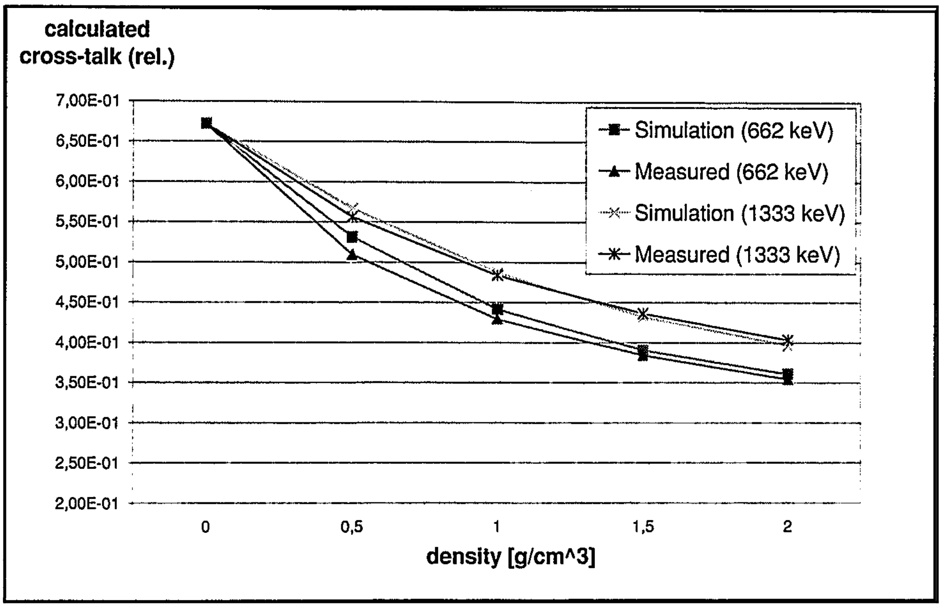


Fig. 4.6: Dependence of cross-talk between neighbouring segments on density

The dependency follows the approximate relationship (analogous for b(i)):

$$a_i(\rho) = a_i(\rho = 0) \cdot C_{self}(T_{i-1})^{-0,28} \qquad (4.16)$$

After deconvolution the total activity can be calculated by summing up the set of $\{A'_i\}_{i=1,n}$:

$$A'_{sum} = \sum_{i=1}^{n} A'_i \qquad (4.17)$$

4.3 Set-up of the prototype system for improved gamma scanning

General description

A prototype system was set-up to test the performance of the new scanning techniques. A transmission source was adapted to the existent gamma scanner GERNOD at FZJ. The necessary hardware and software modifications have been carried out to perform TC-SGS and swivel-scanning measurements including data analysis procedures.

Work performed

A transmission source was successfully adapted to the GERNOD I gamma scanner and the necessary hardware and software modifications have been performed. It consists mainly of a shielding and transport cask made of depleted Uranium (Type B(U) container) and a source capsule. This device (GAMMAMAT TI-F) can be operated by remote control (see Fig. 4.7). The shielding cask has been loaded initially with an Ir-192 transmission source of ca. 5 Ci activity (date: 15.06.98, half life: 74 days). Replacement of the source is scheduled twice a year to guarantee sufficient source activity for transmission measurements.

	TC-SGS parameter for emission scan	TC-SGS parameter for transmission scan
Collimator (cyl.)	D: 40 mm L: 200 mm	D: 10 mm L: 200 mm
Distance:		
detector – drum axis	d: 795 mm	
detector - source		d: ca. 1300 mm
Scan mode	Multi-rotational: (12 * 10) 12 sectors, 10 slices	Multi-rotational: (1 * 20) 1 sectors (360°), 20 slices
Segment spacing	S = 84 mm	S = 42 mm

Tab. 4.4: Standard scan parameters for TC-SGS in the GERNOD II system

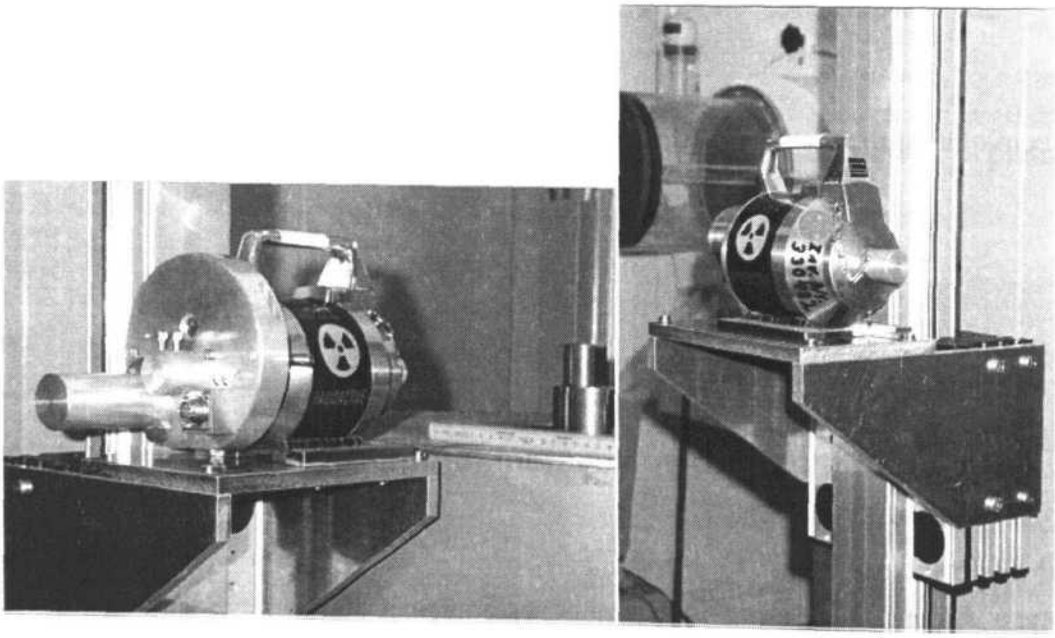


Fig. 4.7: Shielding cask for Ir-192 transmission source attached to GERNOD scanner

The hardware of the gamma scanner has been modified by including a vertical positioning system which is passively synchronised with the movement of the detector platform (see Fig. 4.8).

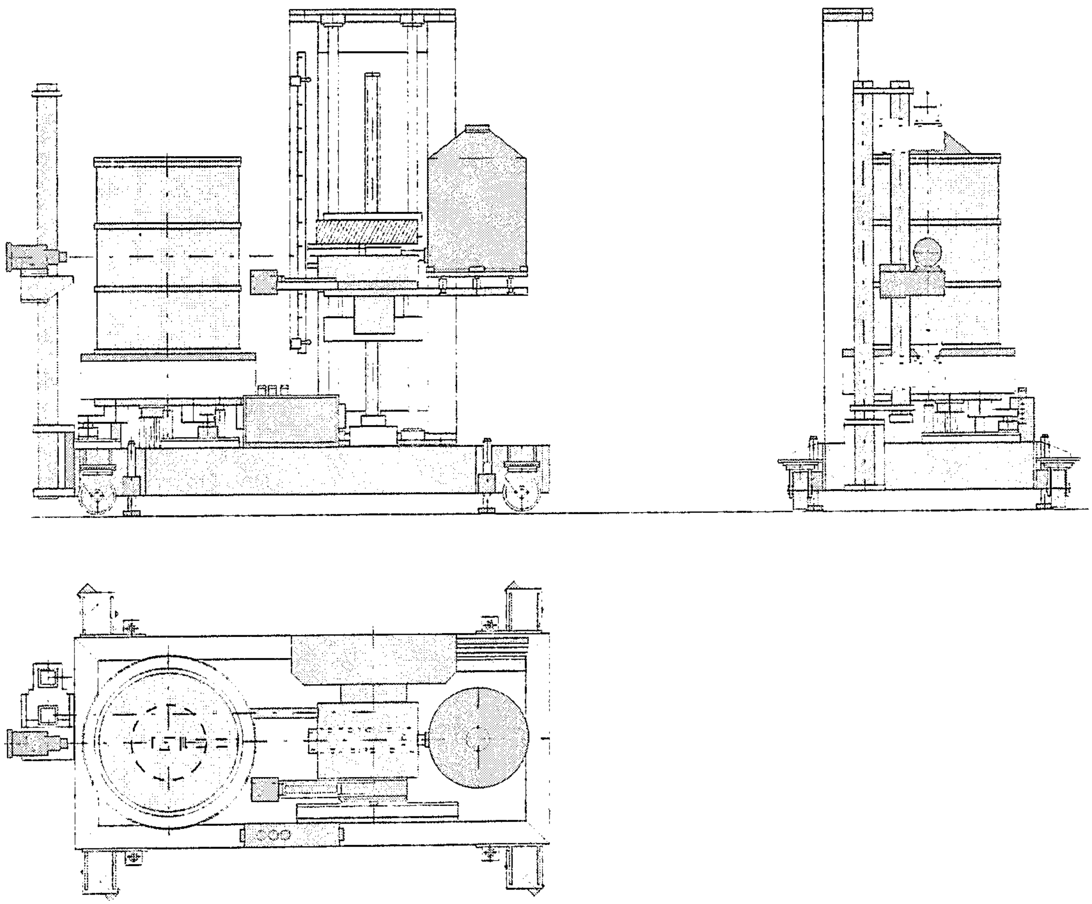


Fig. 4.8: Technical views of the upgraded GERNOD II scanner system

Software has been developed within the project which enables the automatic control of transmission measurements and data acquisition as well as part of the data analysis. The existing scanner software of FZJ was upgraded to perform multiple rotational scans with segment specific transmission, data acquisition and data evaluation.

Results & Achievements

The FZJ-Scanner GERNOD has been upgraded successfully to perform transmission measurements on the basis of multi-rotational segmented scanning with the use of an external Ir-192 source. Calibration and testing has been finished.

4.4 Proficiency tests of the prototype system

General

In this paragraph the description will focus on the first results achieved with the upgraded GERNOD II scanner at Jülich.

Work performed

After system set-up and upgrading of the GERNOD II scanner had been finished the software for operating the GERNOD II scanner with the upgraded hardware was installed and successfully tested. The data acquisition including transmission corrected segmented gamma scanning works properly. Tests of the data analysis package of the modified software including the TRANSFIT-routines have been carried out.

Proficiency testing with the Ir-192 transmission system

Calibration and proficiency testing has been performed with the equipment for transmission measurements using the Ir-192 transmission source (1,5 - 2,5 Ci). The following tests have been defined as important items concerning the performance characteristics of the system:

- repeatability and stability of the measured count rate of the T-source,
- statistical precision of the measured count rate,
- ability to measure mean density values for 200 l drums with densities between 0.4 $g/cm^3 <= \rho <= 2.0\ g/cm^3$,
- precision and reliability of the measured mean density profile.

The results of the analysis of the proficiency tests demonstrate the good performance of the system concerning the characteristics above. Some of the results are presented in the following figures 4.9 - 4.11.

Figure 4.9 shows the statistical precision and stability of the measured count rate for 468 keV as function of the vertical scanning length over a range of 80 cm. Figure 4.10 shows a measurement made on a water filled drum with a wall made of 1.5 mm steel. The measured density was not corrected for the drum wall attenuation, therefore the mean density is somewhat higher than 1.0 g/cm^3.

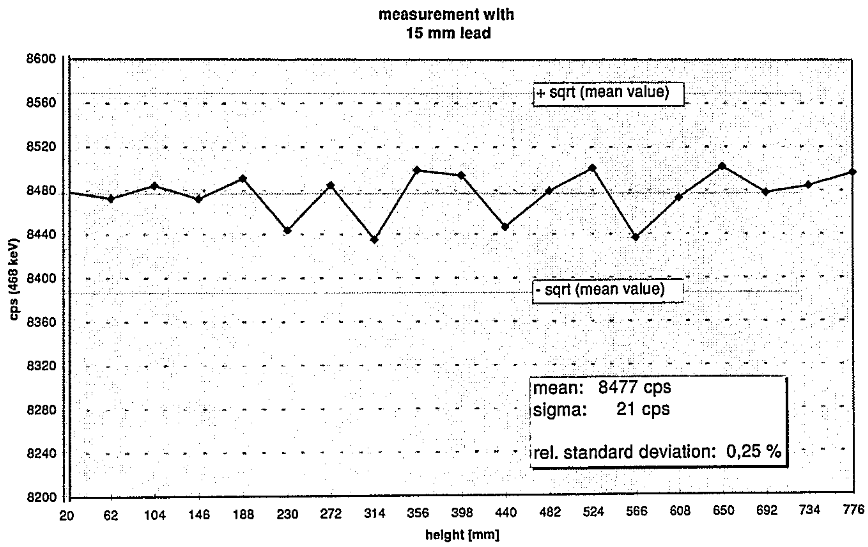


Fig. 4.9: Variation of the measured count rate for 468 keV as function of the height above the bottom of the drum

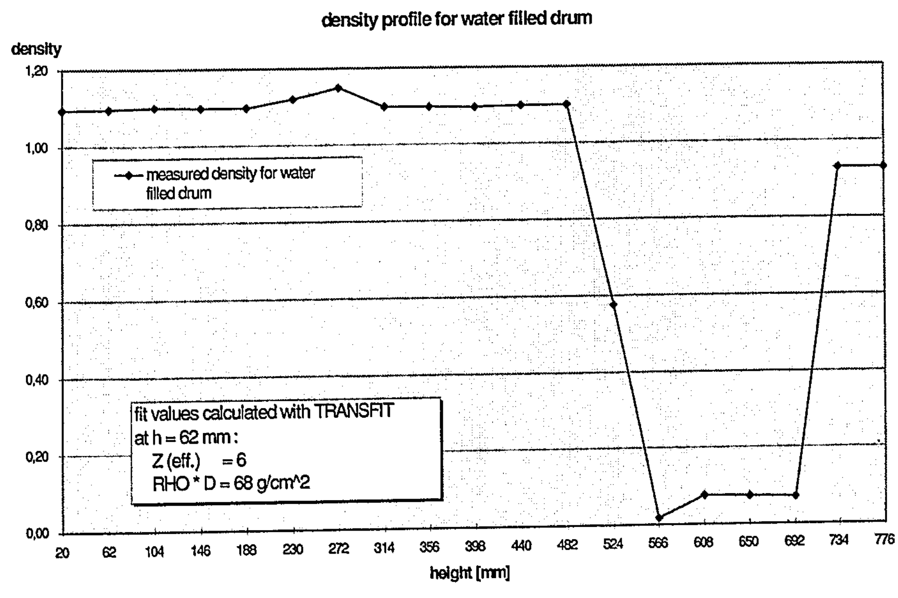


Fig. 4.10: Measured density profile for a 200 l drum filled with water up to ca. 50 cm (drum wall made of 1.5 mm steel)

Figure 4.11 contains two density profiles of the *same cemented drum* measured with two different lead filters (10 mm and 15 mm) and *with a time delay of three month.* This result clearly demonstrates the reliability and stability of the system.

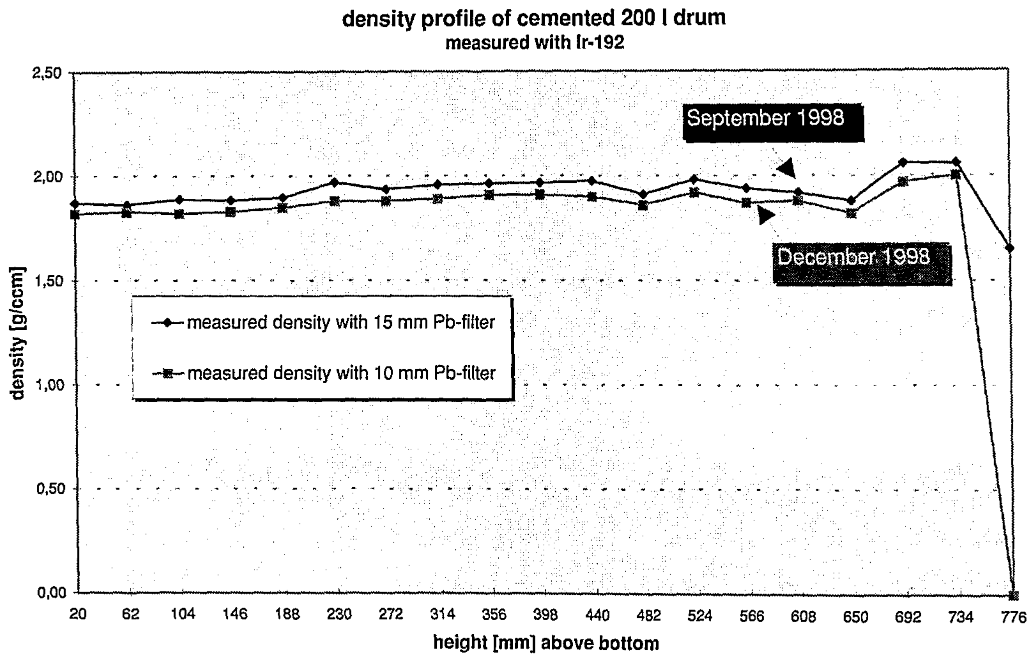


Fig. 4.11: Measured density profile for a 200 l cemented drum at two different dates and with different Pb-filters

Other experiments have been performed to assess the ability of the new system to 'measure' the mean apparent density within a segment for different materials by multi-energy transmission. From the measured transmission T:

$$T = \exp\{-\mu \cdot d\} = \exp\{-\left(\frac{\mu}{\rho}\right) \cdot \rho \cdot d\} \qquad (4.18)$$

it is possible to calculate ρ if d (d: diameter of drum segment) and the type of material are known.

For the 'mock-up' test specimens made of wood, nylon, cement-resin and concrete such measurements have been carried out and the calculated density has been compared to the density value determined by weighing the objects. Figure 4.12 shows the result of this comparison. The mean relative deviation between measured and calculated densities values is less than:

$$\frac{|\rho_{transmission} - \rho_{weighing}|}{\rho_{weighing}} < 2{,}5\% \qquad (4.19)$$

for all materials besides nylon. For nylon the data base of the TRANSFIT programme showed a small deviation for the mean attenuation coefficient (about 5 % lower than the exact value) leading to an overestimation of the density value.

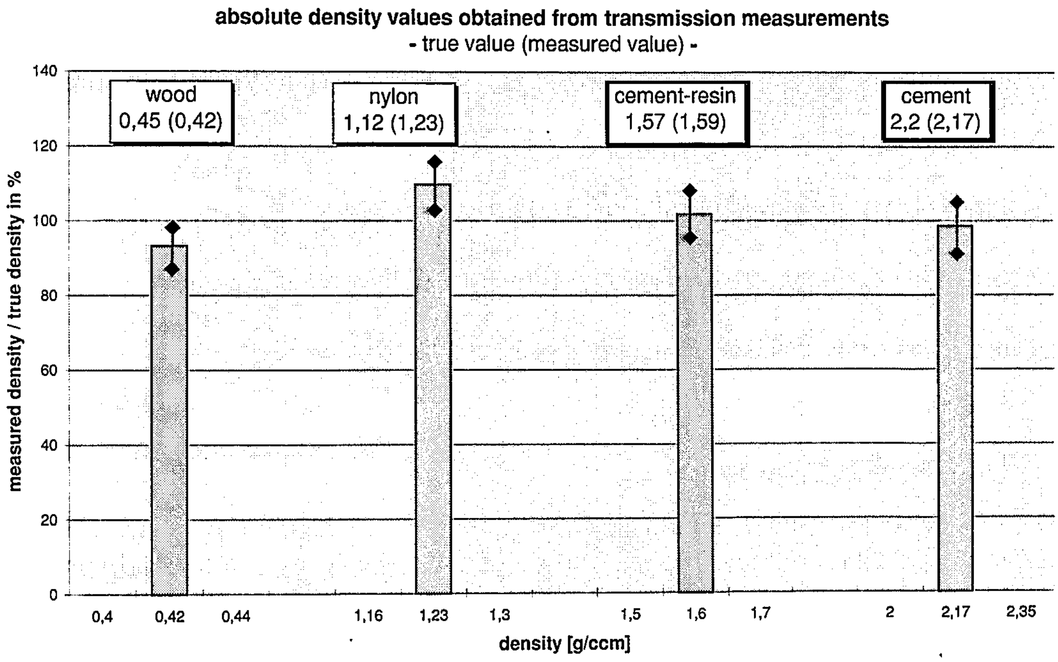


Fig. 4.12: Measured density by transmission compared to real density of 'mock-up' specimens (left and right values on the abscissa indicate the typical range of uncertainty in calculation of density if the type of matrix is not known)

Furthermore figure 4.12 demonstrates that the systematic variations of the density calculation are in the range between 5% and 10% (see errors bars indicated as '♦—♦'), if there is only little information about the material inside the drum (in this case TRANSFIT can be used to assess the mean effective atomic number of the matrix).

Results & Achievements

Calibration and testing of the upgraded Scanner, called GERNOD II, has been finished in the last working period. The system shows good performance characteristics based on the assessment of statistical precision, repeatability and stability of the measured density profiles of 200 l drums.

The accuracy of the determination of the absolute density within a homogeneously filled cylindrical segment has been quoted to be better than 2,5 % for densities ranging from 0,42 g/cm^3 to 2,2 g/cm^3.

4.5 Measurements on 'mock-up' drums with drums with the GERNOD II system

The main objective of this work package was to investigate the performance of the developed techniques for optimised gamma scanning. This task is further subdivided into three main work packages:

- Test measurements on 'mock-up' drums and data evaluation,
- Selection and characterisation of waste drums for 'field measurements',
- Measurements on real waste drums and performance assessment.

4.5.1 Test configurations

The 'mock-up' drums (so called dummies) were produced at CIEMAT /CIE-1/. The test objects were fabricated with typical dimensions of real waste packages. They can be equipped with one or more point or line sources to simulate any activity distribution of interest. The principle design of a cross section is shown in figure 4.13.

Four dummies with four densities from 0.42 g/cm³ to 2.19 g/cm³ were produced. All items consisted of modules of the same size and could be combined to simulate various types of inhomogeneities inside a drum.

Table 4.9 summarises the important physical properties and dimensions of the dummies in a homogenous combination. With these configurations the measurements were performed to produce 'flexible' data for the benchmark tests of the developed scanning procedures. Transmission measurements were performed to check the transmission correction procedure on all dummies.

Matrix	Mass Kg	Density g/cm³
Wood	32.1	0.42
Nylon	86.3	1.13
Resin Concrete	120.9	1.58
Concrete	167.8	2.19

Ring Number	Radius in cm
0	0
1	7.1
2	17.2
3	22.4
4	26.6

Tab. 4.9: Properties of the homogenous matrix combinations of the test dummies used for the benchmark tests.

The structure of the layout is shown in figure 4.13. It is based on the cross-section of 200 l drums. The height of each test specimen is 30 cm, the diameter being 57 cm. The test drums are held together by a 1.5 mm steel belt, which also acts to simulate a typical drum wall.

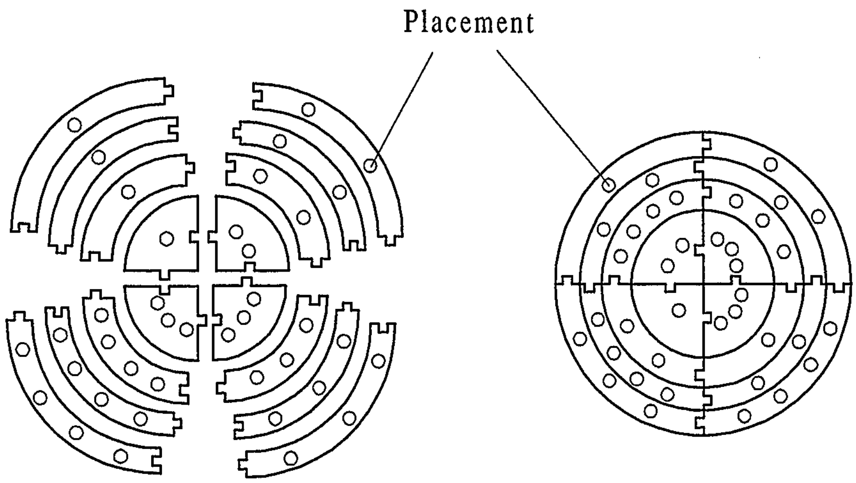


Fig. 4.13: Schematic diagram of the test drum's structure.

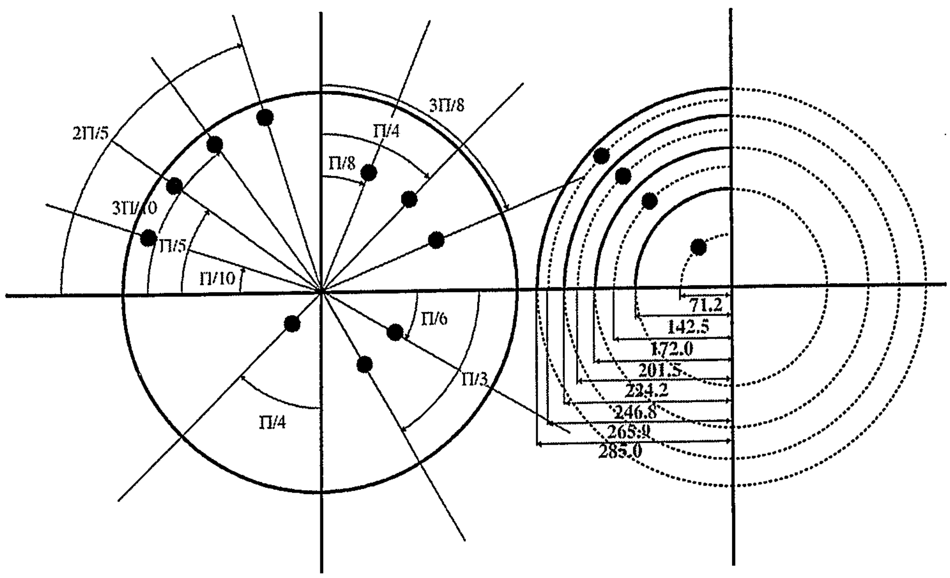


Fig. 4.14: Angles and radii of the source positions of the test drums.

4.5.2 Set-up of test measurements with 'mock-up' drums

The principle configuration of a measurement with the mock-up drums is shown in Fig. 4.15. Activity inside the drum was simulated by using different point sources. For the emission measurements three point sources were used with sufficient activity. These sources and their properties as well as the principle gamma-ray lines of interest are summarised in table 4.10.

Nuclide	Activity MBq	Gamma-Ray keV
^{133}Ba	19.3	356
^{137}Cs	27.7	662
^{60}Co	7.03	1333

Tab. 4.10: Sources used for test measurements with the 'mock-up' drums

With these sources emission measurements were performed in the mid plane of each dummy. The dummy was continuously rotated during the measurement. The sources were placed successively in one of the positions of each ring. For the respective radial source position the dummy was scanned under five discrete swivel angles (0°, 5°, 10°, 15° and 20°). That gives a data set of 270 count rates for all combinations. With this data set the benchmarking of the improved scanning procedures was carried out.

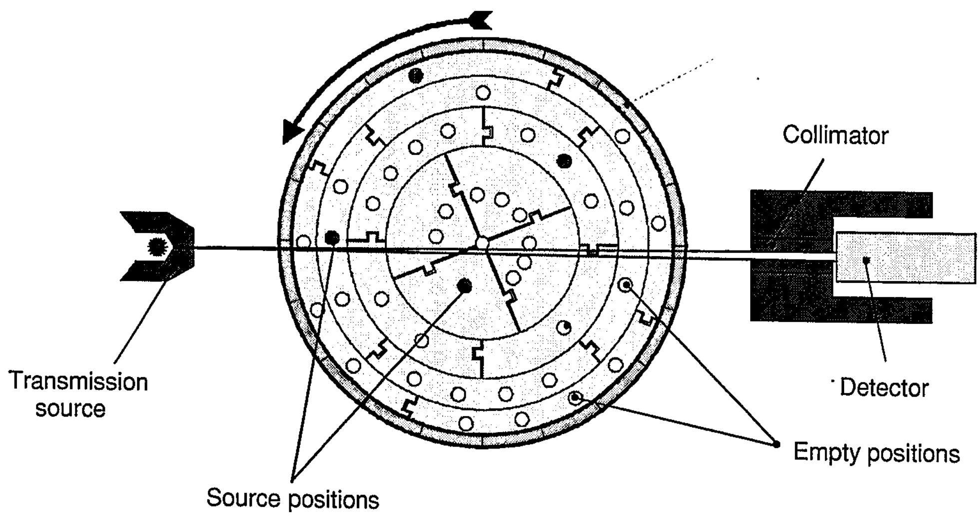


Fig. 4.15: Cross section of a 'mock-up' drum ('test dummy')

Influence of source position on assay result

To illustrate the main reason for the development of the swivel scanning technique figure 4.16 summarises two 'extreme' situations for the activity determination by conventional gamma scanning.

For light matrices and high gamma energies the count rate for a point source in the centre position is twice the count rate of a planar source (i.e. a cylindrical source with horizontal extension equal to the diameter of the drum). For increasing radius the count rate decreases due to the influence of the collimation. The ratio of the normalised count rates of the inner and outer position was found to be 4.6 for the parameters indicated in fig. 4.16 ! Hence the activity determination by conventional methods will also differ by this factor !

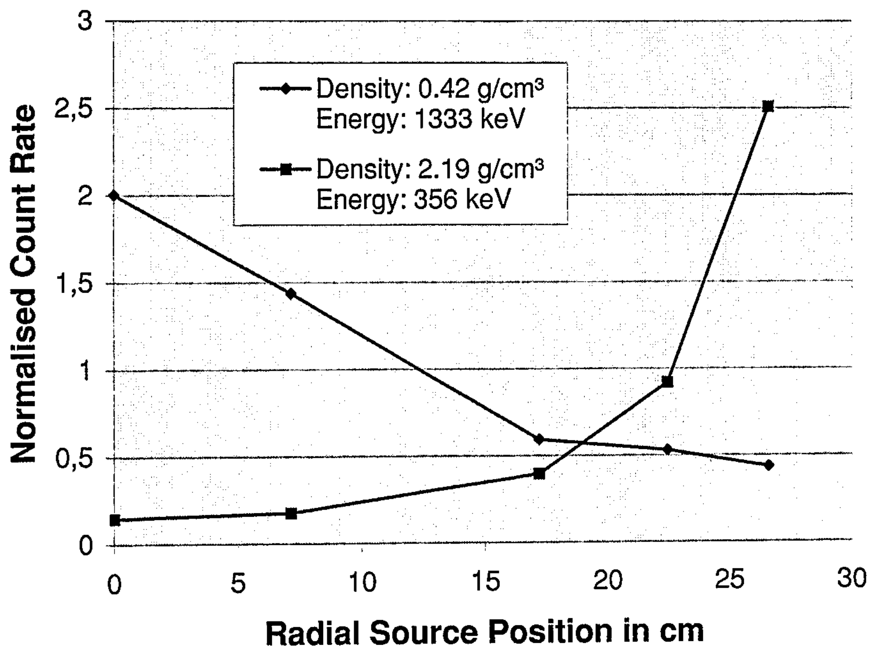


Fig. 4.16: Variation of count rate with radial position for a rotating point source in cases of high and low attenuation in the matrix. The count rates are normalised to the count rate of a homogeneous planar source.

For high densities and low gamma energies the situation is reversed. In this case the collimation is not the most important effect but the absorption in the drum matrix. The ratio of outer and inner count rate was found to be a factor of 17 in this case (see fig. 4.16)! This is the maximum deviation between the activity values determined by conventional gamma scanning for the same source activity. This example impressively proves one of the disadvantages and limitations of the conventional ('volumetric') gamma scanning method.

4.5.3 Results of Performance Assessment for the Swivel Scanning Method

4.5.3.1 Swivel scanning data analysis - matrix inversion method

The swivel scanning method is considered as an additional method to particularly account for spatially localised activity distributions ('hot-spots'). For all radial positions of the three used sources the respective count rates were calculated from the net peak areas of the spectra for 5 swivel angles. In addition the mean of the count rates was used to simulate a homogenous activity distribution in the central plane of the dummy. A (5 x 5) transfer matrix for each density and gamma energy was calculated using the SOLIDANG code. The gamma attenuation properties resulting from the TC-SGS analysis were used as input data for the SOLIDANG simulation.

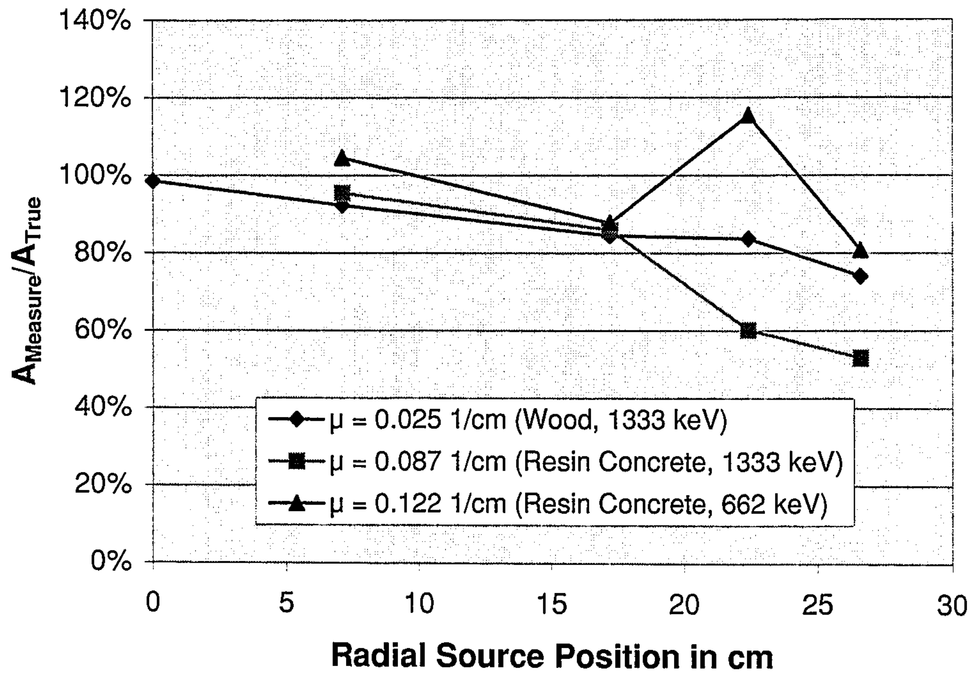


Fig. 4.17: Activity reconstruction using the Inversion Method for three typical attenuating properties. Shown is the ratio of measured to true activity vs. source position.

Calculated total activity for different source positions

The result for three typical situations is shown in figure 4.17. The figure shows that the reconstructed activity for a radius less than ca. 15 cm is within a range of 15 % compared with the true value. There is a tendency of decreasing reconstructed activity with increasing radius. This effect was observed in many measurements and may be due to the used collimator model which has a big influence especially for outer source positions.

Calculated activity distribution for different source positions

Figure 4.18 shows the reconstructed activity distribution of one source in different radial position and the mean distribution of these activities. The reconstructed activity distribution has negative elements. Nevertheless the total activity is close to the true value. This is a typical behaviour of the 'Reconstruction Algorithm'. It demonstrates its limited ability to exactly reconstruct the source position when only a few measurements are used.

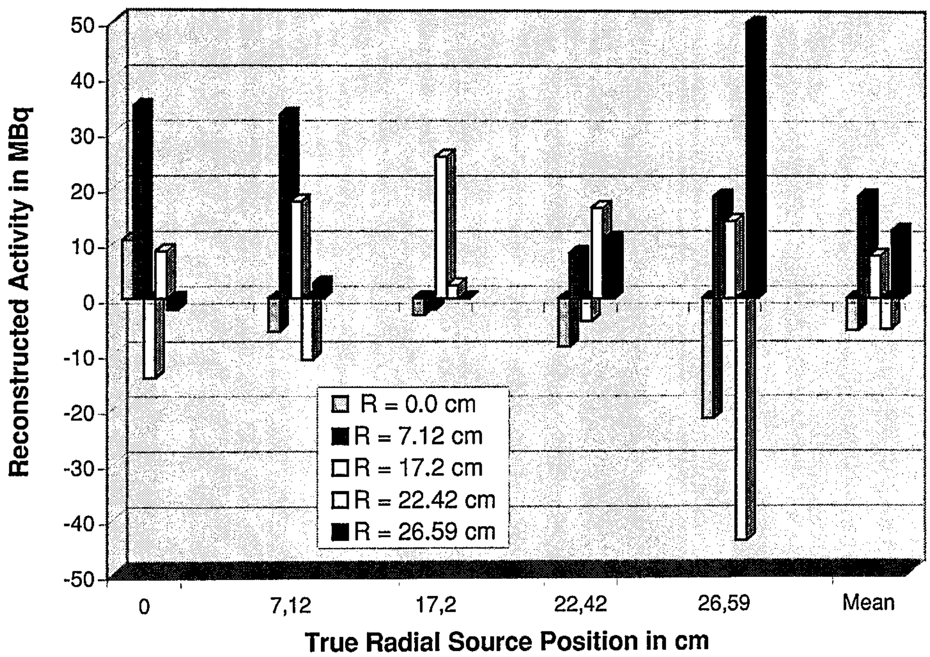


Fig. 4.18: Typical activity distributions reconstructed by the Inversion Method for one point source (Cs-137) at different radii. The true activity was 16.3 MBq.

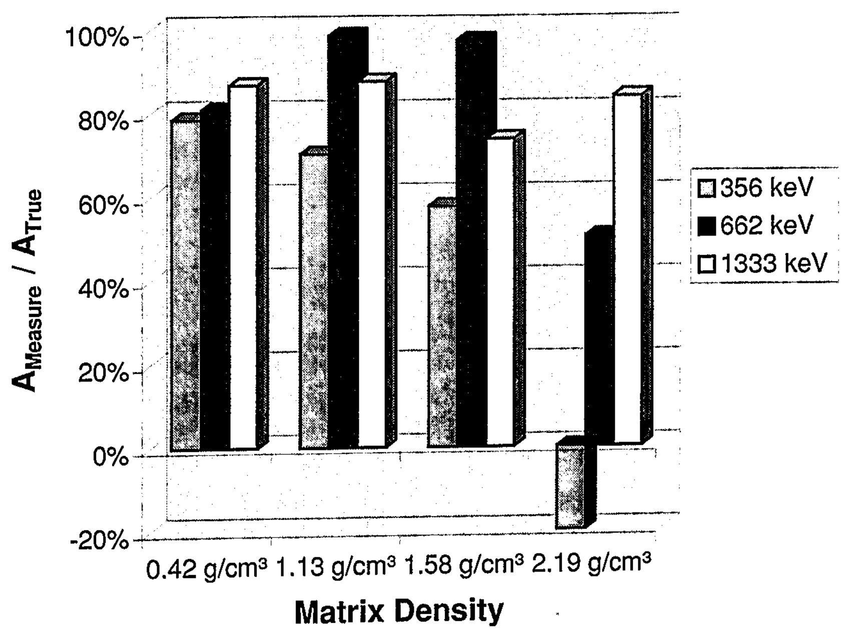


Fig. 4.19: Inversion activity reconstruction of a homogenous planar source for different densities and gamma energies

Calculated activity for simulated homogeneous segments

Additionally the reconstruction method was applied to calculate the activity of several point sources arranged in such a way as to simulate the presence of a homogeneously filled segment in a drum. Results are summarised in figure 4.19.

Obviously, the inversion method gives the best results for situations of low absorption. The worst case is the 356 keV gamma line of ^{133}Ba in the concrete matrix. In this case a reconstruction was not possible. It gives a negative total activity. For the highest used gamma energy of 1333 keV the reconstructed activity shows no clear bias. For all densities and energies the inversion method underestimates the total activity, which was already observed in figure 4.16. This will be discussed statistically in combination with a comparison of all methods at the end of the section.

4.5.3.2 Swivel scanning data analysis - method of radial variation

The radial variation method is an alternative way to analyse swivel scanning data. It is restricted to one point source under observation, Therefore, it is not applicable for all situations but it is a useful tool in addition to the inversion method.

The same data analysed by the inversion method was used for testing the radial variation algorithm. Analogous to the previous section figure 4.20 shows the activity reconstruction vs. the radial position of a point source.

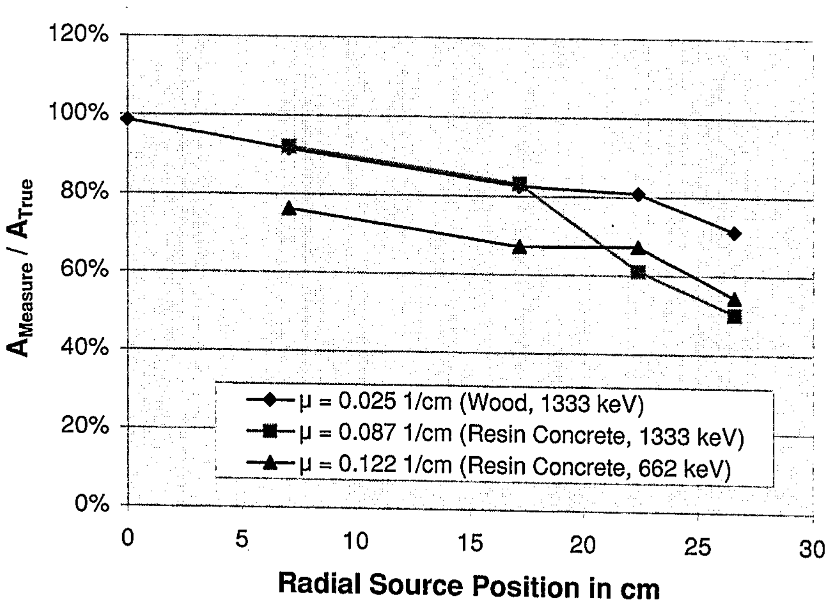


Fig. 4.20: Activity reconstruction using the Radial Variation Method for three typical absorption situations. Shown is the ratio of measured and true activity vs. source position

The same tendency of decreasing reconstructed activity with increasing source distance to the drum centre is observed by this method. This observation indicates that this effect might probably result from inherent systematic uncertainties.

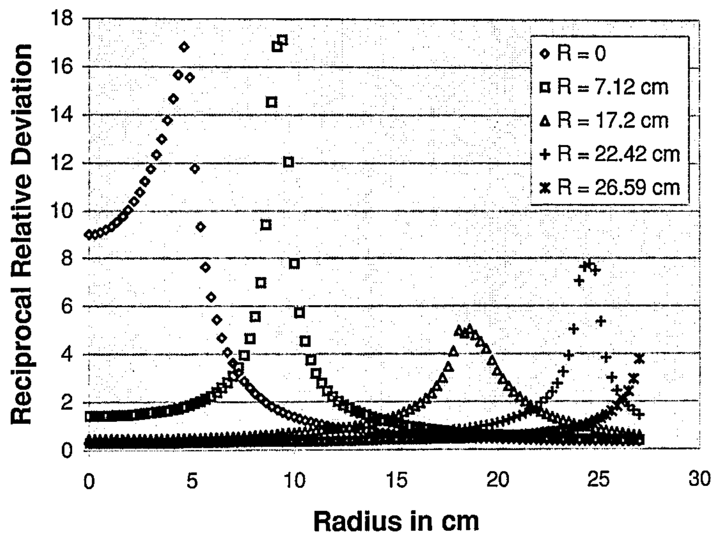


Fig. 4.21: Reciprocals of deviations of the measured and simulated count rates vs radial position for different 'true' source positions.

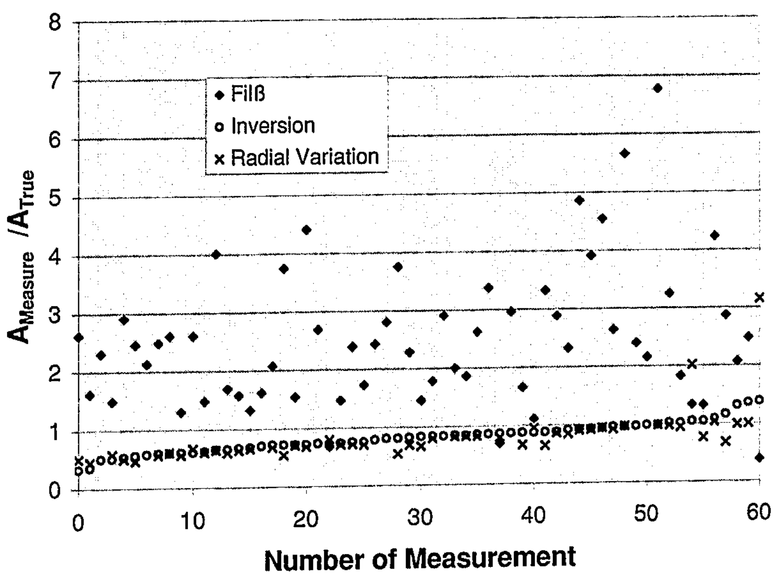


Fig. 4.22: Scatter plot of all reconstructed activities by Filß-, Inversion and Radial Variation Method

4.5.3.3 Discussion of Results and Conclusions (SW)

Figure 4.21 illustrates that the accuracy is in general better for the inner source positions, which is observed for the calculated activity and for the determined source position. Nevertheless, it can serve as an additional verification for the reliability of the result of the inversion method.

In figure 4.22 all results are summarised. The data is analysed by the Filß-, Inversion and Radial Variation Method respectively. The measurement results are ordered according to increasing reconstructed activity of the matrix inversion method.

This figure demonstrates again that the activities calculated for the swivel scanning - independent of the used reconstruction algorithm - underestimate the activity in nearly all situations which can compensate for by an appropriate safety factor. But the swivel scanning data lies 'close' together compared to the 'Filß'-method which overestimates the activity up to a factor of 7. Calculated values for the mean and standard deviation for all three methods are listed in table 4.11.

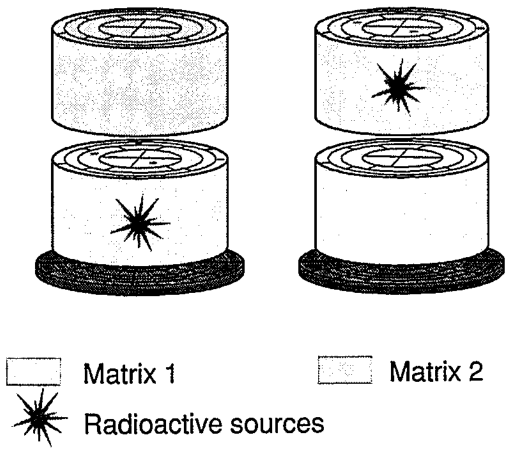
Method used	Mean	Deviation from exact value	Standard Deviation	Relative Standard Deviation
Conventional	2.49	149 %	1.19	48%
Improved:				
Inversion	0.82	- 18 %	0.21	26%
Radial Variation	0.82	- 18 %	0.24	32%

Tab. 4.11: Mean and standard deviation of all evaluated measurements

As pointed out the standard integral ('Filß') method overestimates the activity by a factor of (2.5 ± 1.2) which is a relative uncertainty of about 50 %. The inversion and radial variation method reconstructs a value of 80 % of the true activity with a relative deviation of ca. 25-30 % which is an improvement of a factor of two.

4.5.4 Performance analysis for transmission corrected segmented gamma scanning

For benchmarking the TC-SGS the data was restructured to simulate the situation shown in figure 4.23. Each experimental set up consisted of two matrices with different densities. The matrix of the higher density was placed in the bottom position.



Matrix 1	Matrix 2
Concrete	Resin concrete
Concrete	Nylon
Concrete	Wood
Resin concrete	Nylon
Resin concrete	Wood
Nylon	Wood

Fig. 4.23: Combination of different matrices to simulate vertical density variations. The table on the right lists all combinations used for TC-SGS benchmark testing.

Two measurements were simulated for each combination: point sources in mid-plane of the bottom and top matrix (1 and 2 in figure 4.23) respectively.

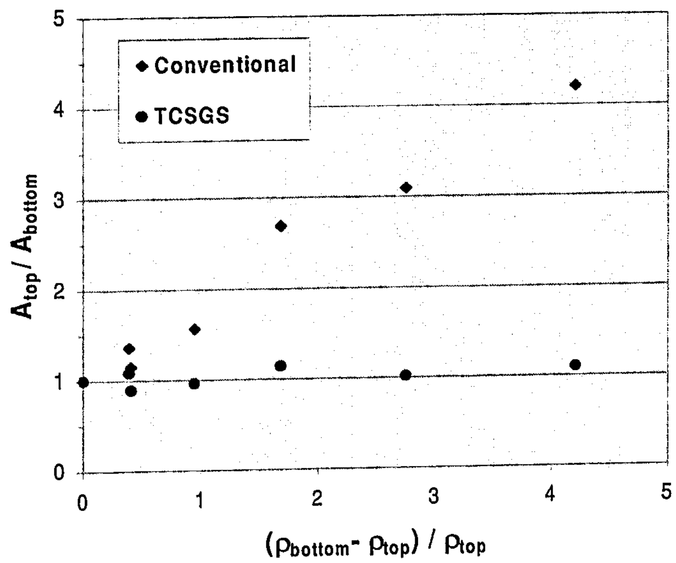


Fig. 4.24: Ratio of the observed activity for source in top and source in bottom matrix vs. relative density difference for ^{133}Ba. The results are normalised on the estimated activity for a homogenous matrix.

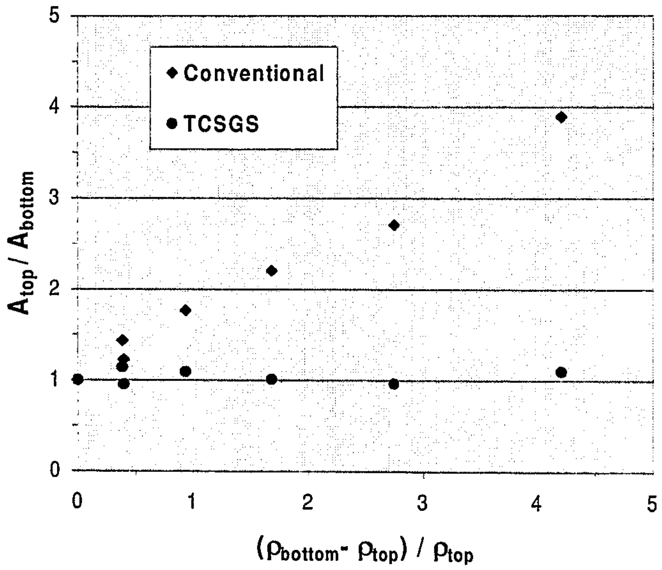


Fig. 4.25: Ratio of the observed activity for source in top and source in bottom matrix vs. relative density difference for ^{137}Cs. The results are normalised on the estimated activity for a homogenous matrix.

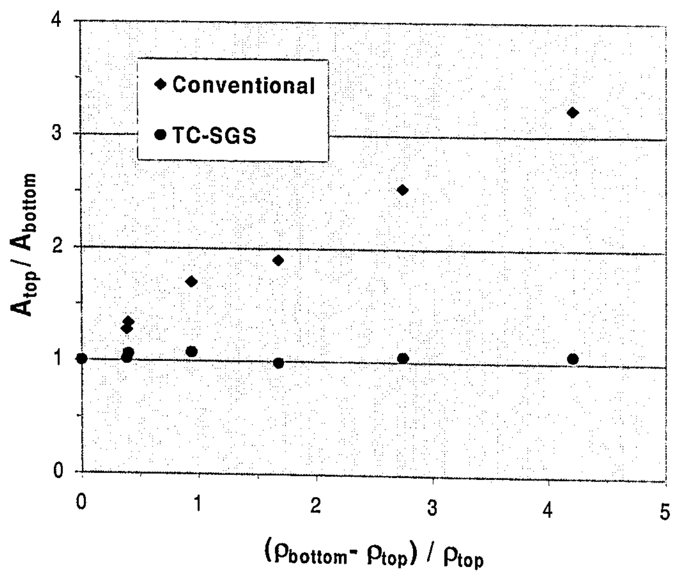


Fig. 4.26: Ratio of the observed activity for source in top and source in bottom matrix vs. relative density difference for ^{60}Co. The results are normalised on the estimated activity for a homogenous matrix.

To illustrate the results, the ratio of the reconstructed activities versus the relative difference of the density of the matrices is shown in the figures 4.24 - 4.26 for different gamma energies.

Discussion of Results and Conclusions (TC-SGS)

The results calculated for all combinations of two dummies as shown in Fig. 4.24 - 4.26 are summarised in table 4.12. For comparison and performance assessment both methods have been applied, i.e. the 'conventional' or 'Filß'-method as well as the developed method of transmission corrected gamma scanning (TC-SGS).

Method used	Ba-133 356 keV	Cs-137 662 keV	Co-60 1,3 MeV
Conventional			
Mean for all measurements	234 %	221 %	200 %
Maximum (true value = 100%)	421 %	389 %	323 %
Standard Deviation	120 %	98 %	76 %
Improved: TC-SGS			
Mean for all measurements	103 %	104 %	104 %
Maximum (true value = 100%)	109 %	110 %	106 %
Standard Deviation	9 %	8 %	3 %

Tab. 4.12: Mean and standard deviation of all evaluated measurements on test dummies

For all matrix combinations A_{top}/A_{bottom} the calculated activity is nearly the same, proving that the activities measured with the TC-SGS method are nearly independent of the density of the segment which contains the activity. The conclusion is that TC-SGS gives the correct result as long as the activity is homogeneously distributed in the respective segment. Furthermore there is no significant bias concerning the energy within the range of tests performed (356 keV up to 1,3 MeV).

For the Filß method only the activity of the homogenous matrix and activity distribution is calculated correctly. As rule of thumb the conclusion can be drawn that; *'the higher the relative difference in density of neighbouring segments, the higher the deviation from the 'true' value'*.

This is mainly due to a strong overestimation in situations where the activity is located in segments of low density, because in such cases the attenuation correction, which is performed on the basis of the average density of the drum, leads to improper correction factors. Furthermore, the overestimation of the conventional method increases with decreasing gamma energy (with stronger attenuation).

4.5.6 Summary of Results of the Test Measurements on 'Mock-Up' Drums

Results & Achievements

In conventional gamma scanning techniques the determined activity for spatially concentrated activity distributions ('hot-spots') can vary by up to about one order of magnitude depending on the absorption properties of the drum matrix and the source position.

The measurements on 'mock-up'-drums prove the advantages of the correction methods developed for inhomogeneous activity and matrix distributions to conventional gamma scanning.

The swivel scanning method was identified as a useful additional technique to TC-SGS to take care of 'hot-spots'. It underestimates the true activity by a factor of about 0.8, but with a relatively small standard deviation of ca. 25 % compared to the 'conventional' gamma scanning method. This is an improvement by a factor of 2. The maximum observed deviation from the inner to outer radial source position was a factor of 2.5 in comparison with 17 for conventional scanning.

The TC-SGS impressively demonstrated its improved performance to conventional methods in situations of high vertical density differences which frequently arise in practice (super-compacted waste). Especially for drums which contain high amounts of activity in drum regions of low density the conventional gamma scanning overestimates the activity drastically (up to 4 times) where as the TC-SGS is close to the 'true' value within 10 % (see table 4.12).

4.6 Selection and characterisation of waste drums for 'field' measurements

After testing the performance characteristics with 'mock-up' configurations it was foreseen to apply the new techniques and methods to real waste drums. The 'field' measurements carried out were intended to demonstrate the ability of the upgraded systems to perform transmission corrected segmented gamma scanning as well as swivel scanning in routine waste assay applications. The second objective was to compare results between standard scanning and optimised scanning procedures in order to see the difference between both methods and to estimate possible improvements achievable with the new techniques. Possible limitations should also be identified to give recommendations for the practical usefulness of the methods.

At FZJ Jülich measurements on 7 real waste packages have been carried out using standard as well as advanced scanning techniques with the GERNOD II system. Drums have been selected and characterised to be used for 'field' measurements on the basis of availability and expected characteristics. Five drums containing compacted pellets and two drums containing cemented waste have been assayed successfully using the new measurement techniques. Two drums have been chosen out of another European research project, i.e. the so called 'Round Robin Test' (FI4W CT 950007). Other drums were taken out of the continuous production of conditioned waste at the FZJ-facility for waste treatment (ZFK-DE).

The following measurement campaigns have been performed to characterise and test the new methods:

- 2 Measurements on homogeneously filled cemented drums
  (FZJ 'Round Robin Test' drums)
  RRT-436
  RRT-699
- 3 Measurements on drums with pellets which showed local activity concentrations
  FZJ-100
  FZJ-200
  FZJ-300
- 2 Measurements on drums with pellets filled with compacted ashes which were expected to have homogeneous activity distribution
  FZJ-400 (3 pellets)
  FZJ-500 (one pellet)

All drums have been assayed successfully using the transmission measurement technique as well as the standard multi-rotational scan with attenuation correction based on drum weighing. Data analysis has been performed. For the drums labelled FZJ-200 and -300 a swivel-scan was carried out for those segments where a high concentration of activity was found (Co-60 and Cs-137).

In the following the main characteristics of the above mentioned waste drums are summarised together with the results achieved.

4.6.1 Measurements on drums RRT-436 and RRT-699

These drums have been used as typical waste drums from FZJ within the round robin test project. Therefore the content has been measured by several facilities independently. The content of these drums can therefore be regarded to be well-known which makes it possible to use the drums as reference drums when comparing the optimised scanning techniques to conventional ones. Both drums have fairly homogenous filling with respect to density and activity.

It was expected to achieve comparable results with standard as well as improved techniques, demonstrating the consistency between both methods for drums with homogenous filling.

The results of the standard integral scan 'I-SCAN' and improved 'TC-SGS' scanning mode are given below. If available a reference value (based on destructive analysis) is also quoted. The following data have been calculated:

RRT436	Integral Scan	TC-SGS	Rel. Difference
Co-60	1,69E+06	1,60E+06	-5,33%
Cs-137	3,33E+08	3,20E+08	-3,90%

RRT699	Integral Scan	TC-SGS	Rel. Difference
Co-60	4,00E+06	3,79E+06	-5,25%
Cs-137	6,17E+07	5,95E+07	-3,57%

Tab. 4.23: Results for drums RRT-436 and RRT-699; rel. difference is: *(I_Scan –TC_SGS)/I_Scan*

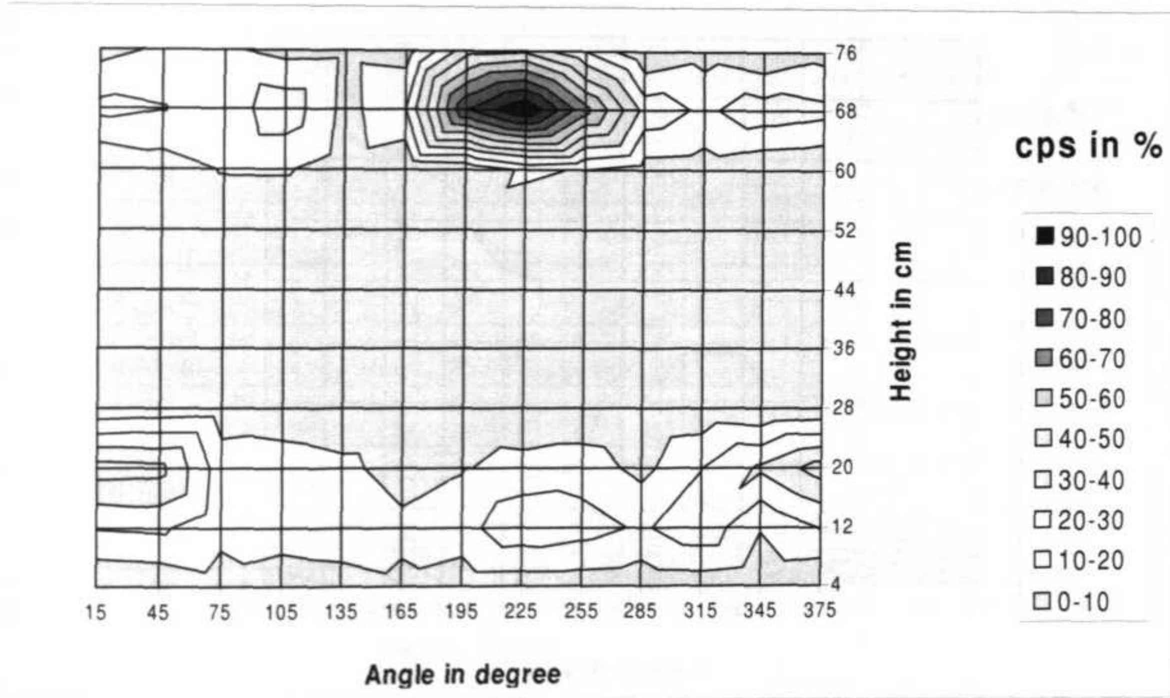
Discussion of Results and Conclusions

For both drums the results of integral scanning and TC-SGS are in agreement. This shows that both methods exhibit no significant difference in cases of homogeneous filling inside a drum.

4.6.2 Measurements on drums FZJ-100, -200 and –300 with TC-SGS

These drums have been selected from a batch of drums with a typical signature of heterogeneous activity concentration. The drums have been assayed with gamma scanning and in addition with nondestructive testing methods (DR, TCT/ECT).

The following figures 4.27 - 4.29 show the results of the count rate distribution as measured by a standard grid scan along the drum surface (intervals: angle: 30 degree, height: 84 mm). The upper picture always shows the count rate distribution for Cs-137 and the lower for Co-60 (1,3 MeV).



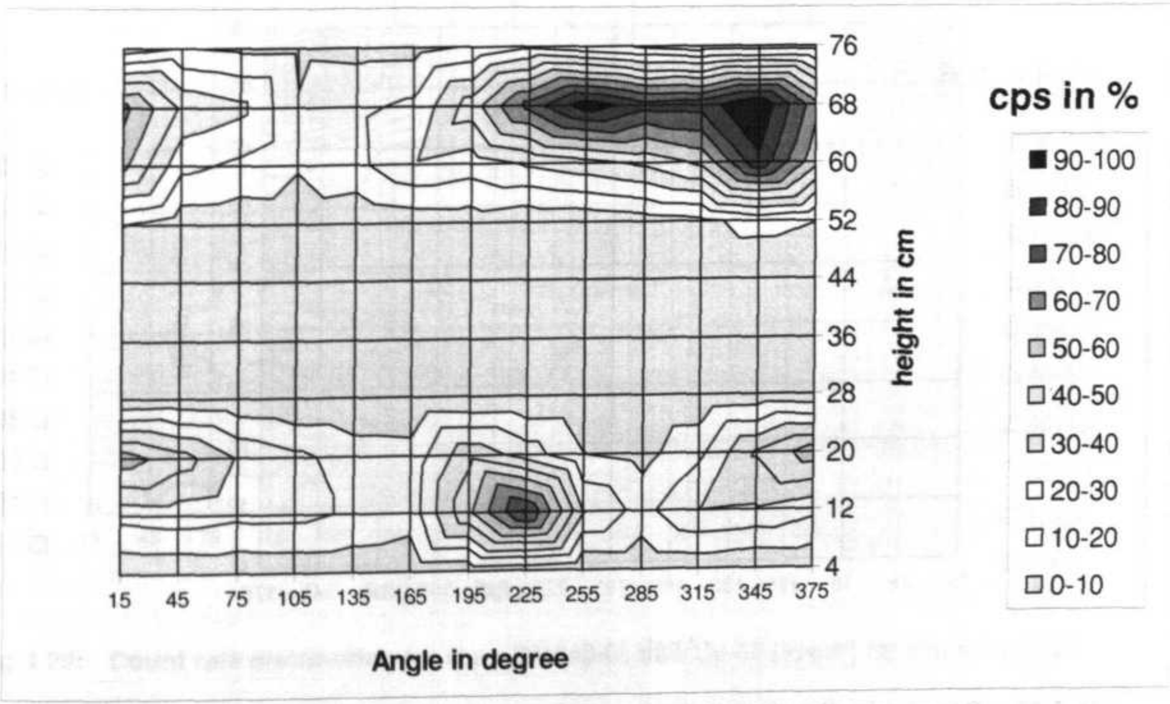
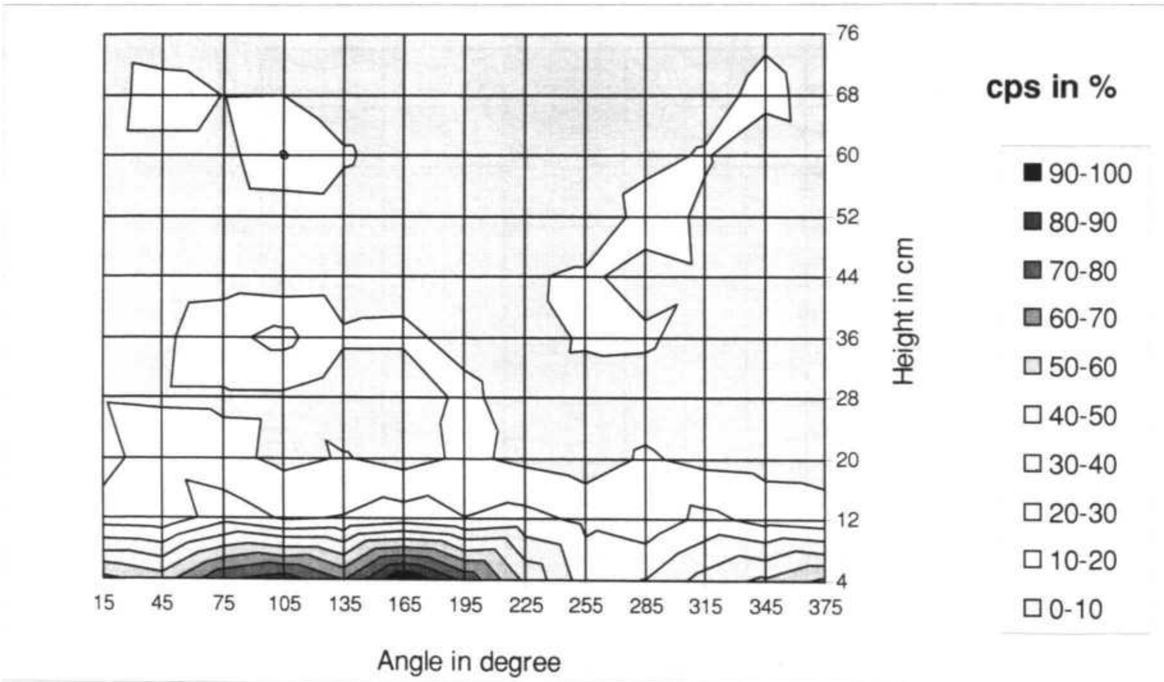


Fig 4.27: Count rate distribution for Cs-137 (upper) and Co-60 (lower) for drum FZJ-100



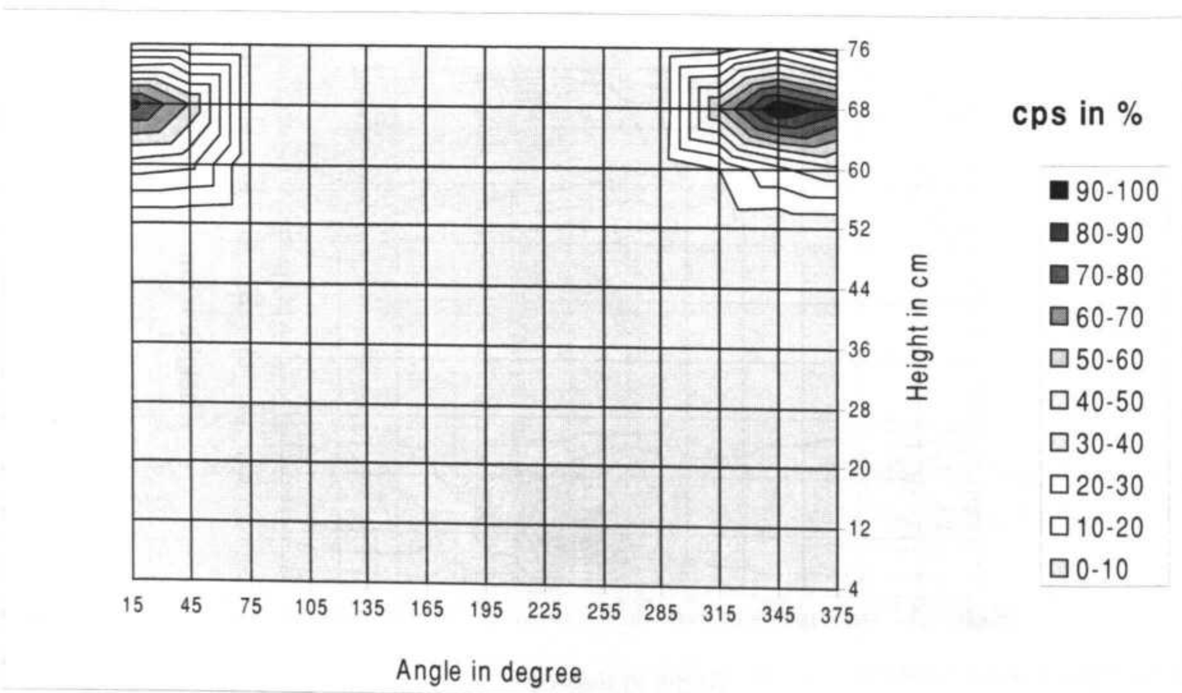


Fig 4.28: Count rate distribution for Cs-137 (upper) and Co-60 (lower) for drum FZJ-200

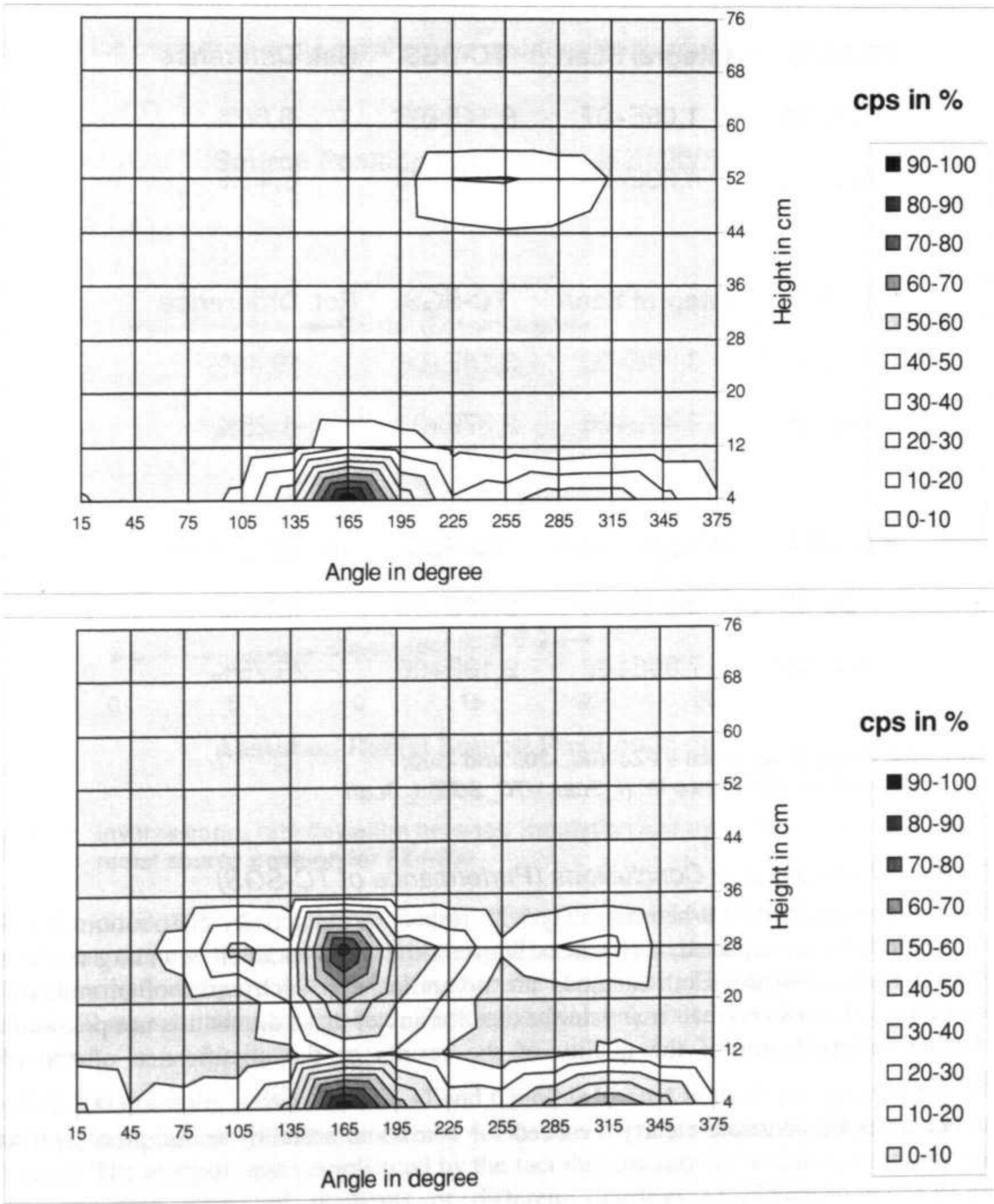


Fig 4.29: Count rate distribution for Cs-137 (upper) and Co-60 (lower) for drum FZJ-300

The following data have been calculated:

FZJ-100	Integral Scan	TC-SGS	Rel. Difference
Co-60	1,00E+07	9,14E+06	-8,60%
Cs-137	4,20E+06	4,47E+06	6,43%

FZJ-200	Integral Scan	TC-SGS	Rel. Difference
Co-60	3,90E+06	3,14E+06	-19,49%
Cs-137	2,40E+06	2,37E+06	-1,25%

FZJ-300	Integral Scan	TC-SGS	Rel. Difference
Co-60	2,67E+06	2,93E+06	9,74%
Cs-137	7,30E+06	9,18E+06	25,75%

Tab. 4.24: Results for drum s FZJ-100, -200 and -300; relative difference is: *(I_Scan –TC_SGS)/I_Scan*

Discussion of Results and Conclusions (Performance of TC-SGS)

All drums showed significant heterogeneity with respect to the activity distribution of Co-60 and Cs-137. Therefore, as expected, differences between the 'conventional' scanning mode and TC-SGS have been measured. Both methods are not reliable in such cases of prominent activity concentrations. Because no real 'true value' exists for any of these drums it is not possible to make any further interpretation of the quality of the results or the significance of the identified deviations.

These examples demonstrate clearly the need for additional scanning techniques, such as AS or SWS.

4.6.3 Swivel Scanning Measurements on FZJ-200 and -300

In addition to the TC-SGS on FZJ-200 and FZJ-300 swivel scanning was employed to take the heterogeneity of the activity distribution of Cs-137 and Co-60 into account.

From figure 4.28 it was concluded for FZJ-200 that the Cs-137 activity is located at the bottom of the drum. Conversely the Co-60 activity was found on its top. The distribution of measured count rates indicated that the Co-60 source is a point source near to the drum wall and that Cs-137 is either distributed over a larger volume or located at a smaller radius. For the top and the bottom region of the drum a swivel scanning measurement was performed to test the ability of method of SWS to estimate the radial activity distribution.

The results of the estimation of the radial source position are illustrated in figure 4.30.

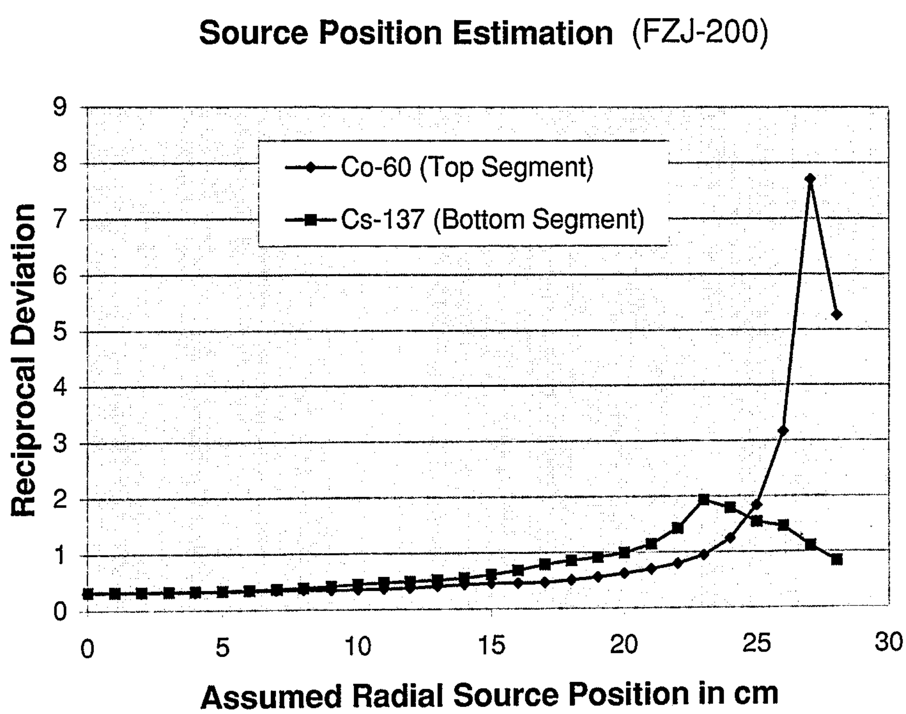


Fig. 4.30: Inverse count rate deviation between simulation and measurement vs. assumed radial source position for FZJ-200

Note that the ordinate is the reciprocal value of the absolute deviation between simulated and measured count rate and not a measure of activity! The suspected distribution of the activity of the count rate distribution (figure 4.30) is reflected in the reciprocals. The distributions show that Cs-137 and Co-60 are spatially concentrated. The distribution calculated for Cs-137 indicates a larger source volume.

For the FZJ-300 drum the activity of Cs-137 and Co-60 is located in the lower third of the drum as indicated by the count rate distribution (figure 4.29). The swivel scanning was therefore restricted to this region. The analysis was complicated by the fact that the activity was located in a part of the drum between two measured segments of different densities (1.27 g/cm³ and 1.97 g/cm³). Therefore, the analysis was carried out for both densities separately. Because of this systematic problem, which is not accounted for by the calibration of this method, only an activity range can be quoted as result.

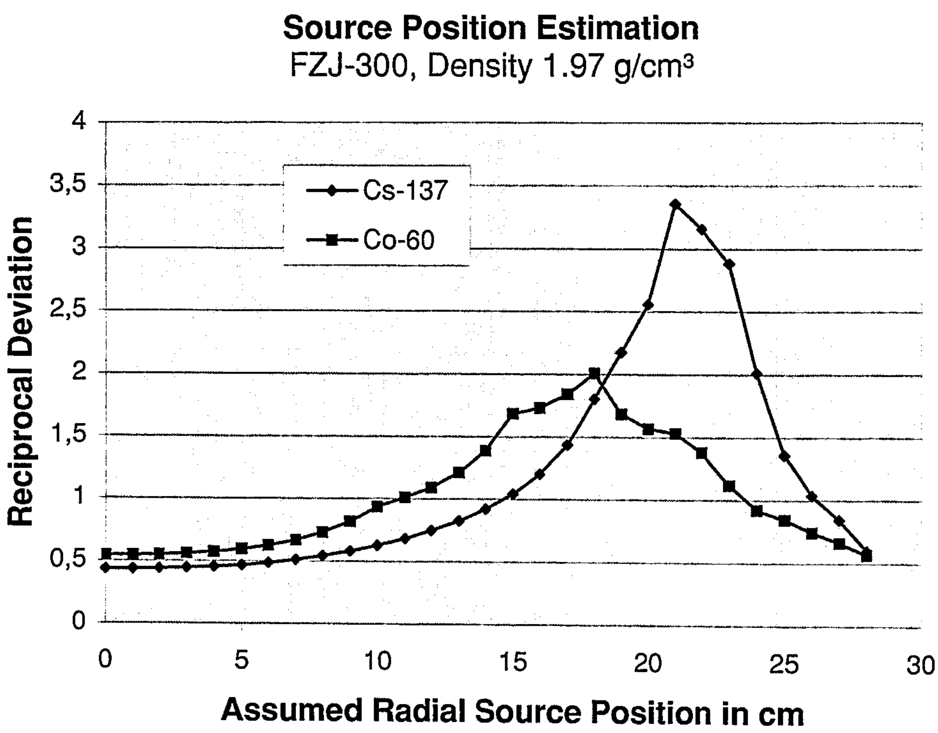


Fig. 4.31: Reciprocal count rate deviation between simulation and measurement vs. assumed radial source position for FZJ-300

In figure 4.31 the results for the determination of the source position are illustrated for drum FZJ-300 having a density of 1.97 g/cm³. In this case both activities seem to be localised 'in the outer region' of the drum. The results of the activity calculation are given in table 4.25.

Nuclide	SWS (1.27 g/cm³) MBq	SWS (1.97 g/cm³) MBq	TC-SGS MBq
Co-60	0.8	1.5	2.9
Cs-137	3.5	6.1	9.2

Tab. 4.25: Results of the activity calculation for drum FZJ-300

Discussion of Results and Conclusions for the SWS measurements

The activity reconstruction by the inversion method for FZJ-200 gives 0.8 MBq for Cs-137 and 1.4 MBq for Co-60. That is a deviation of 35 % and 45 % from the value achieved by TC-SGS. This was expected for spatially concentrated activity distributions in the outer region of a drum segment.

For the low density reconstruction for drum FZJ-300 the difference between swivel scanning and TC-SGS is larger due to the lower attenuation values used in the calculation. This decreases the reconstructed activity by an amount of ca. 40 % compared to the results of the TC-SGS method.

Anyway, the problem discovered during data analysis of having different densities in different parts of a drum segment could be improved by refining the resolution of the vertical transmission measurements. The vertical spacing of measured transmission was chosen to be 42 mm as default value.

For both drums checked by TC-SGS and SWS the activity of the swivel scanning reconstruction is only ca. 40 % of the value of the TC-SGS method. Because the 'true' value is not known it is not possible to assess the performance of both methods in terms of precision or accuracy.

In general, the observed overestimation of the TC-SGS compared to SWS is in the range of expected deviations predicted by simulations.

4.6.4 Measurements on drums FZJ-400 and FZJ-500

These drums have been produced by compaction of ashes. The advantage of these drums was that for all pellets separate sample analysis results are available. So, at least in principle, it could be assumed that every single pellet has been characterised sufficiently by destructive sampling giving the chance to compare in detail the quoted data and measured activity values inside a pellet.

The following figures 4.32 and 4.33 show the results of the measured count rate distribution by a standard grid scan along the drum surface (intervals: angle: 30 degree, height: 84 mm). The upper picture always shows the count rate distribution for Cs-137 and the lower for Co-60 (1,3 MeV).

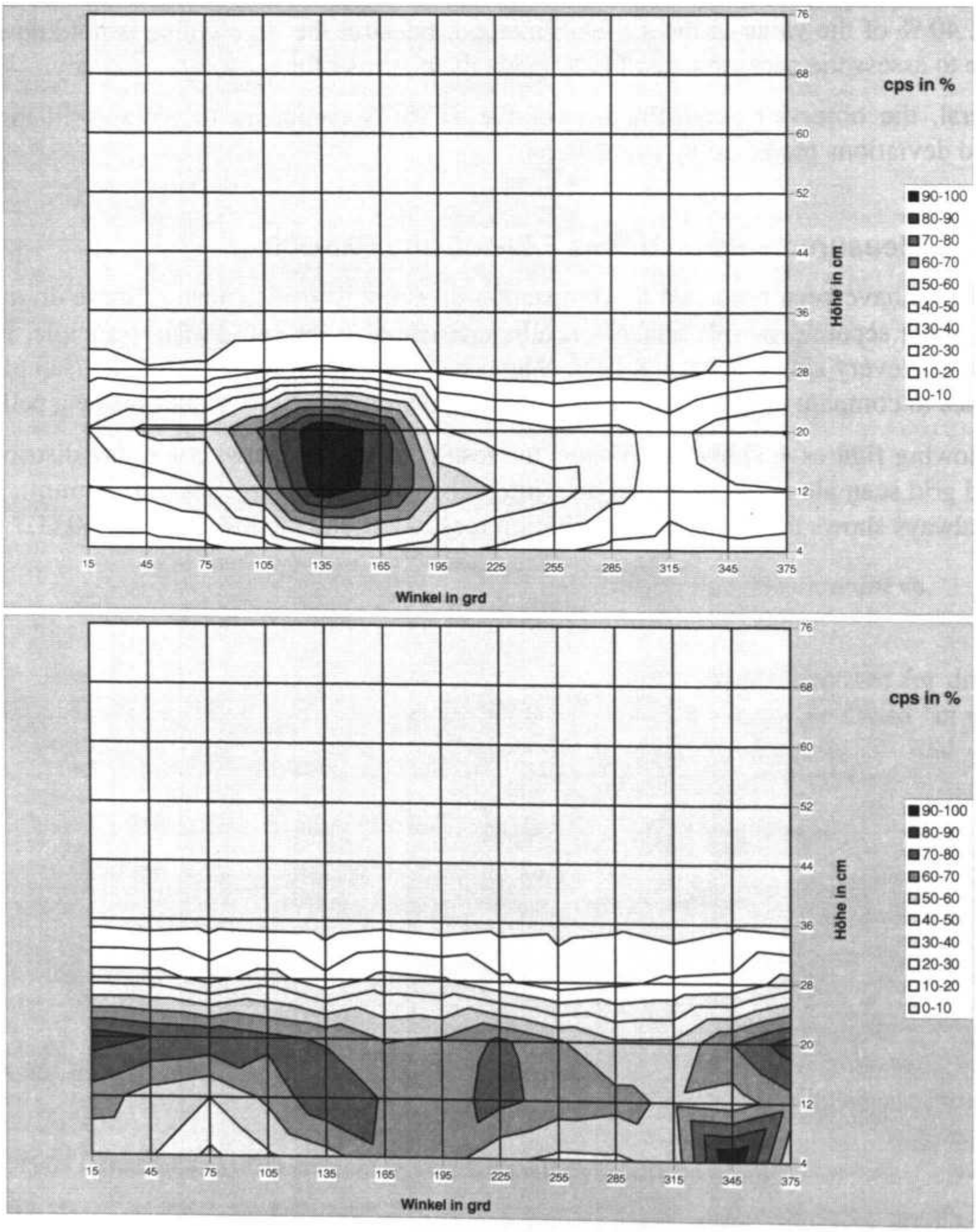


Fig 4.32: Count rate distribution for Cs-137 (upper) and Co-60 (lower) for drum FZJ-500

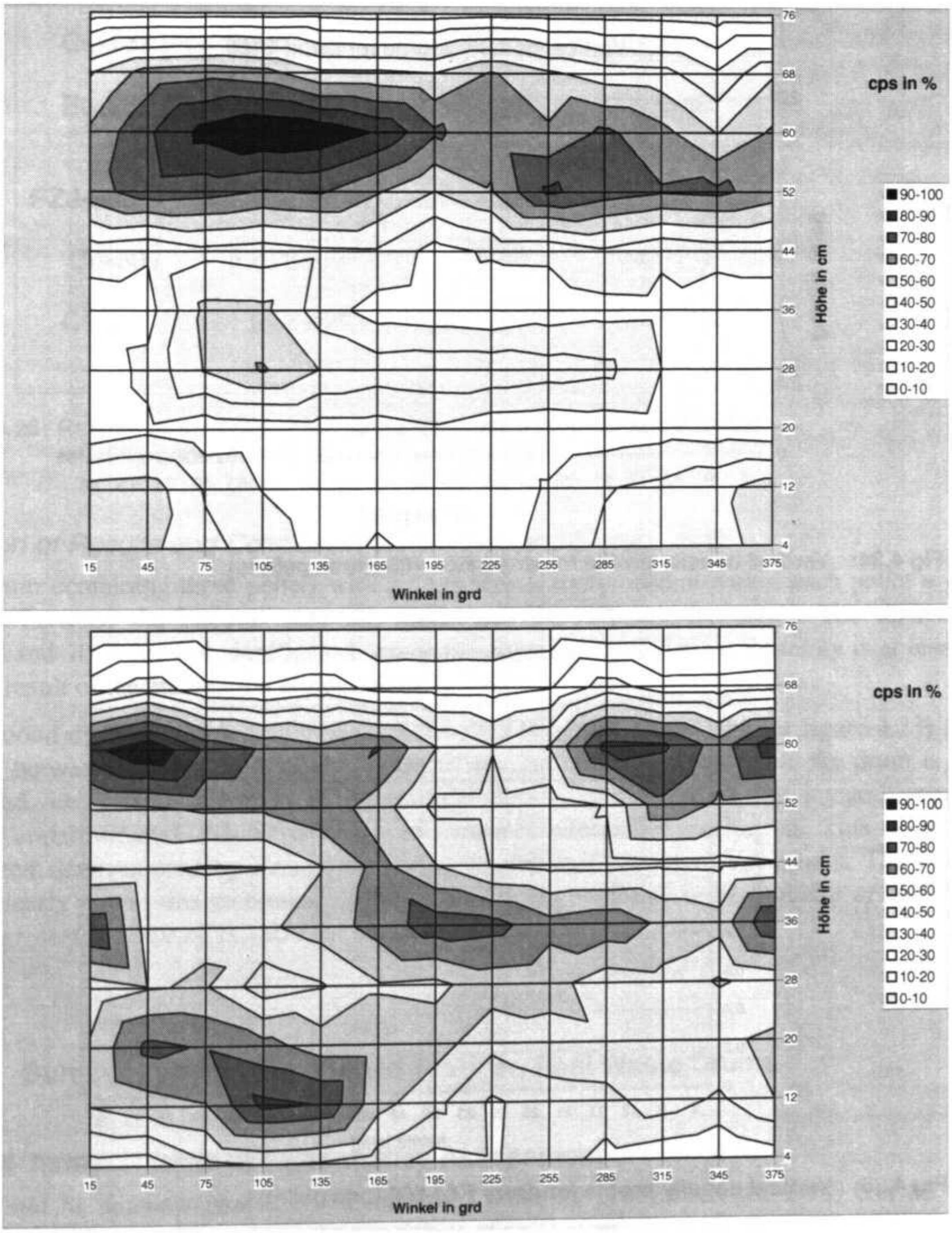


Fig 4.33: Count rate distribution for Cs-137 (upper) and Co-60 (lower) for drum FZJ-400

The calculated density profiles from transmission measurements are plotted in figures 4.34 and 4.35 for drums FZJ-400 and FZJ-500.

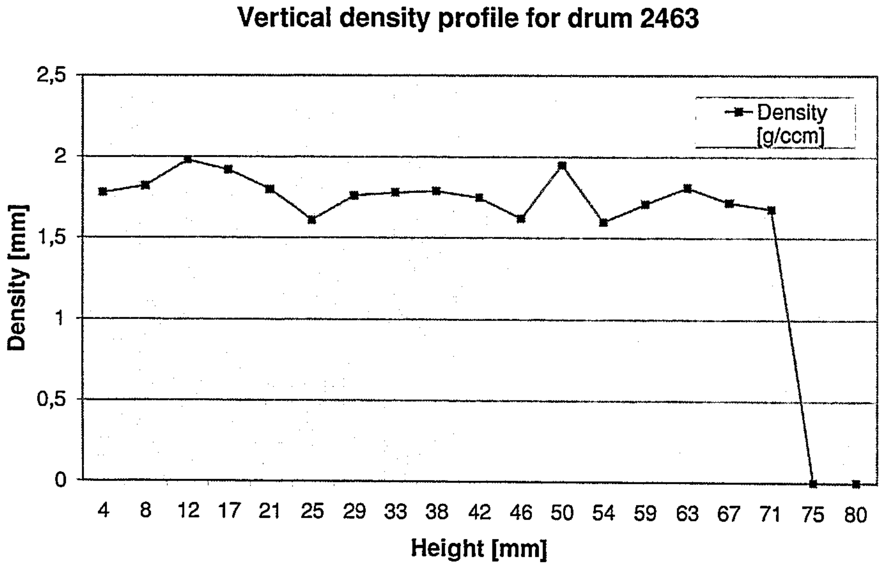


Fig 4.34: Vertical density profile for drum FZJ-400 (three pellets)

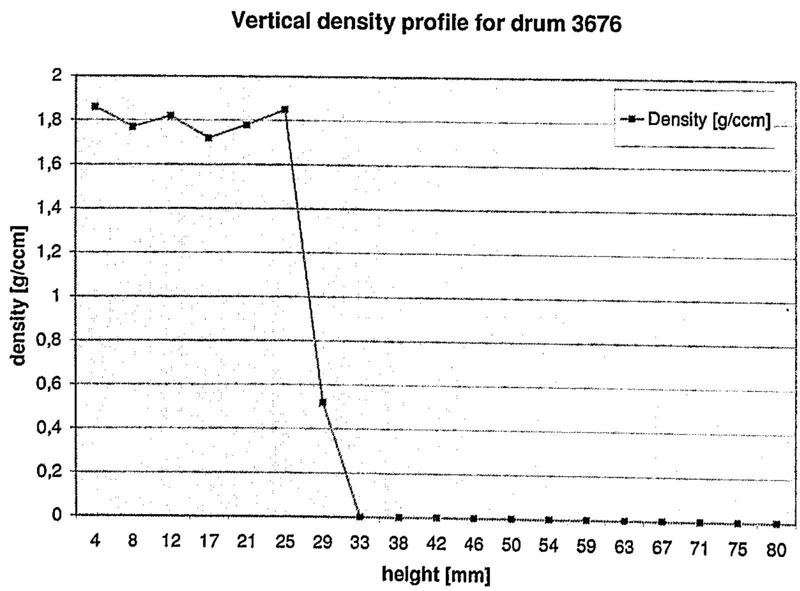


Fig 4.35: Vertical density profile for drum FZJ-500 (one pellet)

The following data have been calculated for those drums:

FZJ-400	Integral Scan	TC-SGS	Rel. Difference
Co-60	2,10E+07	1,95E+07	-7,14%
Cs-137	2,32E+08	2,09E+08	-9,91%
Eu-152	3,30E+07	3,15E+07	-4,55%
FZJ-500	**Integral Scan**	**TC-SGS**	**Rel. Difference**
Co-60	5,87E+06	1,14E+07	94,21%
Cs-137	1,82E+08	3,90E+08	114,29%

Tab. 4.26: Results of the activity calculation for drum FZJ-400 and FZJ-500; rel. difference is: *(TC_SGS –I_Scan)/TC_SGS*

Discussion of Results and Conclusions (TC-SGS for FZJ-400, -500)

For the drum containing three pellets with comparable activity content within each pellet a good agreement between the integral scanning mode and TC-SGS can be found. The differences between 5 and 10 % are not significant because the expected systematic uncertainty is at least ca. 10 % as a result of the attenuation correction in TC-SGS.

For the second drum containing only one pellet with a height of ca. 30 cm (see figure 4.33) a big difference between both methods could be identified. For configurations where the drum is only partly filled, i.e. a large variation of the vertical density profile exists, the integral scanning technique underestimates the activity due to incorrect attenuation correction. This effect has already been demonstrated by simulation and measurements on 'mock-up'-drums. The case in question clearly proves this theoretical expectation. *The difference of nearly a factor of two shows the superior performance of TC-SGS* for such cases.

4.6.5 Summary of Results of Field Tests on Real Waste Drums

Results & Achievements of Performance Assessment

It could be demonstrated that the improved scanning procedures (TC-SGS) can be applied to real waste drums up to density values of ca. 2 g/cm³.

For two drums with homogeneous activity and density distribution the consistency between standard and improved scanning techniques could be proved. The difference between calculated activity values for Co-60 and Cs-137 was lower than the measurement uncertainty.

For three drums filled with pellets and local activity concentrations significant differences between both methods have been observed. Due to the lack of a reference value for those drums it is not possible to tell whether TC-SGS values are more reliable. It should be emphasised that the premises for the application of TC-SGS are not fulfilled for those drums because of their prominent heterogeneity with respect to activity distribution.

The application of 'swivel scanning' for drums FZJ-200 and -300 leads to reconstructed activities of ca. 40 % of the values observed by TC-SGS. This deviation is in the range predicted by simulations and observed by the test measurements on 'mock-up'-drums.

The results for the drum FZJ-400 (three pellets) have shown fairly identical values for Co-60, Eu-152 and Cs-137 with standard and optimised scanning procedures. This is consistent with the fact that all three pellets seem to have comparable activity and density distributions which tends to level out the differences between both methods.

The results for the drum FZJ-500 (only one pellet) have shown large differences for the calculated activities for Co-60 and Cs-137. This result can be explained because of the fact that the drum was only filled to approximately 30 cm height. This leads to the expected situation of underestimation of the self absorption effect by integral scanning. The improved TC-SGS technique corrects attenuation effects much more effectively because of the measured vertical density profile. The activity calculated for the drum by TC-SGS was ***nearly a factor of two higher*** *than for standard scanning.*

The measured results have clearly demonstrated that segmented gamma scanning should always be used in combination with transmission measurements for attenuation correction if there is not sufficient information about the matrix configuration inside a waste package.

A second and helpful tool is to make use of additional scanning techniques which reveal more detailed information about the activity distribution inside the package.

5 SUMMARY OF RESULTS AND CONCLUSIONS

The main results and achievements of the research work carried out by FZJ/ISR are briefly summarised here.

5.1 Overview of Results and Achievements

Development of Correction Algorithms

- A user-friendly software tool has been developed to calculate self-attenuation correction factors based on multi-energy transmission measurements (TRANSFIT).
- Different Correction methods and techniques for gamma attenuation and non-homogeneous source distribution have been developed:

  1. Swivel Scanning (SWS)
  2. Transmission Corrected Segmented Gamma Scanning (TC-SGS)

- Testing of these methods has been performed.

Set-Up of Prototype Systems for Improved Gamma Scanning

- The GERNOD scanner at FZJ has been successfully upgraded with an external Ir-192 transmission source to perform transmission measurements. System upgrading has been carried out to be able to apply TC-SGS and SWS.
- Testing of all the system has been performed and finished successfully within the objectives of the R&D project.

Benchmark Measurements with Test Drums

- Test procedures have been specified in order to carry out well defined benchmark tests for performance evaluation on specially built mock-up configurations.
- Inter-comparison tests have been performed with all systems and performance analysis carried out. The results achieved demonstrate the improved accuracy and reliability of the developed scanning techniques compared to conventional or 'state-of-the-art' techniques used. In some cases the gain in accuracy was found to be dramatic (more than a 4 was found during benchmark testing).

'Field' Measurements on Waste Packages

- Typical waste drums have been selected and characterised for demonstration tests.
- Measurements have been carried out under 'field conditions' and results demonstrated successfully the practical usefulness and applicability of the new techniques in routine waste assay.
- All relevant information has been compiled in respective R&D reports.

The information given in table 5.3 on the exploitation process summarises the actions which have been defined or planned at the time of the termination of the work programme. Other actions will follow after plans for exploitation and dissemination of results are further detailed. This is especially valid for the process of reporting and publishing of results.

Work Area	Description of Result	Partner(s) Involved	Type of Result	Planned Exploitation
A	TRANSFIT Data-Fitting Software for TC-SGS	FZJ	Executable Code	FZJ: copyright
A	SWIVEL SCANNING Improved procedure for gamma scanning	FZJ, TUM	Theoretical Concept for SWS	TUM, FZJ: know-how
A	TC-SGS Improved Procedure for gamma scanning with transmission correction	FZJ	Theoretical Concept for TC-SGS	FZJ: copyright, license
B	PROTOTYPE of UPGRADED GERNOD II Upgraded System for improved gamma scanning with TC-SGS and SWS	FZJ	Hardware, Software, Technical Documentation	FZJ: secret know-how, license

Tab. 5.3 List of Results and Project Deliverables with information on exploitation process

5.2 Conclusions and Recommendations for the Application of the Improved Scanning Techniques

Different ways of improving 'conventional' state-of-the-art NDA-techniques based on gamma spectrometry to quantify the activity inventory in waste drums have been developed, investigated and tested successfully on different 'mock-up' configurations and waste drums.

Although that the developed methods proved to be successful, they must partly be still considered as being in a testing or validation phase. The range of validation, as being limited due to the limited resources available for this part of the project, needs to be extended to more cases than those considered.

Taking into account all results which have been achieved the following conclusions can be drawn by FZJ:

1. TC-SGS has proved to be a reliable technique for routine waste assay with only small additional hardware & software equipment/effort.
2. TC-SGS has clearly shown to be able to improve the reliability of gamma assay on waste drums.
3. TC-SGS gives a much better indication of vertical density variations in the drum, including the actual filling height inside the drum, which makes it on the average less sensitive to matrix inhomogeneities and generates a lower bias in such cases.
4. Comparing results from standard integral scanning with TC-SGS makes it possible to check or validate gamma assay results which is normally not part of a routine assay procedure. If both techniques lead to similar results the reliability of activity values is generally much better.
5. In cases of identified heterogeneous activity distributions (in segments of the drum) additional techniques should be employed to correct for the unknown bias. In such cases 'angular scanning' and/or 'swivel scanning' may be applied to reduce the uncertainty.

The new prototype will be used for routine assay in FZJ's waste inspection service. Because of it's novel features and operation capabilities the design of the GERNOD II system will be 'know-how' protected and the hardware and software developed will be commercialised via a licence agreement between FZJ and an industrial partner.

The impact of the aforementioned improvements on the day-to-day business of NDA-system operators, although being evident for the experts involved, will certainly depend on the way of implementation and practical handling of these techniques.

Looking at the problem of dissemination of results and transfer of experts' knowledge to the level of system operation it would certainly help to have a tool which supports the operator when carrying out data analysis work, especially if non-conventional and more sophisticated procedures and algorithms must be applied.

This objective, which lies outside the scope of the original project, could be achieved by setting-up a kind of *software assistant for NDA-work.* As part of a QA/QC-system such a tool would also have the advantage of supporting significantly the quality control and assurance work for the assay system.

At the end of the performed work the partners would like to summarise their conclusions in two ways:

1. Giving an *overview of gamma scanning systems* including new developed assay techniques
2. Defining a *flow-chart for the application of different scanning techniques* under various conditions

Overview of NDA systems based on gamma-ray measurements

The overview of gamma scanning systems shall illustrate the way in which the features of a specific NDA-system should be designed in order to cope with different degrees of heterogeneity of matrix and activity in a drum (see Fig. 5.1).

For homogeneous waste the upper left case holds, where a simple uncollimated detection system in combination with a turntable may already be sufficient to achieve acceptable results.

On the contrary, if there is not enough information on the type of waste and measurements indicate varying counting rates for different detector-drum orientations, then only the most sophisticated combination of available NDA instruments, i.e. segmented gamma scanning (SGS) and digital radiography (DR) and tomography (ECT/TCT), may help to end up with consistent and valid results.

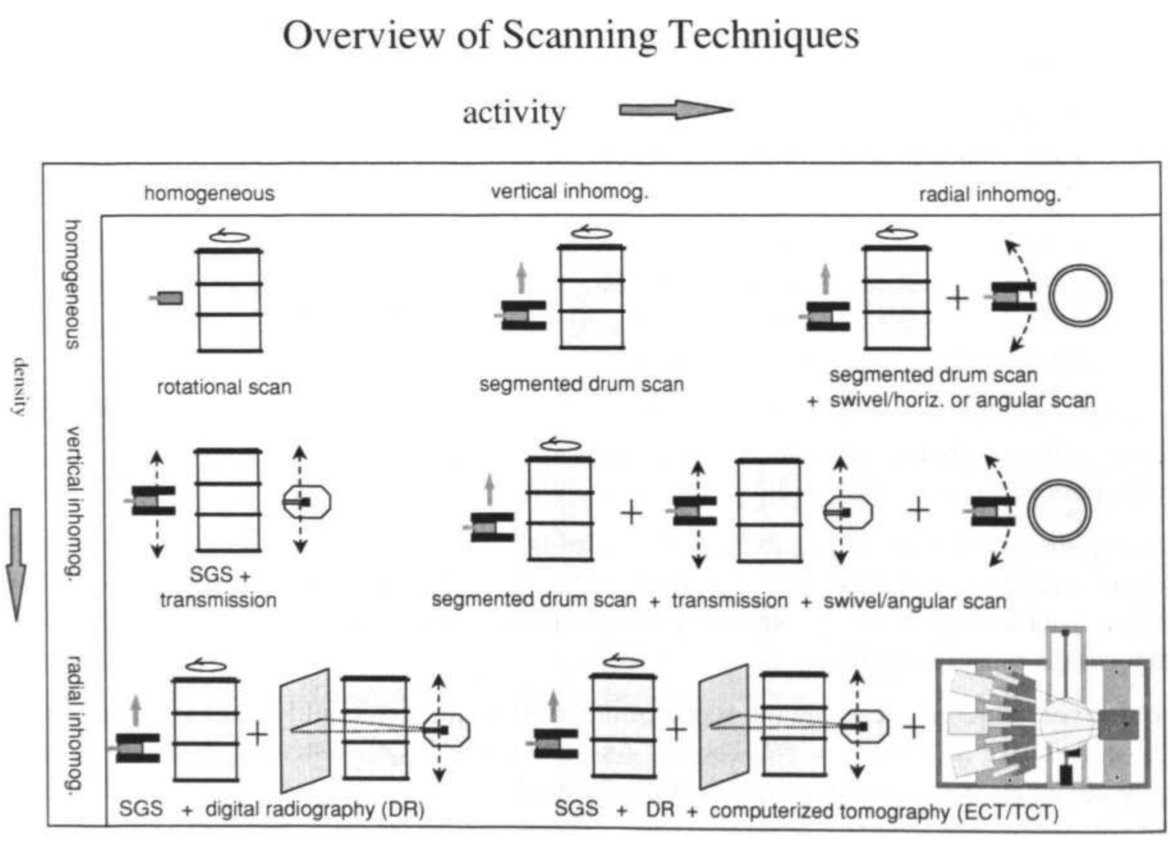


Fig. 5.1: Overview of gamma scanning techniques: System requirements are increasing with increasing heterogeneity of matrix/density (from top to bottom on the vertical axis) and activity (from left to right on the horizontal axis).

It should be emphasised that *quality control of results* implies in nearly all cases the possibility to have more system features available than required for the standard assay procedure. For instance an uncollimated, 'fixed detector position' system may be sufficient, as indicated above, for homogeneous waste drums. But checking whether an item really fulfils this assumption does often require to make additional measurements, such as checking the count rate distribution with a collimated detector and with vertical positioning capability (SGS).

Flow-Chart: Optimised Assay Procedure

The flow-chart illustrates the way in which the new technqiues can be merged together with already existing methods to form a consise and flexible assay procedure (see Fig. 5.2). The principle idea of an *optimised assay programme* is to try to adapt the techniques applied to the characteristics of the sample under inspection.

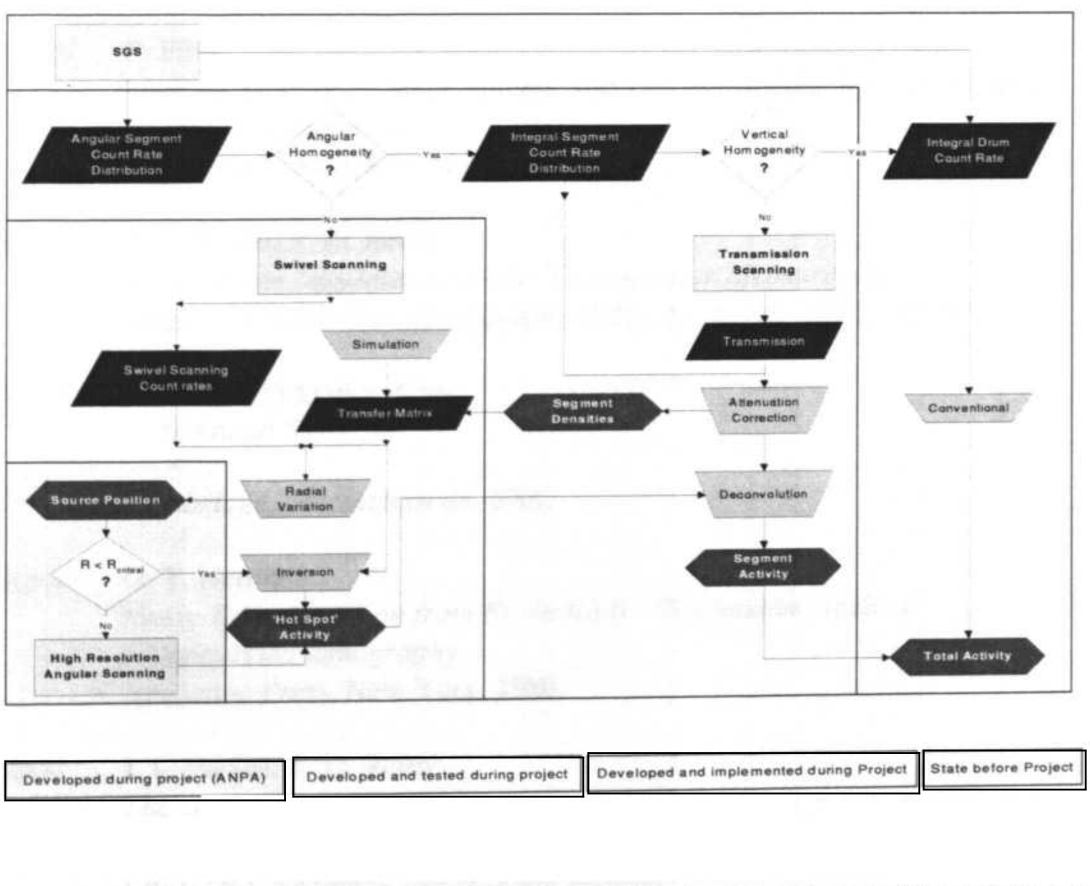


Fig. 5.2: Flow-Chart of assay technqiues: New technqiues may be used in such a way as to refine the standard procedure more and more taking into account the characteristics of the sample package

In this way the effort spend is proportional to the complexity of the object. However, it should be mentioned that an optimised assay procedure has to take into account three ‚ingredients':

1. *The assay system and its features and performance characteristics.*
2. *The item which has to be analysed and its characteristics.*
3. *The objective of the inspection task.*

Only when all of this factors are considered fairly well in relation to one another an optimised inspection procedure can be defined.

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