The 10th Annual ESARDA Meeting was held in the Nuclear Research Centre Karlsruhe from 3-5 May 1988. It was the second internal meeting where members of the Working Groups, Steering Committee and Executive Board were supposed to meet in order to enhance cooperation among ESARDA Groups, to review current activities and to have a look at future trends.

While the first meeting of this kind in Copenhagen 1986 was mainly devoted to the present day status of safeguards techniques, the Karlsruhe meeting was to a large extent devoted to future aspects. For scientific preparation of the meeting on request of the Steering Committee the Coordinators prepared an “Analysis of the Nuclear Fuel Cycle in EC-Countries up to the Year 2000”. This study was distributed to all participants about two months before the meeting in order to provide the possibility to the Working Groups to digest the study and to have preparatory communications.

The meeting opened with a plenary session. After opening by the Chairman and welcome address by the German host the results of the study obtained so far were presented. The motivation to perform such an analysis was the fact that due to present day projections a further increase of nuclear electric capacities is to be expected for the next decade. This will include implementation of advanced techniques in an industrial scale such as recycling and remote handling of nuclear materials. It is to be expected that both aspects will have some impact on safeguards from a quantitative and qualitative point of view.

Regarding the quantitative aspect a general overview on the amounts of nuclear materials circulating through the "European Nuclear Fuel Cycle" up to the year 2000 was given. However it should be noted at this point that a closed European nuclear fuel cycle does not really exist, as some EC-Countries are offering nuclear services also to countries outside EC. This has to be taken into account in particular when capacities or nuclear material quantities are balanced.

The installed capacity in power reactors will increase by some 80% up to 127 GW. Depending on the availability of reprocess-
In the afternoon of the first day and in the morning of the second day the individual Working Groups met in order to prepare a report on their activities of the past two years and to formulate some first reactions on the fuel cycle study.

In the afternoon of the second day each Working Group Convener gave a report to the Plenary Session. Regarding the past and present activities it can be stated that most of the Working Groups followed the line as agreed upon during the Copenhagen meeting, that there was a fruitful exchange of information among the WG-members and that there is a strong interest in a future active life of the Working Groups.

Some first conclusions on future aspects raised in the “Analysis of the Nuclear Fuel Cycle in EC-Countries up to the Year 2000” were presented as well, which gave occasion to interesting exchange of ideas and interventions from the audience. Further analysis will be necessary in order to formulate conclusions to be presented to the Steering Committee for approval. The following remarks have to be read in this context and are to be considered as preliminary.

**Working Group on Destructive Analysis (DA)**

The group does not see the need for the development of substantially new DA measurement methods and will continue its present activities such as:

- regular interlaboratory measurement evaluation programmes (REIMEP)
- updating of target values for measurement and sampling uncertainties
- evaluation of authentication procedures for inspection sampling
- development of advanced techniques and performance tests
- support to other groups.

However this does not exclude that the future nuclear fuel cycle evolution generates some new aspects which have to be taken care of. For example the increasing amount of nuclear materials and consequently increasing if not unrealistic efforts necessary to access nuclear materials inventories have been mentioned. In a preliminary analysis the Working Group has identified the following generic subjects to be treated:

- the processing of C/S data,
- the integration of C/S systems e.g. the combination of C/S devices to enhance the performance of surveillance,
- the development of design criteria for C/S systems,
- the use of surveillance in more function-specific applications,
- the use of intrusion/penetration monitors versus optical surveillance,
- the way of expressing C/S assurance/performance,
- the authentication of C/S devices.

**Working Group on Containment and Surveillance (C/S)**

In the course of discussion it was emphasized that C/S methods will have to play an increased role in the future for safeguarding nuclear materials. As main reasons for that process automation, larger storage areas and increasing if not unrealistic efforts necessary to access nuclear materials inventories have been mentioned. In a preliminary analysis the Working Group has identified the following generic subjects to be treated:

- the processing of C/S data,
- the integration of C/S systems e.g. the combination of C/S devices to enhance the performance of surveillance,
- the development of design criteria for C/S systems,
- the use of surveillance in more function-specific applications,
- the use of intrusion/penetration monitors versus optical surveillance,
- the way of expressing C/S assurance/performance,
- the authentication of C/S devices.

**Working Group on Non Destructive Analysis (NDA)**

The existing NDA methods will remain applicable in the future and the underlying physical principles are not going to change. Consequently future activities will be focused on performance assessment aspects. Furthermore adaptation of the measurement equipment to changing circumstances might be necessary. This certainly includes improvements in relation to automation, accuracy, reduction in measurement time, accessibility of nuclear material and the application of built-in "intelligence".

Beyond that, some nuclear fuel cycle features which will be subject to change in the future will raise some technical questions which have to be investigated. These are for example the use of Gd in light water reactor fuel, the effect of multiple plutonium cans on the multiplication correction factor, higher thermal output of plutonium cans, etc.

With increasing amounts of nuclear material to be safeguarded it appears to be necessary to consider possibilities of using operator equipment for safeguards purposes. In this context the problem of authentication has to be taken care of.

**Working Group on Low Enriched Uranium Conversion/Fabrication Plants (LEU)**

This group will basically continue its present activities which are concentrated on three main areas:

- intercomparison exercises on the use of weighing scales, potentiometric titration, in-field application of DA measurements;
- investigation of the performances of NDA techniques such as the neutron coincidence collars for the measurement of assemblies and the photo neutron interrogating device (PHONID) developed at the IJRC-Ispra for measurements of input and process materials;
- statistical accountability, essentially based on the practical use of NUMSAS (a sta-
Besides that, expected changes in the design of LEU-fuel such as use of mixed oxides, a larger range of uranium enrichment and use of recycled uranium will require some attention.

Furthermore it is intended to evaluate the applicability of ultrasonic sealing systems to PWR fuel assemblies.

**Working Group on Mixed Oxide Fuel Fabrication Plants (MOX)**

The group has decided to redefine its activities and areas of discussion in view of the new development of MOX fuel. Taking into account the difficulties that were encountered in identifying subjects of common interest that are not industrially sensitive and not related to safeguards approaches, the working group will concentrate its activities on the analysis of safeguards techniques and practices, and exchange views on their applicability to large throughput facilities.

**Working Group on Reprocessing Input Verification (RIV)**

The RIV working group has concentrated its activities on the verification of nuclear materials at the input of reprocessing plants. The following items were identified as a basis for future actions:

- input tank calibration, taking into account the effect of temperature, density, radioactivity; use of weighing techniques;
- sample representativeness and treatment (in cooperation with DA working group) and its relation to transportation;
- study of waste streams in order to determine the quantity of waste as a function of the throughput of a plant;
- use of on-line instrumentation and study of performances of some NDA techniques (e.g. K-edge densitometer);
- isotopic correlation techniques.

The general feeling of the group was that the topics that have been or have to be treated are often plant specific and that problems of a general nature are difficult to define. As the activities remain limited to the input for the time being they will not change very much in future even if the throughput is changing considerably.

**Working Group on Mathematical and Statistical Problems (MAT/STAT)**

The group is intended to supply technical advice to other working groups in the field of error propagation of measurement techniques, material balance evaluation and systems analysis. The working group members have participated in other working groups in order to better formulate the problems in mathematical statistical terms. Regular meetings are intended to start again in order to examine new subjects to be treated, taking profit of the past experience.

**Conclusive Remarks**

In the morning of the third day the Steering Committee, the Coordinators Committee and Working Group Convenors resumed to held a final discussion on the subjects raised during the meeting. The focus was placed on future Working Groups activities in the light of the expected nuclear fuel cycle evolution up to the year 2000. Preliminary conclusions for each Working Group have been presented above. It was agreed upon that further analysis will be necessary in order to come to definite conclusions. As a first general result it can be stated that increasing amounts of nuclear materials and advanced design of nuclear installations will require some further R&D activities in order to maintain the present quality of safeguards techniques at an acceptable cost effectiveness level.

After some concluding remarks by the Chairman, the meeting came to an end.

The social and cultural aspects have also been taken care of during the meeting. In the first evening the participants were invited to a dinner buffet in the Nuclear Research Centre which gave the opportunity to relax from the meetings and to meet colleagues of the ESARDA community.

The second evening was occupied by a conference dinner in the castle of Hambach, situated some 40 km away from Karlsruhe, in the centre of one of the most famous wine areas of Germany. Originally built in the 11th century it was destroyed in a 17th century war after having changed ownership between noble houses and church. At the beginning of the 18th century, the castle was bought by a group of liberal oriented Neustadt citizens. In 1832 the “Hambacher Fest”, one of the earliest events of German democratic movement, was held in the area around the castle. It was restored for the 150th anniversary of this event. ESARDA members and spouses enjoyed the marvelous evening, varied by the sweet rounds of a local band.

As a conclusion, it can be said that ESARDA held an interesting meeting in Karlsruhe, reviewing two years of activities since Copenhagen and having a firm look at the future.
News about Esarda

As we received several requests of information about the ESARDA activity in the organization of meetings in the field of Nuclear Safeguards, we are glad to present here the schedule of the most important events in this domain.

The next year 1989 will see the 20th anniversary of the ESARDA. During these 20 years of activity, ESARDA organized numerous meetings and symposia. The first one was held at the Joint Research Centre of Ispra in 1971 and then an important symposium was held in Rome in 1974. In 1979 the series of Annual Meetings started. We are listing here the dates and the types of these annual meetings:

1) 1st Annual Symposium, Bruxelles, Belgium, 25-27 April 1979.
2) 2nd Annual Symposium, Edinburgh, Scotland, 26-28 March 1980.
3) 3rd Annual Symposium, Karlsruhe, F.R. Germany, 6-8 May 1981.
4) 4th Annual Meeting (open specialist meeting), Petten, Netherlands, 27-29 April 1982.
5) 5th Annual Symposium, Versailles, France, 19-21 April 1983.
7) 7th Annual Symposium, Liège, Belgium, 21-23 May 1985.
8) 8th Annual Meeting (restricted to ESARDA working group members), Copenhagen, Denmark, 13-15 May 1986.
10) 10th Annual Meeting (restricted to ESARDA working group members), Karlsruhe, F.R. Germany, 3-5 May 1988.
11) 11th Annual Symposium, to be held in Luxembourg on 29 May-1st June 1989.

Other important meetings were:
- Symposium on Practical Application of R&D in the Field of Safeguards, Rome, Italy, 7-8 March 1974.
Activities of the ESARDA Working Groups

Destructive Analysis

The ESARDA Working Group on Techniques and Standards for Destructive Analysis (WGDA) held its annual meeting at Kernforschungszentrum Karlsruhe (KfK) on 2-4 May 1988. A photograph of the participants is shown below. Apart from its contribution to the general ESARDA Internal Meeting with the other ESARDA working groups and the Steering Committee, the WGDA also treated some items in a separate business meeting:

- Experience of EURATOM and IAEA Safeguards Authorities with "Target values for uncertainty components in the assay of nuclear material". Observations and conclusions were presented by H. Wagner (EURATOM) and E. Kuhn (IAEA).
- Experience with in-field measurements of U element content by Safeguards Authorities.
- Status of the REIMEP programme (PuO$_2$ - UF$_6$ - UO$_2$ powder - UO$_2$ pellets - Uranyl nitrate - Pu nitrate - Spent fuel - MOX).
Statistical Methods for Verification of Measurement Models

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Abstract

At the Karlsruhe Nuclear Research Centre, a computer program called PROSA, was developed to apply truncated sequential test procedures to a given sequence of material accounting periods. The intention of these tests was to detect timely a possible loss of material for a given time period, in this context also questions have to be answered whether the measurement model assumed for quantification of the material is correct. Assuming the data are correct and there is a situation of no loss of material, PROSA allows indicating whether the size of the assumed measurement uncertainties is explainable by the given balance data.

Introduction

Problems of materials accountancy appear in many fields of industry and technique. At the Karlsruhe Nuclear Research Centre, questions of accountancy of nuclear material are a subject of research. In the framework of this project a computer program called PROSA was developed to apply truncated sequential tests to a given sequence of material accounting periods. The intention of these test procedures was to detect a possible loss of nuclear material for a given time period.

In this context also questions have to be answered whether the measurement model assumed for quantification of the material is correct. Assuming the data are correct and there is a situation of no loss of material, PROSA allows indicating whether the size of the assumed measurement uncertainties is explainable by the given balance data. A significant result might indicate too optimistic assumptions of the measurement model.

In this paper first of all the principle of the reference-time period (total balance) and physical inventory is explained. For that reason one switches over to the concept of sequential balancing (Near-real-time accountancy, NRTA). In order to follow that idea, the reference-time period \((t_0, t_N)\) is subdivided into \(N\) balance periods.

With the definitions

\[ l_i : \text{physical inventory at time } t_i \]
\[ T_i : \text{net transfer during } (t_{i-1}, t_i) \]
\[ i = 1, \ldots, N \]

and

\[ MUF_i := l_{i-1} + T_i - l_i \]

we obtain a sequence of MUF values \((MUF_1, \ldots, MUF_N)\). At the end of the \(i\)-th balance period, statements can be made based on all balance results \(MUF(j), j \leq i\), whether an eventual loss or not exists. Thus, trends can be recognized at an early stage and losses may be detected timely related to their occurrence \((/2)\).

Multiple Balance Model

Let us assume a discrete number of balance periods \(k = 1, \ldots, N\) for a well defined class of material. For each period \(k\) we calculate the difference between book and physical inventory

\[ MUF(k) = (l(k-1) + T(k)) - l(k) \]

The concept of multiple balances is primarily used for detection of possible material losses. One application is the international safeguards in nuclear facilities. The detection has to be timely and with sufficiently high probability. The true MUF values are zero in the ideal situation of no losses and no measurement errors. In actual practice, however, nonzero MUF values may occur for a

<table>
<thead>
<tr>
<th>Material Balance</th>
<th>Scheme</th>
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<th>Decision is based on</th>
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</thead>
<tbody>
<tr>
<td>conventional</td>
<td>( t_0 \rightarrow t_N )</td>
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<td>only 1 balance (total balance)</td>
</tr>
<tr>
<td>sequential (NRTA)</td>
<td>( t_0 \rightarrow t_i \rightarrow t_N )</td>
<td>at the end of each balance period ( t_i )</td>
<td>all balances up to the associated point of time</td>
</tr>
</tbody>
</table>

The Material Balance Concept

Let us consider a well-defined box \(/1\) that contains at a given time \(t_0\) some material into which material enters and from which material leaves during a given interval of time \((t_0, t_N)\). This box, which is also called material balance area, may represent, for example an industrial material processing plant or the air above a given land area that contains some pollutants. The material contained in the material balance area at time \(t_0\) is called the physical inventory \(l_0\). The algebraic sum of the amounts of material that enter or leave the material balance area in the interval of time \((t_0, t_N)\) — in which the case of an industrial plant are called receipts and shipments — is called the net transfer \(T\). The physical inventory at \(t_0\) plus the net transfer in \((t_0, t_N)\) gives the book inventory at \(t_N\), i.e. the amount of material that should be contained in the balance area at time \(t_N\):

\[ B := l_0 + T \]

The amount of material actually contained in the material balance area at time \(t_N\) is called physical inventory \(l_N\).

If all material contained in, and passing through, the material balance area in the interval of time \((t_0, t_N)\) is exactly accounted for, and if no material has disappeared or has been diverted, then the difference between book inventory \(B\) at time \(t_0\) and the physical inventory \(l_N\) must be zero. This difference is called MUF (Material Unaccounted For):

\[ MUF := l_0 + T - l_N \]

One application of materials accounting is to detect an unauthorized loss timely. However, the disposition of the material-balance concept as usual gives no possibility to detect an occurred loss soon, because the decision can be made even at the end of the reference time. For that reason one

| Table I - Material balance as usual compared to sequential balancing |
|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
| Material balance            | Scheme                      | Decision is possible        | Decision is based on         |
| conventional                | \( t_0 \rightarrow t_N \)   | only at the end of the reference time | only 1 balance (total balance) |
| sequential (NRTA)           | \( t_0 \rightarrow t_i \rightarrow t_N \) | at the end of each balance period \( t_i \) | all balances up to the associated point of time |
number of reasons, e.g. (a) measurement uncertainties and (b) loss of material. Measurement uncertainties will be included into our model by using the concept of random variables in determining the materials balances.

We assume that \( I(k) \) and \( T(k) \) are random variables that can be written as

\[
I(k) = E(I(k)) + ZI(k) + SI(k), \quad k = 0, ..., N
\]

with

\[
E(I(k)) : \text{true value of the inventory}
\]

\[
ZI(k) : \text{random error of the measurement}
\]

\[
SI(k) : \text{systematic error of the measurement}
\]

\[
T(k) = E(T(k)) + ZT(k) + ST(k), \quad k = 1, ..., N.
\]

A further assumption is that all measurement errors are distributed normally with mean zero and with known variances and are stochastically independent.

The variance for period \( k \) can be calculated as

\[
\text{var}(I(k)) = \text{var}(ZI(k)) + \text{var}(SI(k)) \quad \text{and analogously
\]

\[
\text{var}(T(k)) = \text{var}(ZT(k)) + \text{var}(ST(k)).
\]

For two periods \( i \) and \( j \) we define the covariance of \( MUF(i) \) and \( MUF(j) \) as

\[
\sigma_{ij} = \text{cov}(MUF(i),MUF(j)).
\]

The variance and covariance calculations may be summarized into the variance-covariance matrix \( \Sigma \) also called dispersion matrix of the sequence \( MUF(1), MUF(2), ..., MUF(N) \):

\[
\Sigma = \\
\begin{bmatrix}
\sigma_{11} & \cdots & \sigma_{1N} \\
\vdots & \ddots & \vdots \\
\sigma_{N1} & \cdots & \sigma_{NN}
\end{bmatrix}
\]

The matrix \( \Sigma \) is the condensed form of the measurement model of the facility considered. It is an essential part for the statistical analysis of the MUF sequence. Given a sequence of nonzero MUF values we have to decide whether the reason for nonzero values is due to measurement errors or loss. In our case we use the theory of mathematical statistical hypotheses testing to decide at the hand of a given sequence of MUF values whether the situation of no loss of material is given.

Loss of material may occur in a variety of pattern and we have to take into account that one has no knowledge of the actual loss situation.

We assume two hypotheses for the mean values of the random variables \( MUF(1), ..., MUF(N) \). If there is no loss of material all materials balances have mean zero. This situation is described by the null hypothesis:

\[
H_0: E(MUF(k)) = 0 \quad \text{for all periods } k = 1, ..., N.
\]

A loss of material can take place in one or more balance periods. Taking this into account, we formulate the alternative hypothesis:

\[
H_1: E(MUF(k)) = M(k) \quad \text{and } M = \Sigma M(k) > 0.
\]

Hypothesis \( H_1 \) means that we have a loss of material in at least one balance period \( k \).

The problem now is to find (sequential) test procedures which enable a decision between \( H_0 \) and \( H_1 \). A further problem is to find test procedures with a given probability of type I error \( \alpha \) (false alarm probability) and with a small probability of type II error (decision for \( H_0 \) if \( H_1 \) is true, i.e. we have a loss and we do not detect it). An even further problem is to find test procedures which indicate a loss almost immediately after it has happened.

**Computer Program PROSA**

In the Karlsruhe Nuclear Research Centre (KfK) a computer program called PROSA (Program for Statistical Analysis of Near-Real-Time Accountancy Data) is developed as a tool to apply truncated sequential statistical tests to a sequence of materials balance results the origin of which is a model facility or an existing plant. PROSA is a decision tool to determine on the basis of statistical considerations if a given sequence of materials balance periods a loss of material might have happened or not. The evaluation of the materials balance data is based on statistical test procedures.

One essential part for designing statistical tests for materials accounting data is their expected performance in detecting losses of material. Performance measures include the concepts of loss-detection probability and loss-detection time. The performance of a special test has to be studied under a variety of loss patterns, which have to be selected according to reasonable assumptions.

In the newest version of PROSA, the three statistical tests:

- CUMUF TEST
- GEMUF TEST
- PAGES TEST

are selected /4, 5, 6/.

These three test procedures are the result of several years of research and at the moment are supposed to be the most promising ones with respect to the detection probability for losses of material and to the timeliness of detection of such losses. The evaluation of a given data set can be performed with a chosen false alarm probability \( \alpha \). This enables some sensitivity studies for given data sets.

The measurement model is the basis for the statistical tests applied to a given sequence of material balance results.

**NRTA Test Procedures**

Sequential test procedures are used to evaluate a given sequence \( MUF(1), ..., MUF(N) \) of materials balance data. The sequential test procedures in PROSA evaluate a given sequence of MUF values and give a decision between the two hypotheses:

\[
H_0: E(MUF(k)) = 0 \quad \text{for all } k = 1, ..., N
\]

\[
H_1: E(MUF(k)) = M(k) \quad \text{and } M = \Sigma M(k) > 0.
\]

The sequential tests in PROSA are truncated versions, that means they give a decision at the end of the N-th balance period or earlier. The tests are evaluated with the same selected false alarm probability \( \alpha \).

In the following, the three tests will be described.

**CUMUF test**

CUMUF is used for the cumulative sum of the material balance results \( MUF(k) \):

\[
\text{CUMUF}(k) = \sum_{i=1}^{k} MUF(i) \quad \text{for all } i = 1, ..., N
\]

The test is performed as follows /4/:

- for \( i = 1, ..., N-1 \):
  - if \( \text{CUMUF}(i) > s(i) \) reject \( H_0 \)
  - if \( \text{CUMUF}(i) \leq s(i) \) no decision and go to the next period
- for \( i = N \):
  - if \( \text{CUMUF}(N) > s(N) \) reject \( H_0 \)
  - if \( \text{CUMUF}(N) \leq s(N) \) reject \( H_1 \).

The test thresholds \( s(1), s(2), ..., s(N) \) are determined by Monte Carlo simulations to fulfill a given false alarm probability \( \alpha \).

**GEMUF test**

Testing the single hypothesis \( H_0 \) against a simple alternative

\[
H_2: E(MUF(k)) = M(k) \quad \text{and } M = \Sigma M(k) > 0.
\]

there exists exactly one best test. To use this test you must know the loss pattern \( M(1), ..., M(N) \). However, there exist various possibilities to distribute a loss over the balance periods. So these tests (for each loss pattern one best test) are not applicable in practice. The idea leading to the GEMUF test is the following: the (in general unknown) loss pattern \( M(1), ..., M(N) \) will be estimated as \( MUF(1), ..., MUF(N) \) for MUF(i) is an unbiased estimation for \( M(i) /5/.

We define:

\[
\Sigma(i) = \text{the first } i \text{ rows and columns of } \Sigma
\]

\[
\text{MUF}_i = (MUF(1), ..., MUF(i))^T \quad \text{and}
\]

\[
ZG(i) = \text{MUF}_i \cdot (\Sigma(i)^{-1}) \cdot (\Sigma(i)^{-1})^T.
\]

The test is performed as follows:

- for \( i = 1, ..., N-1 \):
  - if \( \text{MUF}(i) > ZG(i) \) reject \( H_0 \)
  - if \( \text{MUF}(i) \leq ZG(i) \) no decision and go to the next period
As mentioned earlier the condensed measurement model I is the basis to perform the NRTA tests. Up to now investigations about the capability of NRTA tests were carried out with respect to model plants. This means the variance of the measurement uncertainties were assumed to be well-known. With this knowledge in mind, the dispersion matrix $\Sigma$ can be computed and material balances according to this dispersion matrix

$$M(UF) = (M(1),...,M(N))$$

are added to these balances. Then the result is investigated whether the tests can recognize the loss and give an alarm, i.e. whether their statistics cross the thresholds.

This will be shown in the following example.

**Example 1**

For $N = 20$ balance periods we consider a dispersion matrix $\Sigma_0$ which is the exact picture of the based measurement model. According to $\Sigma_0$ a balance series $M(UF)_0$ is simulated:

$$M(UF)_0 = (M(UF)(1),...,M(UF)(20))$$

(see Fig. 1).

This MUF series represents a set of balances according to the exact measurement model $\Sigma_0$ without any loss.

Next we assume a loss pattern $M_20$:

$M_20 = (M(1),...,M(20))$

with

$$M(1) = ... = M(10) = 0$$

and

$$M(11) = ... = M(20) = \text{const.} > 0$$

(i.e. loss occurs in the eleventh and in the following periods).

We add this loss pattern to the first MUF series to obtain a representative of a MUF series according to a loss:

$$M(UF)_0 + M_20$$

(see Fig. 2).

Figure 3 shows that the NRTA measures are able to recognize the loss pattern (alarm by GEMUF and Pages test).

In practice, however, the variances of the various measurements to determine the material balances are not known, they have to be estimated. From the statistical point of view obtained material balances can be considered as a realisation of a random vector based on the exact, but unknown measurement model $\Sigma_0$. The NRTA measures, however, value these balances according to a dispersion matrix $\Sigma$, which is only an approximation of matrix $\Sigma_0$. If the variances were estimated too...
This means - since we have the situation of GEMUF test gives an alarm (see Figure 5). Fig. 4 - Results of the NRTA tests based in the too optimistic dispersion matrix and on the simulated MUF series without loss. No loss - that the balance series is not consistent with the computed measurement model $\Sigma_2$. The consequence of this alarm is that the measurement model $\Sigma_2$ is too optimistic with respect to the measurement uncertainties assumed.

In which manner can an alarm be interpreted in practice? The question is whether it is caused by a too optimistic measurement model or by a loss. In some cases the CUMUF test can give a decision rule. Because the statistic of the CUMUF test is an unbiased estimate for the total loss it is evident that no loss has occurred if the value of the CUMUF statistic is negative in the case of an alarm. So the alarm is caused by a too optimistic measurement model. This means the measurement model is falsified by the NRTA measures (like in example 3). However, if the CUMUF statistic is positive when an alarm occurs it cannot be decided from the statistical point of view what the reason is for the alarm.

Example 2:

By increasing the variances of the inventory measurements we maintain a new dispersion matrix $\Sigma_1$. The MUF series MUF20(2) of example 1 (with loss) is considered as a realisation of a random vector according to this "worse" matrix $\Sigma_1$ when it is valued by the NRTA measures. Figure 4 shows that consequently the tests no longer recognize the loss pattern. On the other hand, if the variances are estimated too small, too optimistic, we can obtain an alarm without any loss. The reason is that the computed measurement model $\Sigma_2$ only accepts lower fluctuations in the balance data than the true model $\Sigma$. This will be demonstrated in the next example.

Example 3:

Reducing the variances of the inventory measurements, we obtain a further measurement model $\Sigma_2$. Valuing the MUF series MUF20(0) (no loss) with this model the GEMUF test gives an alarm (see Figure 5). This means - since we have the situation of no loss that the balance series is not consistent with the computed measurement model $\Sigma_2$. The consequence of this alarm is that the measurement model $\Sigma_2$ is too optimistic with respect to the measurement uncertainties assumed.

Conclusions

For application in practice, the estimate of the "true" measurement model is of great importance. Too "pessimistic" estimates of the measurement uncertainties deteriorate the sensitivity of the NRTA measures, but too "optimistic" assumptions can cause an alarm even in the case of no loss. On the other hand an alarm can be caused either by losses of material or by too "optimistic" assumptions of the measurement uncertainties. A negative value of the CUMUF statistic when an alarm occurs indicates a falsification of the measurement model. If the CUMUF value is positive then from statistical point of view there is no possibility to identify the reason of an alarm.

References


Fig. 4 - Results of the NRTA tests based on the too pessimistic dispersion matrix and on the simulated MUF series with loss.

Fig. 5 - Results of the NRTA tests based in the too optimistic dispersion matrix and on the simulated MUF series without loss.
Why a theory of randomization?

Since the IAEA’s resources are not expanding in proportion to the growth in the world’s peaceful nuclear fuel cycles, a way of maintaining safeguards effectiveness and deterrence under manpower constraints is needed. Reducing the frequency of inspections at some facilities, while at the same time coping with ever greater safeguards requirements, expanding in proportion to the growth in the safeguards activities, is one way to approach this problem. Performing random inspections at nuclear facilities was suggested some time ago /1/ as a means for the IAEA to cope with ever greater safeguards responsibilities. The idea was discussed in SAGSI as well as by an advisory group on the implementation of Art. 81c of INFCIRC/153, so-called fuel cycle safeguards.

An important question to address is whether it is possible to measure quantitatively the loss (or gain) in effectiveness of IAEA safeguards introduced by randomization. Such a measure would provide a conceptual bridge to the current policy of trying to implement all agreed inspection activities. It would also give the IAEA a basis for judging the degree to which random inspections might profitably be used.

The authors have investigated this problem in detail in a series of papers, /2,3,4,5/, and have developed a theory for quantifying inspection randomization. Although the ideas are straightforward, they do rely quite heavily on some aspects of game theory. The intention of the present article, as its title implies, is to make our results plausible and transparent to the general safeguards community, especially those experts who have neither the time nor the inclination to struggle with rather long mathematical proofs /6/.

A Ruritanian example

Let us suppose that the Agency’s Division of Ruritanian Operations is faced with the task of inspecting all two of the nuclear facilities of Ruritania’s fuel cycle. Both plants require a significant amount of inspection effort, but the Agency has determined that the maximum diversion detection probability that can be achieved with current technology at one plant (call it plant A) is 50% whereas at plant B a detection probability of 100% is attainable. The division is short of manpower and would like to inspect the facilities on a random basis. Can it do this without sacrificing detection capability? Provided the potential diverter /7/ is also aware of the detection probabilities, the answer is yes.

First of all, what is the detection capability if diversion occurs at only one plant and randomization is not implemented, i.e. both plants are always inspected? Clearly it is 50%, since the diverter will never divert from plant B, knowing that if he did so he would be detected for sure.

Now consider the following inspection randomization strategy:

Inspect plant B with a probability of 50%.
Always inspect plant A.

On average, the operations division will now save one half of the manpower normally required for inspection of plant B and the operator of plant B will be spared the nuisance of inspection half of the time. But what is the detection probability? Evidently it is still 50%. For if the diverter chooses to divert from plant A he will be caught with 50% probability due to the nature of the inspection measures applied here. Whereas if he diverts from plant B he will be caught for sure if an inspection takes place, and an inspection will take place with a probability of 50%.

All of this seems no doubt painfully obvious, if not thoroughly trivial. But what happens if the detection probability at plant B is only 90%? Can we still maintain an overall detection probability of 50%? Or, suppose the sum of the inspection probabilities is 1.3 instead of 1.5. What would the detection probability be in that case? The answers to questions of this kind can be found in refs. /2-5/ where we generalize to an arbitrary number of facilities, and where we also include manpower restrictions and allow for the possibility of false alarms. But in order to understand how the more general results are obtained, it is sufficient to stay with our simple example.

So, having stated the obvious, let us now proceed to prove it.

A (very) little theory

We’ll call the detection probabilities for the two plants $P_A$ and $P_B$ whereby $P_A \leq P_B$ and, of course, $0 \leq P_A(B) \leq 1$. The probabilities of inspection we define to be $l_A$ and $l_B$ with

$$l_A + l_B = 1 \leq 2. \quad (1)$$

$l'$ is the parameter which defines the degree of randomization. If $l = 2$ there is no randomization, while if $l = 0$ there is no inspection at all (which would be carrying randomization a bit too far!).

Similarly, the diversion probabilities are $D_A$ and $D_B$ with

$$D_A + D_B = 1. \quad (2)$$

These two probabilities must sum to unity since we assume that diversion will take place with certainty (no affront to Ruritanian intended). Again, $0 \leq l_A(B) \leq 1$ and $0 \leq D_A(B) \leq 1$.

It is now easy to see that the overall detection probabilities is just

$P(l_A,D_A) = l_A D_A P_A + l_B D_B P_B \quad (3a)$

or, equivalently,

$P(l_A,D_A) = l_A D_A P_A + (1 - l_A)(1 - D_A)P_B \quad (3b)$

Let us call $l_A$ the optimal strategy from the inspector’s point of view, in ignorance of the diverter’s intentions, and $D_A$ the optimal strategy for the diverter, similarly ignorant of the inspector’s intentions. These two optimal choices, if we could find them, could be put into equation (3b) to give us the guaranteed detection probability

$$P^* = P(l_A(D_A)).$$

But what precisely do we mean by an optimal strategy? Simply this: if the inspector were to inspect facilities A or B with optimal strategies $l_A$ and $l_B = 1 - l_A$, respectively, then no matter what the diverter does, he cannot push the detection probability below $P^*$. Conversely, if the diverter were to divert from facilities A or B with optimal probabilities $D_A$ and $D_B = 1 - D_A$, respectively, the no matter what the inspector does he cannot push the detection probability beyond $P^*$. These two statements can be summarized concisely in the two inequalities

$$P(l_A,D_A) \leq P(l_A(D_A) \leq P(l_A,D_A) \quad (4)$$

which are called the saddle point conditions.
Now we can write down the solution to the game, that is the values of $l_A$ and $D_A$ that satisfy the saddle point conditions. It turns out that the solution is dependent upon the sum $I$ of inspection probabilities.

For $0 \leq I \leq 1 + (P_B/P_A)$ the solution is

$$l_A^* = IP_B/(P_A + P_B), \quad D_A^* = P_B/(P_A + P_B) \quad (5a)$$

giving a guaranteed detection probability from equation (3b) of

$$P^* = IP_A P_B/(P_A + P_B). \quad (5b)$$

For $1 + (P_A/P_B) \leq I \leq 2$ the solution is

$$l_A^* = 1, \quad D_A^* = 1 \quad (6a)$$

giving a guaranteed detection probability of

$$P^* = P_A. \quad (6b)$$

These results are very easy to prove. Simply note that the optimal probabilities are between 0 and 1, as they must be, and then check that the saddle point conditions are satisfied. Here is an example:

Consider the solution for $0 \leq I \leq 1 + (P_B/P_A)$ and the left inequality of (4). We get, upon substituting for $D_A^*$

$$l_A^*(P_B/(P_A + P_B))P_A + (1-I)(P_B/(P_A + P_B))P_B \leq (P_A P_B/(P_A + P_B))$$

which is equivalent to $I \leq 1$.

A statement that few would argue with.

We see, then, that the largest guaranteed detection probability attainable is $P^* = P_A$ and that it is attained when $l_A^* = 1$ and $I = 1 + (P_A/P_B)$ or $l_A^* = (P_A/P_B)$ Any inspection effort which leads to $I > 1 + (P_A/P_B)$ is wasted.

**Ruritania revisited**

In our simple example we assumed that $P_A = 0.5$ and $P_B = 1.0$. Thus, according to (5)

$$P^* = 0.5, \quad l_A^* = 1.0, \quad l_B^* = 0.5.$$

This was our intuitively obvious result.

We then asked about the situation in which $P_B = 0.9$. The limit for $I$ which still yields $P^* = P_A$ is $1 + (P_A/P_B) = 1.556$. That means that plant B must be inspected with probability $l_B^* = 0.556$ rather than 0.5.

Finally, if we have $P_B = 0.9$ and $l_A + l_B = 1.3$, then we get according to (6b)

$$P^* = (1.3x0.5x0.9)/(0.5 + 0.9) = 0.42$$

and the optimal inspection strategy

$$l_A^* = (1.3x0.9)/1.4 = 0.84, \quad l_B^* = 1.3 \cdot 0.84 = 0.46.$$

**A fuel cycle approach**

In [4] a scheme for the implementation of random inspections is proposed which we have called RFUV (reduced frequency unannounced verification). On the basis of an assessment of the a priori detection probabilities for the various facilities in a state’s fuel cycle the Agency calculates its optimal strategy for the verification of the plant operators’ scheduled physical inventory taking. The verification is then done on a random basis. As we have seen in our simple example, facilities with high a priori detection probabilities will receive, on the average, less inspection effort, but the overall detection capability as measured across the state’s fuel cycle will remain unchanged. Thus the RFUV model optimizes effectiveness by efficiently channeling limited inspection resources into the most sensitive parts of the fuel cycle.

**References**

/1/ A. PETIT “De la nécessité d’approfondir le consensus international quant aux implications pratiques des concepts de base des garanties internationales”, Proc. 6th ESARDA Symposium, Venice, 1984, p. 41


/6/ André PETIT is one of these, and it is at his suggestion that we have prepared this paper.

/7/ The Ruritanian Minister for Peaceful Co-existence.
Cooperative Support Programme in the Field of R & D in Safeguards between the Commission of the European Communities and the IAEA

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CEC, JRC-Ispra

Introduction

The Cooperative Support Programme in the field of R & D for Safeguards was established in May 1981 between the European Atomic Energy Community and the International Atomic Energy Agency (IAEA).

The main features of the programme have been previously described in a paper presented at the 23rd Annual Meeting of INMM /1/. This paper provides updated information on the programme and its evaluation.

The work related to this programme is carried out in the Joint Research Centre (JRC) of the Commission of the European Community, mainly as part of the nuclear safeguards R & D programme of the Commission. Three establishments of the JRC are concerned with the support programme to the Agency: Geel (Central Bureau for Nuclear Measurements), Ispra and Karlsruhe (Transuranium Institute).

Yearly review meetings between IAEA and CEC representatives have been organized in order to focus on and define the tasks of common interest taking into account the existing expertise and facilities of the JRC and the other existing support programmes to the IAEA. In addition, the project officers of the single tasks maintain frequent contact.

Objective of the Programme

The objective of this Safeguards Cooperative Support Programme, as mentioned in the formal exchange of letters between the two organizations, is to provide technical assistance in fields where expertise is required, in the evaluation of R & D priorities as a function of the requirements of the European fuel cycle, in the harmonization of procedures and techniques of potential use in the safeguards implementation and in the training of inspectors /2/.

The support programme is concerned with four main areas of work:

1. Containment and surveillance
2. Measurement technology
3. Information, data treatment and evaluation
4. Training courses.

The complete list of the tasks active at present is reported in Table I. A short description of the different areas concerned is given below.

<table>
<thead>
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<td><strong>Containment and Surveillance</strong></td>
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**Measurement Technology**

| MT 1.a | Development of a New Generation of NDA Instrumentation |
| MT 2 | Pu Isotopic Ratio Measurements by NDA |
| MT 3 | Development and Demonstration of an Instrument for Bulk Nuclear Material Assay (PHONID Family) |
| MT 7.a | Measurement Uncertainty Estimates in Reprocessing Plant Input |
| MT 8.a | Direct Mass Determination of Fissile Materials by Tracer Technique in Input Accountancy Tanks |
| MT 8.b | Input Methodology Using Metallic Spikes |
| MT 9 | Evaluation of Reprocessing Input Analysis |
| MT 10.a | Preparation and Characterization of Reference Materials |
| MT 10.b | Characterization of Pu PERLA Standards |
| MT 13.b | UF6 Interlaboratory Measurement Evaluation Programme |
| MT 14 | Automatic Analysis and Data Evaluation |
| MT 14.a | Automatic Sample Conditioning by Robots |
| MT 14.b | Field Test for On-Site Sample Conditioning by Robots |
| MT 17 | Performances of Pu Calorimetry for Safeguards |

**Information, Data Treatment and Evaluation**

| NMA 3 | NRTA and Verification Systems for Fabrication Plants |
| NMA 5 | Field Data Processing with Portable Microcomputers |
| NMA 6.a | Development of a Decision Support Module for Statistical Accountancy and Cross Verification of State Declaration and CIR's Data |
| NMA 7 | Design and Implementation of a Knowledge Based System for Transit Matching |

Training Courses

| T 1 | Inspectors Training Course in NDA |
| T 2 | Physical Inventory Verification (PIV) Exercise |

The chief characteristic of the programme is to tackle technical problems of direct interest to international safeguards inspectors and is oriented to the development of practical tools (instruments and evaluation methods) and their testing in field conditions. A great emphasis is given to the problems of harmonization and standardization of the measurement techniques, the preparation of reference materials as well as to the normalization of data acquisition and evaluation. This should substantially contribute to the harmonization of inspection procedures used by EURATOM and IAEA inspectors where these tools are implemented.

A close interaction with the IAEA is taken as a guideline for the whole support programme. The Agency is informed of the results of R & D work quickly so that the inspectorate, as is already the current practice for EURATOM, can make suitable remarks and give valuable suggestions for improvement before the measurement systems or information systems are finalized. As a matter of fact the general idea of the support is that the final result should be the fruit of close cooperation during the development.

In many cases equipment and information systems developed at the JRC are made available to the Agency for testing in field conditions or at the headquarters. In other cases, participation of the IAEA staff is arranged in experiments being performed at JRC facilities (Geel, Ispra, Karlsruhe). In general the IAEA informs the JRC of its findings and suggestions as a basis for further fruitful cooperation with the aim of obtaining improvements for the final developments.

It is worthwhile mentioning that the JRC has a large and very comprehensive programme of support to the EURATOM inspectorate, covering both immediate and medium term requirements in the areas mentioned above.

Several of the tasks developed for the IAEA are also of direct interest to EURATOM.

Description of the Tasks

**Containment and Surveillance**

Six tasks are presently covered by this area ranging from underwater ultrasonic monitoring of seals for containers and spent fuel stacks to the laser surveillance of
storage pools. The various tasks in this field are reported below.

One of the tasks is concerned with the development of ultrasonic seals capable of spending long periods underwater and locking spent fuel stacks (Fig. 1). These seals are basically made of a solid stainless steel body and enclose a uniquely identifiable "finger print" obtained by random cavities and read ultrasonically by means of ad hoc reading tools and instruments. The development of an ultrasonic sealing bolt for closing large transport/storage containers and portable instruments for in situ verification is now in progress. Field tests for the re-identification of underwater bolt seals have been performed. This task has obtained encouraging results on a prototype scale and a larger production of seals is planned /3/.

Fuel assembly sealing systems have been under development at the JRC-Ispra for many years. This task was previously performed in cooperation with the F.R. Germany support programme and is based on the same principle, allowing a BWR fuel assembly to be sealed by locking one of its tie rods with ultrasonic seals. A successful demonstration of the possibility of sealing, uniquely identifying and re-identifying after the fuel assembly has been in the reactor for one year or two years, was made at the Kahl reactor /4/. The present task is oriented to keeping the basic concepts used for the BWR seal and trying to solve the problem of locking the upper and lower end of a PWR fuel assembly by means of ultrasonic seals. This project is being carried out in close cooperation with Sandia National Laboratories (SNL). A formal steering group with IAEA, SNL and Commission representatives has been set up to monitor the progress and give guidelines to this project. The introduction of MOX fuel in LWR gives this project a particular dimension.

A general purpose cable seal called TITUS I has been developed in cooperation with the Commissariat à l’Energie Atomique (CEA, France) and two companies /5/. It also uses ultrasonic technique but it embodies its own low cost transducer and only needs an electrical connection to be read. The TITUS I seals have undergone thermal cycles and proved their reliability and unambiguity of identification even after long periods and thermal shocks. The Agency already has other seals (e.g. COBRA) under test as potential replacements for type E seals, but there is still interest in general purpose seals such as TITUS for some specific cases (e.g. in the case of high radiation field).

Another aspect of the problem of sealing is the identification of items such as containers on fuel pins by means of surface topography. Studies in the field have been carried out at the JRC-Ispra for many years. The first results were presented at the 3rd ESARDA Symposium (Karlsruhe 1981) /6/.

One of the most important aspects of the application of optical surveillance is the film and videotape review (Fig. 2). A task is being defined for the application of image processing techniques by computer vision to detect scene changes independent of illumination variations and small movements of the sensors (vibrations). This development is expected to be a great help to inspectors who are now spending a considerable part of their time in film and video review. Two prototype systems have been developed /7/.

The first one is now being tested on films produced during inspections. A second system based on a new approach concerning the detection of scene modifications (polygon lines crossing) will be delivered soon.

In the area of surveillance a new laser-based system is being developed for application to spent fuel storage pools or dry storage facilities. The feasibility of such a system, called LASSY, was demonstrated...
by the IAEA /8/. The system is based on two beams of laser light which can scan large areas in air or relatively small areas underwater (Fig. 3). When an assembly penetrates the light plane, the system response calculates via computer the position of the disturbance. A two year research contract has been established with the IAEA to develop an engineered prototype which may be used in air or underwater.

**Measurement Technology**

Fourteen tasks have been defined and are actually carried out. In addition several tasks have already been completed in this area. They are related to nondestructive techniques, to destructive assay techniques and reference material preparation, to fissile mass determination by tracer techniques and to the measurement of uncertainty estimates in reprocessing plants.

One of the tasks for nondestructive assay concerns the development of a new generation of NDA instrumentation based on a new instrument called Safeguards Intelligent Assistant. The first prototype is being developed for measurement of Pu by gamma ray spectrometry. Its software will embed a novel approach, whereby an inspection procedure knowledge base will assist the inspector in carrying out his job. This instrument is based on a dedicated data acquisition module linked to a personal computer (MS-DOS).

A second task for nondestructive assay is related to the Pu Isotopic Ratio Measurement with high resolution gamma spectrometry. The task is based on a systematic comparison, to be carried out in the PERLA laboratory, of the different spectrometers available for assessing the effect of the different algorithms and analyzing the results in order to identify optimum approaches in terms of counting chains and spectrum analysis algorithms in typical field conditions. The most significant algorithms have been installed on a central computing system. A large variety of Pu samples with different isotopic composition and different U/Pu ratios has been procured. A general experimental scheme for performing measurement and analysing data is now completed.

Another task is based on the development and application of neutron interrogation and prompt fission counting to bulk neutron material assay by means of the PHONID (Photo Neutron interrogation Device) family. An improved version of PHONID 3 is being developed and an instrument of totally new design (PHONID 4) was built which will be easily transportable for the assay of some typical items (Fig. 4).

As part of the activities of PERLA laboratory it is intended to study the performances of calorimetry (water bath and air) when applied to bulk Pu samples in near field conditions. Fig. 5 shows a water bath calorimeter, developed by the Mound laboratory, which is presently used in PERLA. The characterized Pu PERLA standards, now available at the JRC-Ispra, will be used for this purpose.

For the destructive analysis and preparation of reference materials, several tasks are being carried out. One of them, performed in cooperation with DWK (FRG) in the input method using metallic spines. It is used to assay directly undiluted input samples for U and Pu concentration and improve the accuracy under routine conditions. The metallic spines were prepared and characterized at the JRC-Geel. A measurement campaign is planned in the F.R. Germany.

The work on the UF6 interlaboratory measurement evaluation programme, now part of REIMEP (Regular Interlaboratory Measurement Evaluation Programme) is actually dedicated by the JRC-Geel to several other U or Pu bearing materials such as UO2 (powders and pellets), PuO2, spent fuel, U nitrate, Pu nitrate and MOX. This task is expected to develop considerably in the future.

Two tasks are related to the preparation of reference materials. One is being carried out at the JRC-Ispra and has already provided the IAEA with eight primary reference materials of U and Pu to be used for nuclear material assay. The other task, carried out by the JRC-Ispra in collaboration with IAEA (SAL), CEN/SCK Mol and Alkem, concerns the characterization of Pu PERLA standards. This material is being accurately characterized by destructive analysis. The Pu samples

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*Fig. 3 - View of the laser surveillance system (vertical section and top view)*
have been analyzed by three independent laboratories. MOX and HEU materials were also procured for this task /9/. The standards are now available for NDA calibration.

Three tasks are being carried out by the JRC-Karlsruhe (Transuranium Institute, TUI) in the field of automatic destructive analysis. One is dedicated to the rationalization of the analytical work, in particular in respect to reprocessing plant samples. The experience in operating an automatic laboratory at Karlsruhe is made available to the IAEA. The work is being performed in cooperation with the FRG support programme carried out at KfK. Two new tasks were recently introduced in the use of robots in analytical chemistry (Fig. 7). One concerns the automatic conditioning of samples by robots in a glove box. An automated system, already developed and used at TUI /10/, is needed for the large number of analyses performed by the SAL (Seibersdorf Analytical Lab.) on samples from reprocessing facilities. The benefits of such an automated system include higher throughput, more reproducible processing of samples and lower radiation exposure of the personnel. The installation of such a system in SAL by TUI is planned. The use of robots for on-site sample conditioning is now being studied and field testing is planned in cooperation with the EURATOM Safeguards Directorate.

Three other tasks are related to reprocessing plants. One of them, being developed at the JRC-Ispra, is concerned with the direct determination of fissile materials by tracer techniques in input accountancy tanks. Lutetium and erbium tracers have been used at EUREX and Rotondella reprocessing pilot plants in cold conditions /11/ and it is now expected that this method will be applied in real conditions in the near future and compared with other techniques.

A second task carried out at the JRC-
JRC-Ispra developed a verification simulator (NEWSIM) which was installed on the IAEA mainframe computer. The flow of the nuclear material between different work stations has been modelled. Measurement uncertainties of operators but also for verification by inspectors at each stage are included. In this way a sensitivity analysis may be performed for different plant flow configurations and measurement strategies. After a number of tests carried out with NEWSIM a new generation of plant simulator is now being developed at JRC-Ispra. In particular it deals with the study of NRTA in fuel fabrication plants such as MOX facilities and will be extended later to reprocessing plants.

A second task is concerned with field data processing with portable microcomputers. This development has resulted in the preparation of a software package for the stratification of operator data, the evaluation of MUF and Var MUF and the generation of a sampling plan. The system, implemented on a Macintosh PC, is now being transferred onto an MS-DOS compatible computing system. The software package has been tested to make parametric analysis of the uncertainty components of material balance for MOX fuel fabrication plants with different throughputs and inventories.

Another task is concerned with the development of a decision support module for statistical accountancy and cross verification of state declaration and computerized inspection report (CIR) data. This task is aimed to enhance the analytical capacity of the IAEA data evaluation through the possibility of comparing the operator’s data with the corresponding CIR’s data. A JRC expert has spent some time at the IAEA to analyze the detailed requirements of such a system and to define the functional specifications. A first interactive system was installed at the Data Evaluation section of the IAEA. A further development of the system is envisaged.

A third task being developed at the JRC-Karlsruhe is dedicated to the evaluation of reprocessing input analysis. A software package, including an expert system, has been prepared for the quality control of reprocessing input analysis results. Criteria for screening measurement data are being defined and a file of historical data isotopic correlation techniques and error sources is being established. The software was installed at the IAEA and is now being critically analysed.

Information, Data Treatment and Evaluation

Four tasks are presently active in this field. One tackles the problem of how an NRTA (near real-time accountancy) system, installed by an operator for management purposes, could be efficient for International Safeguards Authorities. For this task the JRC-Ispra concerns the measurement uncertainty estimates in reprocessing plant input. A model of the procedure by which the operator of a plant determines the quantities of U and Pu present in each dissolution and a model of the measurement performances by the inspector were prepared. Uncertainties are established with each step of the procedure. The various uncertainties are then composed and propagated in order to determine the final uncertainties of the quantities of U and Pu. This computerized model called SPRIT has been developed in cooperation with Rome University /12/ and the simulation is being tested for tank calibration with ENEA.

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Training courses

The training of inspectors is mainly envisaged in two areas, i.e. the use of NDA and DA techniques and physical inventory verification (PIN).

The first task aims to provide courses for IAEA inspectors. The content and duration of the courses are to be agreed case by case. Two training courses have been organized with the participation of IAEA and EURATOM inspectors for the use of the SIGMA device and for the in-field use of titrimetry.

The second task concerns the training of inspectors in the verification of physical inventory in HEU fuel fabrication plants. A course has been organized in the PERLA laboratory which was attended by eight IAEA and four EURATOM inspectors /14/. The programme of the course was established by the JRC-Ispra in collaboration with LANL, NUKEM, the EURATOM Safeguards Directorate and in close connection with the US SUPPORT PROGRAMME (ISPQ). The course covered NDA methods for verification, sample size determination and data evaluation of both operator and inspector data (Fig. 9).

Conclusions

The cooperative support programme between the Commission of the European Communities and the IAEA has been existing for more than seven years. Presently 26 tasks are being conducted in the field of a) containment and surveillance (C/S), b) measurement techniques, c) information, data treatment and evaluation methods, and d) training.

Nineteen tasks have been completed in the course of the years and in many cases their results are being used during safeguards implementation by the IAEA directly or in combination with EURATOM inspections.
Near Real Time Materials Accountancy using SITMUF and a Joint Page's Test: Comparison with MUF and CUMUF Tests

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Abstract

The paper reports a theoretical comparison of the performance of a joint Page's test on SITMUF with the MUF and CUMUF tests, and also a joint Page's test on MUF. It explains that, for the CUMUF test, and the joint Page's test on MUF, the significance thresholds cannot be accurately set to give a chosen campaign false alarm probability until the errors associated with the data for the whole campaign are known. The joint Page's test on SITMUF does not suffer from this difficulty, and it is superior to the others as a materials control tool. It gives the highest detection probability for abrupt loss, and is the most robust test to a range of protracted loss scenarios.

The investigations were carried out using data from a model with characteristics similar to those which British Nuclear Fuels expects of its new Thermal Oxide Reprocessing Plant (THORP).

Introduction

Operators and the Inspectorates may be more accustomed to using the traditional MUF and CUMUF tests, and may be reluctant to calculate SITMUF /1/ and apply the joint Page's test /2,3,4/ on account of the increased need for computer processing of data and the apparent difficulty in the interpretation of the results.

MUF and CUMUF tests, and a joint Page's test on MUF, are compared with the joint Page's test on SITMUF. Performance is judged on the basis of sensitivity and timeliness for abrupt loss, and average loss per campaign for protracted loss.

Description of Plant Characteristics

Previous work /3,4/ has chosen a campaign length of 240 days, divided into 40 balance periods of 6 days. The standard deviation of the throughput measurement error per balance period, \( T \), set at 1 kg gives a standard deviation of the campaign throughput measurement error of 6.325 kg. This, and the standard deviation of the inventory measurement error, \( I \), of 2 kg, is consistent with predictions for the THORP materials accountancy and control system /5/. The above values for \( I \) and \( T \) will be used in this study.
data streams were modified, as appropriate, prior to application of the test. The exception to this procedure was made for the study of the joint Page's test on SI'TMUF; here results were derived by calculation, with the accompanying improvement in the quality of results and economy in computing time.

Testing Procedures and False Alarm Probabilities

**MUF Test**

The test statistic, $Z$, is defined by

$$Z_i = \frac{\text{MUF}_i}{\sigma_{\text{MUF}_i}}$$

for $i = 1, \ldots, 40$

An alarm is given if $Z_i \geq z$, the significance threshold.

As explained above, a significance threshold of 1.6449 standard deviations of the campaign MUF gives a 5% FAP for a single MUF test carried out at the campaign end. Suppose the MUF test is applied sequentially to the values MUF, ... MUF$_{40}$ using a significance threshold of 1.6449 standard deviations of the period MUF, then one way of calculating the FAP for the campaign would be to use the following equation:

$$\text{Campaign FAP} = 1 - (1 - 0.05)^{40} = 0.8715 = 87.15\%$$

This is true only if the values MUF, ... MUF$_{40}$ are independent. In practice successive MUF values will be negatively correlated on account of the common inventory determination. A simulation experiment using 10,000 data streams was used to determine the occurrence of campaign false alarms for a significance threshold of 1.6449, for a range of values of $I$. Results are shown in Table I.

### Table I: Number of Campaigns Ending in an Alarm

<table>
<thead>
<tr>
<th>$I$ (kg)</th>
<th>False Alarms</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>8,734</td>
</tr>
<tr>
<td>0.5</td>
<td>8,822</td>
</tr>
<tr>
<td>1.0</td>
<td>8,823</td>
</tr>
<tr>
<td>1.5</td>
<td>8,845</td>
</tr>
<tr>
<td>2.0</td>
<td>8,867</td>
</tr>
<tr>
<td>2.5</td>
<td>8,872</td>
</tr>
<tr>
<td>3.0</td>
<td>8,853</td>
</tr>
<tr>
<td>3.5</td>
<td>8,842</td>
</tr>
<tr>
<td>4.0</td>
<td>8,836</td>
</tr>
<tr>
<td>4.5</td>
<td>8,833</td>
</tr>
<tr>
<td>5.0</td>
<td>8,842</td>
</tr>
<tr>
<td>10.0</td>
<td>8,865</td>
</tr>
</tbody>
</table>

Note that, in the limiting case of no inventory measurement error, 8,734 false alarms are consistent with the value of 87.15% calculated above. However, when inventory measurement error is taken into account, the observed false alarm rates are consistently larger than the value of 87.15% appropriate to uncorrelated MUFs.

Using a similar experiment and a process of iteration, values were found for the significance threshold (in terms of the period MUF standard deviation) corresponding to exactly 500 alarms in the particular 10,000 simulated data streams. Results are shown in Table II.

The values of the significance thresholds in Table II are those which were obtained from one specific set of 10,000 simulated data streams. Another set of data would give
different periods, will depend on four contributing effects:
- the first component behaves like the MUF test and has an enhanced response in the first and last periods;
- the response of the second component improves during the early periods as the expected value of the statistic, \( S_2 \), increases;
- the second component shows a tailing-off in response over the last few periods when the benefit of the "knock-on" effect cannot be realised, and
- some fluctuation in the response profile due to simulation errors.

The overall response is shown in Figure 7.

**Joint Page's Test on SITMUF**

The characteristics of this test have been described elsewhere /2,3,4/. The response to a fixed loss, occurring at different periods, is shown in Figure 8.

**Criteria for Comparison of Tests for Detection of Abrupt Loss**

Criteria have been proposed previously /3,4/. Any testing procedure aimed at detecting abrupt loss should:
- detect abrupt losses quickly;
- have a good response to a loss occurring in any period, and
- have an ultimate response at least as good as conventional accountancy.

The concept of a timeliness period, 30 days here, was used to make sure that response within a stipulated time was considered. Robustness is an important criterion for selection and maximization of the minimum probability of detection for a range of scenarios (in this case the period of the abrupt loss) is regarded as crucial. These minimum values are shown in Table VII.

**Timely Detection of Protracted Loss**

As illustrated in Figure 4, a loss of 20.807 kg would be detected by conventional accountancy with a probability of 95%. However, for the practical purpose of materials control, the probability of ultimate detection of protracted loss has no relevance; what matters is that loss of material should be minimized. One way to evaluate the effectiveness of the materials control system is to calculate the average loss per campaign for a variety of loss scenarios. In each loss scenario, the overall loss is the same (20.807 kg) but a selection of beginning and ending periods for the loss have been examined. The expected (ie average) loss, \( E(L) \), per campaign is calculated using the following equation:

\[
E(L) = \frac{1}{2} \sum_{i=1}^{n} (L_i - (p_i - p_{i-1})) = L_{\text{end}} - p_{\text{end}}(1 - p_{\text{end}})
\]

where \( L \) is the cumulative loss and \( p \) the cumulative detection probability by period \( i \).

The performance of the test with regard to control of materials loss is shown in Tables VIII - XI.

**Criteria for Comparison of Tests for Control of Protracted Loss**

Earlier papers /3,4/ do not make it clear that the testing procedure should respond to a systematic error, bias or protracted loss which lasts for only part of the campaign, and may occur at any time during the campaign. Therefore, amended criteria are proposed.

Any testing procedure aimed at detecting protracted loss should:
- quickly detect losses occurring at a slow rate;
- have a response which is relatively insensitive to the rate, time, and duration of the loss;
When comparing tests, the aim should be to select the test which minimizes the maximum average loss per campaign for a range of scenarios (in this case the starting and ending point of the protracted loss). These maximum values are shown in Table XII.

### Table XII: Comparative Response to Abrupt Loss of 10,403 kg

<table>
<thead>
<tr>
<th>Test</th>
<th>Minimum Number of Campaigns Ending in Alarm</th>
</tr>
</thead>
<tbody>
<tr>
<td>MUF</td>
<td>6,600</td>
</tr>
<tr>
<td>CUMUF</td>
<td>1,560</td>
</tr>
<tr>
<td>Joint Page / MUF</td>
<td>5,055</td>
</tr>
<tr>
<td>Joint Page / SITMUF</td>
<td>7,838</td>
</tr>
</tbody>
</table>

### Table VIII: Average Loss per Campaign (kg)

<table>
<thead>
<tr>
<th></th>
<th>MUF Test (10,000 Simulated Data Streams)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Starting Period</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>31</td>
</tr>
</tbody>
</table>

Concluding Remarks

The CUMUF test and the joint Page's test on MUF both suffer the serious drawback that it not possible to set the relevant test parameters given knowledge only of the expected number of balance periods. For these tests, FAPs and the response to losses will be influenced by the extent to which the plant's behaviour can be accurately predicted.

Furthermore the tests were compared by their power to detect an abrupt loss of 10,403 kg, and their ability to control a protracted loss of 20.807 kg.

The MUF test has a creditable (about 66%) and robust response to abrupt loss but is useless for control of protracted loss (Worst Average Loss 20.09 kg).

Whilst the CUMUF test is traditionally regarded as a test for detection of protracted loss, it performs well for the detection of abrupt loss in the early periods. However, the test is not robust and its response to losses occurring later in the campaign is poor (Lowest Detection Probability 15.65%).

The CUMUF test is very good for the control of protracted losses which begin early in the campaign. Unfortunately, its performance deteriorates dramatically if the loss starts later. The test is not robust and must be considered poor for control of protracted loss (Worst Average Loss 16.24 kg).

The joint Page's test on MUF has a useful but not very robust response to abrupt loss (Lowest Detection Probability 50.55%). In contrast to the CUMUF test, the joint Page's test on MUF is good for the control of protracted losses which begin late in the campaign. Unfortunately, its performance deteriorates if the loss starts early. The test is not robust and must be considered poor for control of protracted loss (Worst Average Loss 17.11 kg).

The joint Page's test on SITMUF has a high and robust response to abrupt loss (Lowest Detection Probability 78.38%). Furthermore, the test is effective for the control of protracted loss and is robust for the range of loss scenarios examined (Worst Average Loss 14.79 kg).
Table IX: Average Loss per Campaign (kg)
CUMUF Test (10,000 Simulated Data Streams)

<table>
<thead>
<tr>
<th>Starting Period</th>
<th>Ending Period</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>40</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8.021</td>
<td>8.881</td>
<td>10.152</td>
<td>11.348</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td></td>
<td>12.463</td>
<td>12.967</td>
<td>13.731</td>
<td></td>
</tr>
<tr>
<td>21</td>
<td></td>
<td></td>
<td>14.874</td>
<td>15.018</td>
<td></td>
</tr>
<tr>
<td>31</td>
<td></td>
<td></td>
<td></td>
<td>16.242</td>
<td></td>
</tr>
</tbody>
</table>

Table X: Average Loss per Campaign (kg)
Joint Page’s Test on MUF (10,000 Simulated Data Streams)

<table>
<thead>
<tr>
<th>Starting Period</th>
<th>Ending Period</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>40</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>17.109</td>
<td>15.999</td>
<td>15.170</td>
<td>14.528</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td></td>
<td>14.570</td>
<td>13.551</td>
<td>12.978</td>
<td></td>
</tr>
<tr>
<td>21</td>
<td></td>
<td></td>
<td>13.365</td>
<td>12.390</td>
<td></td>
</tr>
<tr>
<td>31</td>
<td></td>
<td></td>
<td></td>
<td>12.428</td>
<td></td>
</tr>
</tbody>
</table>

Table XI: Average Loss per Campaign (kg)
Joint Page’s Test on SITMUF (Calculation)

<table>
<thead>
<tr>
<th>Starting Period</th>
<th>Ending Period</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>40</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td></td>
<td>14.682</td>
<td>13.503</td>
<td>12.821</td>
<td></td>
</tr>
<tr>
<td>21</td>
<td></td>
<td></td>
<td>13.788</td>
<td>12.546</td>
<td></td>
</tr>
<tr>
<td>31</td>
<td></td>
<td></td>
<td></td>
<td>13.012</td>
<td></td>
</tr>
</tbody>
</table>

Table XII: Comparative Control of Protracted Loss of 20.807 kg

<table>
<thead>
<tr>
<th>Test</th>
<th>Maximum Average Loss (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MUF</td>
<td>20.09</td>
</tr>
<tr>
<td>CUMUF</td>
<td>16.24</td>
</tr>
<tr>
<td>Joint Page / MUF</td>
<td>17.11</td>
</tr>
<tr>
<td>Joint Page / SITMUF</td>
<td>14.79</td>
</tr>
</tbody>
</table>

These results show that the joint Page’s test on SITMUF has the highest response to abrupt loss, and achieves the best control of protracted loss.

For the future, it is recommended that the joint Page’s test on SITMUF is adopted and developed for practical use in the control of materials loss.

References


CORRIGENDUM

The ESARDA WGDA asked to consider the following amendment for the title published in the ESARDA Bulletin No. 13, page 8:

1988 Target Values for
Random Uncertainties in Sampling and Element
Assay of Nuclear Materials.

Achievable Uncertainties when Nuclear Materials are Sampled
and Assayed for Element Content by Destructive Analytical
Methods