Synopsis of Neutron Assay Systems

Comparison of Neutron Determining Systems and Measuring Procedures for Radioactive Waste Packages

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T. Bücherl, Ch. Lierse von Gostomski

European Network of Testing Facilities for the Quality Checking of Radioactive Waste Packages

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Preface

At the second meeting of the Working Group 4 of the ‘European Network of Testing Facilities for the Quality Checking of Radioactive Waste Packages’ held in Arnhem, The Netherlands, 15. November 1995, it was decided by all members to create a synopsis of existing systems for the neutron measurement of radioactive waste packages, comparable to those for gamma scanning systems [BUC98]. A questionnaire on the set-up and on the operation modes of neutron assay systems was compiled and distributed to the members of the Working Group. The summary of the answers and a general information on neutron assay are presented within this synopsis. Its intention is to help people interested in setting up or in upgrading an existing assay system in their decision for an appropriate system for their specific requirements. A list of institutions and contact persons working in this field of application is added to enable the user of this synopsis to get quick access to further information and to exchange experiences.

Garching, September 2001

The authors
1 Introduction

Radioactive waste can originate from different producers such as nuclear power plants, research institutes, nuclear medicine and others. It has to meet certain specifications and acceptance criteria defined by regulatory and management authorities. These criteria differ depending on the form and type of radioactive waste and on the individual country regulations.

Appropriate control procedures to ensure the compliance with these restrictions and limitations are necessary for quality control. They can take place either at the origin of the radioactive waste generation, during the conditioning or at the final conditioned waste package. Preferably non-destructive testing methods are used in order to minimise the radiation dose to the personnel, to avoid secondary radioactive waste and to minimise costs. Furthermore, with destructive testing there will always be the essential question of taking a representative sample.

In recent years several non-destructive methods for quality checking of radioactive waste packages have been developed and tested. They can be distinguished by the measured quantity, mainly gamma radiation and/or neutrons, and due to their operation mode, i.e. passive or active measuring modes. A summary of conventional assay is given in Table 1.

This synopsis focuses on the passive neutron assay used for the characterisation of radioactive waste packages, i.e. the detection of neutrons emitted by spontaneous fission (sf) or by (α,n)-reactions in a waste package. No external neutron or gamma interrogation source is applied.

The synopsis aims in summarising the basic principles of operation, the required equipment and the layout of a system. Information on technical terms, existing systems and contact persons or institutions for further information are given in the annexes.

Table 1: Measuring modes conventionally used in quality control of radioactive waste packages.

<table>
<thead>
<tr>
<th>gamma radiation</th>
<th>neutrons</th>
</tr>
</thead>
<tbody>
<tr>
<td>passive</td>
<td>total neutron counting</td>
</tr>
<tr>
<td>dose rate measurements</td>
<td>segmented neutron counting</td>
</tr>
<tr>
<td>gamma counting</td>
<td>time correlation methods</td>
</tr>
<tr>
<td>segmented gamma scanning</td>
<td></td>
</tr>
<tr>
<td>active</td>
<td>interrogation techniques</td>
</tr>
<tr>
<td>radiography</td>
<td></td>
</tr>
<tr>
<td>tomography</td>
<td></td>
</tr>
<tr>
<td>interrogation techniques</td>
<td></td>
</tr>
</tbody>
</table>
2 Principle of Neutron Measurements

2.1 General

The main objective of passive neutron assay is to prove the presence of neutron emitters within a waste package and to quantify them in terms of a $^{240}\text{Pu}_{\text{equiv}}$ mass. An isotope specific identification and quantification is not possible since the neutron emission spectra of different isotopes measured outside a waste package do not show characteristic differences like e.g. gamma spectra. But using time correlation methods (TCM) a general distinction and quantification between spontaneous (sf) and ($\alpha$,n)-reaction neutron sources is possible.

A suitable neutron assay system consists typically of:

- a number of neutron detector systems,
- a moderator,
- a background shielding,
- a manipulator,
- a control unit,
- a data evaluation unit and
- optional additional equipment (e.g. turntable, transmission source, time correlation method systems etc.).

The design of a passive neutron assay system and the choice of the most appropriate additional equipment must be adapted to type and to size of the waste packages to be characterised and to the measurement modes to be applied.

2.2 Neutron Counting System

Neutrons cannot be detected directly like charged particles or gamma radiation. Therefore nuclear reactions are used to convert neutrons in energetic charged particles like protons, $\alpha$-particles, etc. These secondary particles then can be detected using conventional radiation detectors like proportional counters, scintillation detectors, etc. [KNO89]. The cross section for the interactions of neutrons with the target material strongly depends on neutron energy for most materials, resulting in different techniques and designs for neutron detectors. For the neutron assay of waste packages conventionally thermal neutron detectors are used, although fast or epithermal neutron detectors may also be applied. This synopsis only focuses on the use of thermal neutron detectors as these are the most frequently used ones.

Neutron detectors can be simple counting tubes or one- or two-dimensional position sensitive detectors, typically using $^3\text{He}$ as conversion material. The use of the first will give mainly integral information on the neutron emitters while position sensitive detectors offer the possibility of segmented neutron counting.

A block diagram of a typical neutron detection system is shown in Figure 1.

The detector may be a $^3\text{He}$-counting tube, a BF$_3$-counting tube, a Gd- or B-loaded scintillation detector, a fission chamber, etc. [KNO89]. In most current operating systems $^3\text{He}$-counting tubes are used.

The high voltage power supply is required for the operation of the detector and is conventionally called detector bias supply.

The output of the detector is a small burst of charge which cannot be dealt with in the subsequent electronic components without an amplification step. This is performed by the preamplifier. It is located as close as possible to the detector.

![Block diagram of a typical neutron detection system.](image-url)
The linear amplifier which is connected to the preamplifier provides two elements in the pulse processing chain: pulse shaping and amplitude gain. The amplification factor or gain is conventionally adjustable over a wide range and must be adjusted carefully since it influences the signal-to-noise ratio.

The discriminator filters out signals not originated by neutrons but by other effects, e.g. by gamma-ray background, etc. The discriminator level must be set carefully not to cancel out neutron signals but to account for gamma background, etc.

After discrimination the analogous signal is triggering a logical pulse which is used for further processing (e.g. counting, registration of arrival time etc.) by a computer.

Several additional components in the detection chain (Figure 1) are available and sometimes in use (e.g. pulse generators for calibration purposes).

A calibration of the discriminator settings has to be performed after each shut down of the system and of individual detector chains, respectively. Furthermore, the discriminator settings have to be checked periodically for quality control and if any doubts on the correctness of the actual calibration may occur (e.g. strong fluctuations of the count-rates of neighbouring detectors).

To achieve a high detection efficiency the complete waste package should be surrounded by neutron detectors, i.e. the neutron detectors should be arranged as close as possible to a 4\(\pi\)-geometry.

2.3 Moderator

The energy range of the neutrons emitted by sf or \((\alpha,n)\)-reactions generally is about 1 MeV to 10 MeV. For an effective detection using thermal neutron detectors these fast neutrons must be slowed down to energies of less than 1 eV, i.e. the emitted neutrons must be moderated to thermal energies. This is performed by surrounding the neutron detectors with moderating (i.e. thermalising) material, e.g. polyethylene. The thickness of this material must be adapted to the moderation properties of the waste packages to be characterised and is typically about 1 cm to 3 cm of polyethylene.

Conventionally several detectors are grouped together within a moderator block.

The moderator blocks may be lined with cadmium foils to limit matrix effects and induced fission multiplication effects for time correlation system-measurements. Additional shielding (e.g. lead) might be necessary for protecting the neutron counters against gamma radiation which may influence the measured count-rates but may increase the background signal due to spallation processes.

2.4 Background Shielding

The detectors record the number of neutrons emitted by the waste package and some background signals which can origin for example from

- natural radioactivity in the surrounding,
- neutrons created by spallation effects,
- neutron emitting facilities (e.g. reactors) or sources (radioactive sources),
- other radioactive waste packages.

Because the magnitude of the background ultimately determines the minimum detectable signal a shielding of the detectors is preferred. Shielding materials commonly used are polyethylene, cadmium, etc. for neutron shielding and lead, tungsten, etc. for gamma radiation shielding.

For shielding purposes some passive neutron assay systems are housed within a polyethylene cube with wall thickness of up to 20 cm.

An appropriate choice of the place of operation of the passive neutron assay system may significantly influence the minimum detectable signal and may reduce the required shielding dimensions.

2.5 Manipulator

In general the neutron emitters are not distributed homogeneously within the waste package. Therefore, an integral determination of the neutron count-rate, i.e. the sum of the count-rates of all individual detectors, will not give representative information on the content of the waste package. Evaluation of the individual detector count-rates will improve the information, but depending on the detector arrangement, additional manipulation of the waste package may be necessary to gather further information, e.g. performing segmented neutron counting. This will result in a much more reliable and representative characterisation of the waste package than by simple integral counting.

Conventionally the manipulator system is limited to a single turntable for rotating the waste package.
2.6 Control Unit

The control unit, usually a computer, controls both the movements of the manipulator system and the measuring process. Conventionally these tasks are synchronised. The measured data, i.e. the count-rates of the individual detector chains and/or the neutron arrival times, is stored on appropriate media (e.g. harddisk of the computer) together with additional information (e.g. measuring date and time, position of the waste package, etc.) necessary for data evaluation and for the final documentation.

2.7 Data Evaluation Unit

Using the measured and stored data the quantification of the neutron emitting material present in the waste package is performed by appropriate software programs. This data evaluation can be performed on an additional computer system or is included within the control unit.

2.8 Additional Equipment

Most recently set-up passive neutron assay systems are equipped with time correlation method (TCM) systems. These systems distinguish between neutrons originating from sf and from \((\alpha,n)\)-reactions.

A correction of the attenuation properties of the matrix is based on the use of an external neutron source (e.g. \(^{244}\text{Cm}\), \(^{252}\text{Cf}\), etc.). This matrix interrogation is conventionally performed as a simple transmission measurement.

3 Measurement Modes

3.1 General

In passive neutron assay of (large volume) waste packages the measured data does not contain nuclide specific information for identifying the neutron emitter like in gamma scanning [BUC98]. Without additional a priori information only general information in terms of a reference material (e.g. \(^{240}\text{Pu}_{\text{equiv}}\)) can be given.

Nevertheless, different measurement modes are known differing in the number of resulting data and in the application of additional equipment.

Integral and segmented measurements both aim in determining the total (i.e. the combined sf- and \((\alpha,n)\)-reaction) neutron count-rates on the surface of the waste package being investigated.

A further distinction between neutrons emitted by sf- and \((\alpha,n)\)-reactions can be performed when applying additional equipment like time correlation systems.

3.2 Total Neutron Counting

Total neutron counting is an integral measurement. It is the most simplest measuring mode in passive neutron assay simply summing up the signals of all individual detectors.

During the measurement the waste package may be rotated which is recommended when only a small fraction of the waste package surface is “seen” by the neutron detectors, levelling out small inhomogeneities of the neutron emission-rate distribution on the surface of the waste package.

The evaluation of that data is only representative and reliable for a nearly homogeneous distribution of the neutron emitters within the waste package and a nearly homogeneous matrix.

3.3 Segmented Neutron Counting

In segmented neutron scanning (SNS) the distribution of the neutron emission-rates on the surface of the waste package is determined.

For this purpose the waste package surface is subdivided into \(M\) (equidistant) segments and each segment is subdivided into \(N\) sectors. Additionally, bottom and top of the waste package are subdivided into \(N_B\) and \(N_T\) sectors, respectively. For each sector the neutron emission-rate has to be determined. This requires either (2-dimensional) position sensitive detectors surrounding the waste package or, alternatively, a special arrangement of vertically and horizontally arranged neutron detector tubes in combination with an appropriate manipulation (i.e. rotation) of the waste package. Next a deconvolution of the measured data is performed resulting in a set of \((N \cdot M + N_B + N_T)\) data giving information on the distribution of the neutron emission rate on the waste package surface [BUC99].
Based on these data a verification of the assumptions of homogeneity required for applying the total neutron counting evaluation procedure can be performed and hot spots can be detected.

### 3.4 Time Correlation Methods

Application of time correlation methods aims in separating the neutron emission-rates on the surface of a waste package originating from sf- and \((\alpha,n)\)-reactions, respectively.

The signals of all individual detectors are summed up and fed into a special time correlation method system.

During the measurement the waste package may be rotated which is recommended when only a small fraction of the waste package surface is “seen” by the neutron detectors, levelling out small inhomogeneities of the neutron emission-rate distribution on the surface of the waste package.

### 3.5 Selection of Scan Modes

Depending on the available and reliable a-priori information given on the waste package and by the specific task description the most appropriate method must be chosen.

If information on the amount of sf- and \((\alpha,n)\)-reaction neutrons is required an appropriate time correlation method must be applied. For this purpose different methods are known like e.g. the shift register method, the neutron coincidence counting (NCC) and the neutron multiplicity counting (NMC). The shift-register method has proven to give acceptable results for waste packages containing low density materials but often fails for dense matrices. NCC, which needs information on the matrix properties, and NMC have shown their applicability not only for light matrices but also for metallic matrices [BUC99]. NMC is self-calibrating, i.e. no information on the matrix properties must be known, and is to some extend insensitive to the actual source distribution, but its application is limited to \(^{240}\text{Pu}_{\text{equiv}}\)-masses of at least 100 mg. Furthermore, it is strongly sensitive to background effects.

### 4 Data Processing and Evaluation

#### 4.1 General

The results of passive neutron measurements are count-rates. The quantification is conventionally based on the total net count-rate, assuming a homogeneous distribution of the neutron emitters and of the matrix. The distribution of neutron emitters, measured with the segmented neutron counting mode, give information on the correctness of that assumption. Improved evaluation procedures are known (e.g. [BUC99]) but usually not applied in practice due to the increased requirements for the operators skills and for the time needed for measurement and data evaluation.

The conventionally applied evaluation procedures calculate the \(^{240}\text{Pu}_{\text{equiv}}\)-mass usually in a conservative way, i.e. for an inhomogeneous distribution of neutron emitters the \(^{240}\text{Pu}_{\text{equiv}}\)-mass will be lower than calculated.

#### 4.2 Basic Relations

The method of calculating the \(^{240}\text{Pu}_{\text{equiv}}\)-mass \(M\) from the total net count-rate \(Z\) is given by the basic relation

\[
M = \frac{Z}{k}
\]

with \(M\): \(^{240}\text{Pu}_{\text{equiv}}\)-mass [g]

\(Z\): net count-rate [s\(^{-1}\)]

\(k\): transfer or correlation factor [s\(\cdot\)g\(^{-1}\)]

The transfer or correlation factor \(k\) can either be determined experimentally or by mathematical calculations.

#### 4.3 Experimentally Determined Correlation Factor

This method is based on a set of calibration measurements. Well defined standards being representative for the types of waste packages to be investigated are measured and the correlation factors between the well known neutron emission-rates and the measured count-rates as a function of matrix and source distribution are determined (using equation 1) and stored in a look-up table.
Knowing the matrix and source distribution of a waste package either from a-priori information or from additional matrix interrogation and segmented neutron counting measurements the corresponding correlation factor can be selected from the look-up table for data evaluation.

Very often the properties of the investigated waste package do not completely fit to the properties of a calibration standard. Then the correlation factor has to be determined by an appropriate combination (e. g. averaging) of existing correlation factors being representative for similar matrices and distributions of the neutron emitters.

The disadvantage of this calibration method is the necessity of a large number of calibration drums, depending on the number of different types of waste packages and matrices to be investigated.

4.4 Calculated Correlation Factor

The calculation of the correlation factor is mostly based on the use of Monte-Carlo methods. This modelling requires at first a detailed and complete description of the measuring device (i. e. detector system, shielding, moderator, etc.). Using a set of modelled standards, a look-up table can be calculated.

If the properties of the investigated waste package do not completely fit with the properties of a standard, the corresponding correlation factor can either be determined by an appropriate combination of correlation factors for similar matrices and distributions of neutron emitters, or the correlation factor is determined by a new Monte-Carlo calculation using the specific properties of that waste package.

Nevertheless, some calibration drums are still recommended to validate the correctness of the calculated correlation factors.

The disadvantage of this calibration method is the large calculation time for determining one calibration factor and the necessity of an expert to perform these calculations.

4.5 Remarks

The accuracy of the results obtained from both methods strongly depends on the knowledge about the composition of the matrix and of the distribution of the neutron emitters. If no or only a little information is available an improvement can be achieved experimentally by using the results of additional matrix interrogation measurements and of segmented neutron counting, respectively.

In general, the neutron emitters are not homogeneously distributed over the complete volume of the waste package. If the waste package is not completely surrounded by neutron detectors and/or the arrangement of the neutron detectors is not the same for each position (e. g. when using horizontal and vertical detector tubes) then an averaging is achieved by rotating the waste package. This enables a quantification assuming a homogeneous activity distribution.

5 Validation

The passive neutron assay system must be verified to ensure the accuracy of the results. The verification must be performed after each restart of the system, when a new calibration is performed and in regular intervals during routine operation. Therefore, dummy waste packages with well defined compositions and activity contents similar to those, which have to be characterised in practice, are measured and evaluated. These waste packages must not be the same as used for any calibration procedure in order to avoid the abolishment of systematic errors.

If the results of the validation measurements deviate from the declared values of the dummy waste packages, the system has to be checked, repaired and new calibrated. All waste packages characterised since the last verification shall be characterised once again. Alternatively, if the reason for and the date of the first deviation can be determined precisely corrections of the results may be performed.

6 References


Technical Terms

To avoid misunderstandings in discussion of neutron measurement of waste packages, the most relevant technical terms as used within the Working Groups of the “Network” are given below. They are in accordance with ISO\(^1\) [ISO99].

\[(\alpha,n)\text{-reaction:} \quad \text{reaction which induces neutron emission via an alpha-particle}\]

\[\text{background shielding:} \quad \text{shielding of the measurement chamber against neutrons from the surrounding, i.e. not emitted from the investigated package}\]

\[\text{container:} \quad \text{package envelope}\]

\[\text{control unit:} \quad \text{system for controlling the manipulator system and the data acquisition process}\]

\[\text{data evaluation unit:} \quad \text{system for evaluation of the measurement data}\]

\[\text{detector:} \quad \text{device providing an electrical signal proportional to the neutron flux irradiating it; the signal depends of the neutron energy}\]

\[\text{passive neutron assay:} \quad \text{system for measurement of the neutrons emitted from a package without the use of any external neutron interrogation source}\]

\[\text{Pu}_{\text{eff}}\text{-mass:} \quad \text{mass [g] of pure }^{240}\text{Pu that would produce a signal identical to the one recorded by the measurement device}\]

\[\text{reference package:} \quad \text{mock-up representative of a package with precisely known characteristics; the radioactive characteristics are determined with respect to a reference material}\]

\[\text{matrix:} \quad \text{inactive material contained in the package}\]

\[\text{neutron counting system:} \quad \text{system for measurement of neutrons}\]

\[\text{package:} \quad \text{object to be characterised, comprising the leak tight envelope}\]

\[\text{PSD:} \quad \text{position sensitive detector}\]

\[\text{segmented neutron counting:} \quad \text{performing subsequent neutron measurements at different height positions}\]

\[\text{sf:} \quad \text{abbr.: spontaneous fission}\]

\[\text{time correlation method:} \quad \text{measurement of the time dependence of the neutron detection within a passive neutron assay}\]

\[\text{transmission source:} \quad \text{external neutron source for determining the matrix properties by transmission measurements}\]

\[\text{waste package:} \quad \text{package containing waste}\]

---

Comparison of Technical Data of Neutron Assay Systems

Appendix B offers a fast abbreviations on all relevant technical data of the individual passive neutron assay systems. Which are described in general in the subsequent Appendix C. The association between the columns of the technical terms and the owners of the systems is made by the abbreviations listed below.

RCM: Institut für Radiochemie, Technische Universität München, Walther-Meißner-Str. 3, D-85748 Garching, Germany

ENEA: ENEA, CR CASACCIA – Via Anguillarese, 301 - 00060 S. Maria di Galeria (Rome), Italy

JRC: Joint Research Centre, I-21020 Ispra (VA), Italy

SCK: SCK•CEN, Boeretang 200, B-2400 Mol, Belgium
## Synopsis of Neutron Assay Systems

### Appendix B-2

<table>
<thead>
<tr>
<th>General</th>
<th>RCM</th>
<th>ENEA</th>
<th>JRC</th>
<th>SCK</th>
</tr>
</thead>
<tbody>
<tr>
<td>commercial system</td>
<td>no</td>
<td>no</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>company</td>
<td>-</td>
<td>-</td>
<td>ANTECH, A.N.Technology, GB</td>
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</tr>
<tr>
<td>model</td>
<td>-</td>
<td>-</td>
<td>Drum Monitor Series 2200</td>
<td></td>
</tr>
<tr>
<td>mobile</td>
<td>yes</td>
<td>yes</td>
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### Labour

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<th>Commercial</th>
<th>Research</th>
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<tbody>
<tr>
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<td>80 %</td>
<td>50 %</td>
</tr>
<tr>
<td>research</td>
<td>60 %</td>
<td>20 %</td>
<td>50 %</td>
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### Mechanical Specifications

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<tbody>
<tr>
<td>movement of</td>
<td>rotation</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>waste package</td>
<td>no</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>detector(s)</td>
<td>no</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>others</td>
<td>interrogation source</td>
<td>semi-automatic drum loading</td>
<td>interrogation source</td>
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### Waste Package

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<tbody>
<tr>
<td>max. size</td>
<td>400 l drum</td>
<td>400 l drum</td>
<td>220 l drum</td>
</tr>
<tr>
<td>max. weight</td>
<td>2000 kg</td>
<td>1000 kg</td>
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### Detector System

<table>
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<tbody>
<tr>
<td>type</td>
<td>$^3$He-counting tube</td>
<td>$^3$He-counting tube</td>
<td>$^3$He-counting tube</td>
</tr>
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<td>company</td>
<td>Berthold, Germany</td>
<td>XERAM, France</td>
<td>XERAM, France</td>
</tr>
<tr>
<td>number</td>
<td>30 (+6)</td>
<td>64</td>
<td>64</td>
</tr>
<tr>
<td>length</td>
<td>1.0 m (0.45 m)</td>
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</tr>
<tr>
<td>diameter</td>
<td>2.5 cm</td>
<td>2.54 cm</td>
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</tr>
<tr>
<td>gas</td>
<td>$^3$He</td>
<td>$^3$He + Ar</td>
<td>$^3$He</td>
</tr>
<tr>
<td>pressure</td>
<td>4 bar</td>
<td>4 bar + 1 bar</td>
<td>4 bar</td>
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### Detector Arrangement

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<th>Research</th>
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<tbody>
<tr>
<td>hexagonal arrangement of 31 detectors + 5 top detectors</td>
<td>decagonal arrangement of 40 detectors + 12 top detectors and 12 bottom detectors</td>
<td>10 vertical modules forming a decagon, 3 modules on top, 3 modules on bottom</td>
<td>36 in a hexagonal arrangement + 12 top + 12 bottom</td>
</tr>
</tbody>
</table>

### Moderation System

<table>
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</tr>
</thead>
<tbody>
<tr>
<td>PE</td>
<td>PE</td>
<td>HD-PE</td>
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European Network of Testing Facilities for the Quality Checking of Radioactive Waste Packages  
## Synopsis of Neutron Assay Systems

### Background Shielding

<table>
<thead>
<tr>
<th></th>
<th>RCM</th>
<th>ENEA</th>
<th>JRC</th>
<th>SCK</th>
</tr>
</thead>
<tbody>
<tr>
<td>general</td>
<td>measuring system is placed in a cube having PE-walls of 20 cm thickness</td>
<td>outer stainless steel liner (1 mm) inner cadmium liner (1 mm)</td>
<td>22 cm of HD-PE, 1 mm Cd</td>
<td>Paraffin castle with PE roof and doors</td>
</tr>
<tr>
<td>background count-rate</td>
<td>ca. 3 s⁻¹</td>
<td>ca. 3 s⁻¹</td>
<td>2.4 s⁻¹</td>
<td>Singles : 1.85 s⁻¹ Doubles: 0.052 s⁻¹ Triples : 0.007 s⁻¹</td>
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### Electronics

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<td>Model 1001 Neutron Time Correlation Analyser (Antech A. N. Technology Ltd.)</td>
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### Synopsis of Neutron Assay Systems

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### Software

| control of system | X   |     | X   | X   |
| manipulator       | X   |     |     | X   |
| data acquisition  | X   | X   |     | X   |

### Analysis of

| total counting   | X   | X   | X   | X   |
| time correlation analysis | X   | X   |     | X   |
| signal frequency distribution of neutron pulse trains |     | X   | X   | X   |
| coincidence counting | X   | X   |     | X   |
| multiplicity counting | X   | X   |     | X   |

### Measurement Modes

| total neutron counting | X   |     | X   |   |
| segmented neutron counting | X       |     | X(angular) |   |
| coincidence counting   | TCA  | NMC, NCC, TCA | X | X   |

### Calibration

| general             | no  | X   | no  |   |
| waste dependent     | 5 mock-up drums with different homogeneous matrices by Monte-Carlo modelling | - | mock-up drums + Monte Carlo modelling |

### Sources

| ²⁵²Cf  | 5e+6 n/s | certified standards |
| ²⁴⁴Cm  | 3e+5 n/s | some |
| ²⁴¹Am  | 4.3e+2 n/s, 9.6e+2 n/s | Am/Li certified standards |
| Am/Be  | | certified standards |
| Pu     | 5e+0 n/s to 3e+2 n/s | certified standards |
| PuO₂   | 1.5e+2 n/s | certified standards | Set of well characterised Pu-sources |

### Detection Limit

| ²⁴⁰Pu (total counting) | 10 mg | 1-2 mg | 1 mg |
| ²⁴⁰Pu (coincidence counting) | 10-20 mg | 10 mg |
### Synopsis of Neutron Assay Systems

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<td>absorption correction</td>
<td>by matrix interrogation and modelling</td>
<td>by MCNP modelling</td>
<td>by analysis</td>
<td>by add-a-source technique + modelling for interpolation</td>
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| Additional Equipment | | | |
|----------------------|--------------------------|
| matrix interrogation | yes | yes | |

| TCA | Model 1001 Neutron Time Correlation Analyser (Antech A. N. Technology Ltd.) | Model 1001 Neutron Time Correlation Analyser (Antech A. N. Technology Ltd.) | |
| NCC | JSR-12 (Canberra) | JSR-12, JSR-14, AMSR | |
| TIA | GT657-TIA (GEOTEX) | GT657-TIA (GEOSTEST) | |
| NMC | | | |
| MGA-equipment | X | | Gamma Scanner + MGA |
| HP-Ge detector | | | Gamma Scanner |

### References

- Compilation of fission yields and multiplicity data
Description of the Individual Passive Neutron Assay Systems

In Appendix C general descriptions of the passive neutron assay systems are given. For each system the abbreviation as defined in Appendix B, the address of the owner and its main features are listed together with a photograph of the system. A short general information summarizes the applications and features followed by the principle of operation. A short summary of the system components and a list with the main specifications completes the general overview. For more detailed information refer to Appendix B with the technical data table or to Appendix D with the list of contact persons.
SANDRA (RCM)
Special Arrangement for Neutron Detection in Radioactive Waste

Address
Institut für Radiochemie
Technische Universität München
Walther-Meissner-Str. 3
D-85748 Garching
Germany
Tel.: ++49-89-289-1 22 02
Fax: ++49-89-3 26 11 15

Features
- Mobile system
- Segmented neutron scanner
- Object dimensions up to 1.0 m diameter, 1.0 m height and 2000 kg weight
- 36 $^3$He-counting tubes
- Typical detection efficiencies: 3 % to 15 %
- Detection limit for 240Pu eff: 10 mg minimum
- Software control of data acquisition and analysis
- Time Correlation Analyser
- Matrix interrogation technique

General
The mobile neutron assay SANDRA is designed for the non-destructive characterisation of transuranic material in radioactive waste packages by their neutron emission due to spontaneous fission (sf) or $(\alpha,n)$-reactions. The system is integrated in a 19” container for transportation by a lorry with a transportation bed.

System Description
The passive neutron assay SANDRA measures the emitted neutrons by scanning the surface of the container using 36 $^3$He-counting tubes, all embedded in 7 polyethylene benches. Six of them set-up a hexagonal array surrounding the waste package. Each is equipped with 5 vertical counting tubes of 1.0 m active length, except one bench equipped with 6 horizontal counting tubes of 0.45 m active length. The remaining detector bench is placed on the top of the waste package containing 5 counting tubes of 1.0 m active length.

Principle of Operation
In a typical inspection measurement a sequence of 6 independent measurements is performed with a rotation of 60° in between, therefore scanning the complete surface of the waste package with the horizontal and vertical detectors. Then a two-dimensional surface distribution of the count-rates is determined by combining the results of the measuring sequence. Matrix interrogation measurements using a $^{243/244}$Cm-source with a neutron emission rate of $8\times10^5$ n/s give information on the matrix properties by performing a number of subsequent transmission measurements at different height position covering the complete height of the waste package. During the measurement the waste package can be rotated by 360° to cancel out angular inhomogeneities of the matrix. The count-rate distribution and the information of matrix properties are then merged to determine the 240Pu eff mass using appropriate models. The results of the Time Correlation Analyser (TCA) allows to distinguish between neutrons created by spontaneous fission and by $(\alpha,n)$-reactions.

Specifications

Container
- Separate loading area, measuring chamber and control room
- Outer dimensions: 6.0 m x 2.5 m x 2.85 m (L x W x H)
- Total weight: 15000 kg maximum
- Loading of waste package: Top loading by crane (hatchway) or side loading by fork lift at the rear door.
Mechanical transfer of waste packages from the loading position to the measuring position and back by a carriage
- Transportation: Lorry with transportation bed
- Power requirements: 3 x 230 V/50 Hz

**Measuring Chamber**
- Outer dimensions: 2.0 m x 2.0 m x 2.4 m (L x W x H)
- Inner dimensions: 1.6 m x 1.6 m x 1.7 m (L x W x H)
- Walls: 0.2 m polyethylene at each side including top, bottom and doors, supported by steel frames
- Turntable: 2000 kg maximum load
- Size of waste packages up to 400 l drums

**Detector System**
- 25 vertical $^3$He-counting tubes (1.0 m length, 2.5 cm diameter, 4 bar pressure) embedded in 5 polyethylene (PE) moderator blocks of 1.0 m height, 0.6 m length and 0.1 m width. Thickness of PE-layer towards measuring object: 2.5 cm
- 1 PE bench of identical outer dimensions equipped with 6 horizontal $^3$He-counting tubes (0.45 m length, 2.5 cm diameter, 4 bar pressure)
- 1 PE bench on the top of the waste package equipped with 5 $^3$He-counting tubes (1.0 m length, 2.5 cm diameter, 4 bar pressure)

**Data Acquisition and Signal Processing**
- Amplifier/discriminator: 36 independent channels with preamplifiers (0.5 µs shaping time) and fast pulse discriminators
- Logical OR and analogue sum of the amplifier signals at positive or negative polarity
- Pulse counting: 4 software controlled plug-in modules for 40 channels (CIO-CTR10, Plug-In)
- Measurement time: 0.1 s to 100000 s per interval, number of cycles arbitrary
- Controller: Time control, data acquisition, on-line indication of current measurement, mechanical movements and data analysis by a PC 486
- Background: Less than 0.1 cps/counter (depending on environment)
- Gross counting efficiency: 3 % to 15 % concerning 200 l drums (depends on matrix properties)
- Detection limit: 10 mg $^{240}$Pu equiv at minimum (1000 s time interval)

**Hardware**
- Control of mechanics, data acquisition and data evaluation: PC 486/66
- Control of TCA: PC 486/66

**Software**
- Operating system: Windows 95
- Control, data acquisition and data evaluation: NESDAQ 1.0 (RCM)

**Additional Equipment**
- Matrix interrogation unit: Source $^{243/244}$Cm, $8E10^4$ n/s, lifting range: from 0.0 m up to 1.0 m height
- Time Correlation Analyser (TCA): Model 1001 Neutron
SMNP (ENEA)
Sistema di Misura Neutronica Passiva

Address

ENEA-RAD-LAB
C.R. Casaccia
I-00060 S. Maria di Galeria (Rome)
Italy
Tel.: ++39-06 3048 6586
Fax: ++39-06 3048 6590

Features

- Transportable system, fixed geometry
- Can accommodate drums up to 400 l, 1000 kg
- 64 $^3$He-counting tubes
- Typical detection efficiency: 20 %
- Detection limit for $^{240}$Pu$_{eff}$: 10 mg minimum
- Software controlled data acquisition and analysis
- Neutron Multiplicity Counting (JRC-Ispra)
- Neutron Coincidence Counting (LANL)

General

The SMNP (Sistema di Misura Neutronica Passiva) was designed for the assay of radioactive waste drums containing α-contaminated material. The instrument based on an original JRC-Ispra design measures the neutron emission from spontaneous fission and from $(\alpha,n)$-reaction.

System Description

The detection head is constituted by one vertical section decagon shaped with 4 detectors for 10 sectors and two horizontal sections (top and bottom of the sample cavity) with 4 detector for 3 sectors each. An eight input channel digital mixer receives the analogue signals from the nuclear electronics, converts them into TTL standard signals which are then fed to the Time Correlation Analyser (TCA), Shift Register (SR) and Time Interval Analyser (TIA) modules allowing the simultaneous operation of the three systems of analyses. The loading of the waste package is carried out through two mobile side walls (doors) of the decagon by a crane manually operated (hatch-way).

Principle of Operation

The measurement is performed with the waste package suspended in the middle of the cavity without rotating the drum. The simultaneous operation of the analyses system allows measurement of a waste package by the three different techniques implemented. In a typical inspection measurement the sequence is:

- Single measurement of ten minutes to estimate the neutron count-rate.
- Series of “long-time” measurements (typ. 6 measurements).
- Series of “short-time” measurements (typ. 15).

For each measurement the results of TCA, SR and the pulse train collected by TIA are stored for subsequent analysis by software.

Specifications

Capacities

Size:
- Height: 1100 mm
- Diameter: 700 mm
- Weight: 1000 kg (max.)

Measuring Chamber

Outer dimensions:
- Length: 1463 mm
- Width: 1540 mm
- Height: 1890 mm

Inner dimensions:
- Diameter: 745 mm
- Height: 1170 mm

Background shielding

- Walls: 220 mm polyethylene, 1 mm outer stainless
steel liner and 1 mm inner cadmium liner at each side including top, bottom and doors.

**Detector system**

- 40 vertically mounted \(^3\)He-Ar counters (5 bar pressure), 1000 mm active length, 25.4 mm diameter, embedded in 10 polyethylene moderator blocks of 1040 mm height, 244 mm length and 102 mm width.
- 1.0 mm cadmium liner.
- Thickness of PE-layer towards measuring object 100 mm.
- 2 polyethylene benches of identical mechanical dimensions with 24 horizontally mounted \(^3\)He-Ar counters (4+1 bar pressure), 1000 mm length, 25.4 mm diameter on the top (12) and on the bottom (12) of the measuring chamber.

**Physical**

- Maximum burden: kN.
- Clearance size: 3200 x 2250 x 3055 mm.

**Data Acquisition and Signal Processing**

- 16 quadruple preamplifiers
- 16 linear amplifiers/discriminators grouping 16 detectors
- 4 HV power supplies
- Time Correlation Analyser (TCA, JRC Ispra design)
- Neutron Coincidence Counter (NCC, JSR-11 Jomar, Canberra)
- Time Intervall Analyser card, PC-AT bus compatible (ALL DATA mod GT657); 16 input channels, 2 MB ram, time resolution and measurement rate up to \(1 \times 10^7\) s\(^{-1}\), resolution 20 ns
- Controller: Time control, data acquisition on-line indication and data analysis by PC 286 (TCA), Shift Register JSR-11 (NCC), Pentium 75 (TIA)
- Simultaneous operation of the three counting systems assured by eight input channel digital mixer
- Background: 5cps (depending on environment)
- Detection limit: 10 mg \(^{240}\)Pu\textsubscript{equiv}

**Hardware**

- Control of TCA: PC 386
- Control of TIA: Pentium 75
- NCC operated by Jomar-Canberra electronics JSR-11

**Software**

- Operating system: DOS, Windows 95
- TCA software for data acquisition and analysis (JRC-Ispra)
- TIA software ATEasy 2.0 (GEOTEST) for data acquisition
- Self-developed C++ software implementing NCC, NMC, bi- and three-dimensional Rossi-Alpha algorithms
JRC Drum Monitor (JRC)
Assay of Pu bearing intermediate and low level waste in 220 litre drums

Address

European Commission
Joint Research Centre
Institute for Systems, Informatics and Safety
I-21020 Ispra (VA)
Tel: +39-0332 789802
Fax: +39-0332 785072

Features

- Modular design for easy assembly on site
- Drum volume up to 220 litres and mass up to 1000 kg
- Detection efficiency of 19% with 64 He-3 detector tubes
- Detection limit for Pu-240eff: 1–2 mg (Totals counting)
- Semi-automatic drum loading/unloading
- Absolute Pu mass assay employing the triple neutron correlation analysis
- Mechanical design in compliance with requirements for CE certification

General

The JRC Drum Monitor is a comprehensive measurement system for the determination of plutonium mass in intermediate/low level waste in 220 litre drums. The operation of the instrument is based on passive neutron coincidence/multiplicity counting. The design is the result of 30 years experience in the Joint Research Centre in the field of passive neutron assay. The JRC Drum Monitor has characteristics which are optimised for the Pu mass determination by the so called neutron correlation analysis.

System Description

The neutron detection system employs 64 He-3 tubes grouped in 16 rectangular polyethylene modules each with 4 tubes connected to a high voltage junction box containing the charge sensitive pre-amplifier/amplifier circuit and connections for high voltage, low voltage, and signal cables. The detector modules are fixed inside an outer shield of polyethylene of 220 mm thickness and covered in stainless steel. The internal and external module surfaces are covered in cadmium. The design is based on a modular concept to facilitate easy assembly and flexibility in operation mode. For example the inner cadmium can be removed to increase the detection probability to achieve very low level detection with total neutron counting, the moderator thickness can be varied for special applications, a lead shielding may be added between the modules and the drum for highly gamma active waste. The current drum loading system consists of a manually operated crane and automatically operated doors. This system is easily modified into a semi-automatic drum loading/unloading operated via the host computer. The commercial version of the JRC Drum Monitor employs a conveyer belt instead of the crane for the drum manipulations.

Principle of Operation

Spontaneous fission neutrons emitted from the Pu bearing drum are detected in the detector modules. The signal pulse train, representing the time of detection of neutrons, is analysed with a signal frequency analyser. The frequency analyser currently used is the ANTECH 1000 Series multiplicity counter. The analysis of the frequency histograms is done according to either the pair correlation method or the triple correlation method. In the pair correlation method the measured Reals are used with a pre-determined calibration curve to
determine the Pu-240 eff mass and hence the total Pu mass. For a wide range of Pu containing materials, however, the neutron multiplication may be considered unitary and the triple correlation method may be applied for the absolute determination of the Pu mass. With this procedure the Pu mass is determined without the use of a calibration function and the matrix characteristics are determined from the measured detection efficiency.

**Specifications**

**Capacity**
- 220 litre (55 gallon) drums (Max diameter 700mm, max height 1100mm) 1000 kg weight

**Measuring Chamber**
- Diameter: 749 mm
- Height: 1115 mm

**Background Shielding**
- 220 mm of polyethylene, 1 mm of cadmium

**Detector System**
- 64 3-He detectors (active length 1000 mm)
- 64 pre-amplifiers/amplifiers
- Operating voltage 950 V
- Detector efficiency 20 %
- Die-away time 68 µs

**Physical**
- External dimensions: 3200 x 1760 x 2150 mm (H x W x L)

**Hardware**
- Sealed air-conditioned cabinet containing:
  - Electronics for amplifier diagnostics and regulation,
  - ANTECH 1000 Series multiplicity counter,
  - Host computer with Windows NT and data storage,
  - Un-interruptible Power Supply, printer.

**Software**
- Windows NT based software controls data acquisition and analysis algorithms. Option for computer controlled automated measurement cycle.
Hexagon Passive Neutron Counter (SCK)

Hexagon Passive Neutron Counter

Address

SCK•CEN
Boeretang 200
B-2400 Mol
Belgium
Tel.: ++32-14 33 22 63
Fax: ++32-14 32 15 29

Features

- 60 \(^3\)He detectors
- 20 detector benches of 3 detectors
- 16 individual counting channels
- Cadmium lined sample chamber
- Matrix interrogation with external source
- Software control of data acquisition and analysis
- Neutron Counting with Time Interval analyser
- Computed Neutron Coincidence Counting (CNCC)
- Multiplicity Counting

General

The passive neutron assay system is built with 20 detector modules which are fixed to a modular frame. The frame is currently dimensioned to form a detector cavity for 220 l waste drums. The detector cavity has 12 detectors on top and 12 detectors at the bottom, the remaining 36 detectors are positioned vertically in a hexagonal configuration. The frame contains 2 hinged doors through which the drum is entered in the system. The neutron counter is installed in a paraffin castle for background suppression. The drum is manually entered in the system via two rails.

Principle of Operation

The \(^3\)He detectors detect neutrons emitted by the waste package. The neutron arrival time of each detected neutron is measured with a Time Interval Analyser board with a resolution of 20 ns. The arrival times are continuously processed by software modules which compute the neutron coincidence information via Rossi-Alpha spectra. No pulse pile-up exists between pulses in different channels.

System Description

The detector assembly contains 60 \(^3\)He detector tubes of 1 m active length. The detector tubes are arranged in 20 equal detector blocks made of high density polyethylene. The detector blocks are fixed on a modular frame in a 4\(\pi\) detection geometry. One side of the detector blocks is cadmium lined. The 4 detector blocks of respectively top and bottom of the cavity are connected 2 by 2 to an OR-gate to constitute 4 channels. In total 16 individual channels are available for neutron emission rate monitoring.

Data acquisition is made by a Time Interval Analyser (TIA) board plugged in to a PC. Software is used to implement coincidence and multiplicity counting. The TIA is applicable far waste assay with moderate neutron emission.
used to determine the activity distribution in the drum from which correction factors for the source distribution can be computed.

**Specifications**

**Cavity & Detectors**

- $4\pi$ detection configuration
- 60 $^3$He detectors, 4 bar, 1 bar Argon, 1.0 m length, 2.5 cm diameter
- 20 identical detector benches: 1.0 m length, 0.2 m width, 0.1 m depth, 1 mm cadmium lining, 2.5 cm thick PE moderator, 5 cm thick PE reflector
- Max. detection efficiency 12% (point source in centre of cavity)
- 20 Amptek preamplifiers/discriminators (1 amplifier per 3 detectors)
- System dimensions (outer): 1.0 m length, 1.0 m width, 1.5 m height (220 l drum configuration)
- Sample loading via two roller rails and 2 hinged doors of the cavity
- Max. load: 1000 kg

**Background shielding**

- Paraffin castle with 40 cm thick walls and 2 sliding doors in PE houses the neutron counter
- An active background rejection filter is used in the multiplicity counting mode to reduce high multiplicity events due to spallation neutrons caused by cosmic rays
- Background levels: Singles: 1.85 c/s Doubles 0.052 c/s Triples: .007 c/s

**Electronics**

- Amplifiers: Amptek 111A
  16 channel TIA board

**Data Acquisition and Signal Processing**

- 16 channel TIA board (Geotest)
- 20 ns Pulse to Pulse resolution
- 10 M pulses/s data acquisition
- 20 k pulses/s on-line data processing
- Evaluation and acquisition: Pentium 200 MHz

**Hardware**

- Control of mechanics, data acquisition and data evaluation: PC Pentium (200 MHz)

**Software**

- Control and acquisition: SCK•CEN software based on LabView interfacing with TIA board

**Additional Equipment**

- Matrix interrogation unit
# List of Contact Persons

<table>
<thead>
<tr>
<th>Contact Person</th>
<th>Institute</th>
<th>Tel./Fax/e-mail</th>
</tr>
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<tbody>
<tr>
<td>BRUGGEMAN, Michel</td>
<td>SCK•CEN</td>
<td>Tel.: ++32-(0) 14 33 22 63</td>
</tr>
<tr>
<td></td>
<td>Boeretang 200</td>
<td>Fax: ++32-(0) 14 32 15 29</td>
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<tr>
<td></td>
<td>B-2400 Mol</td>
<td>e-mail: <a href="mailto:mbruggem@sckcen.be">mbruggem@sckcen.be</a></td>
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<td>BELGIUM</td>
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<tr>
<td>BÜCHERL, Thomas</td>
<td>Institut für Radiochemie</td>
<td>Tel.: ++49-(0)89-289-1 43 28</td>
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<tr>
<td></td>
<td>Technische Universität München</td>
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</tr>
<tr>
<td></td>
<td>Walther-Meissner-Str. 3</td>
<td>e-mail: <a href="mailto:Thomas.buecherl@ch.tum.de">Thomas.buecherl@ch.tum.de</a></td>
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<tr>
<td>DODARO, Alessandro</td>
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<tr>
<td></td>
<td>CR CASACCIA</td>
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<td></td>
<td>Via Anguillarese, 301</td>
<td>e-mail: <a href="mailto:alessandro.dodaro@casaccia.enea.it">alessandro.dodaro@casaccia.enea.it</a></td>
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<tr>
<td></td>
<td>I-00060 S. Maria di Galeria (Rome)</td>
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<td>ITALY</td>
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<tr>
<td>PEDERSEN, Bent</td>
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<td></td>
<td>Institute for Systems, Informatics and Safety</td>
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<td>I-21020 Ispra (VA)</td>
<td>e-mail: <a href="mailto:bent.pedersen@jrc.it">bent.pedersen@jrc.it</a></td>
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<tr>
<td>VICINI, Carlo</td>
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