10th Annual ESARDA Meeting : "Medium and Long Term Trends in ESARDA Working Groups Activities"

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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 GWe. Depending on the availability of reprocess-
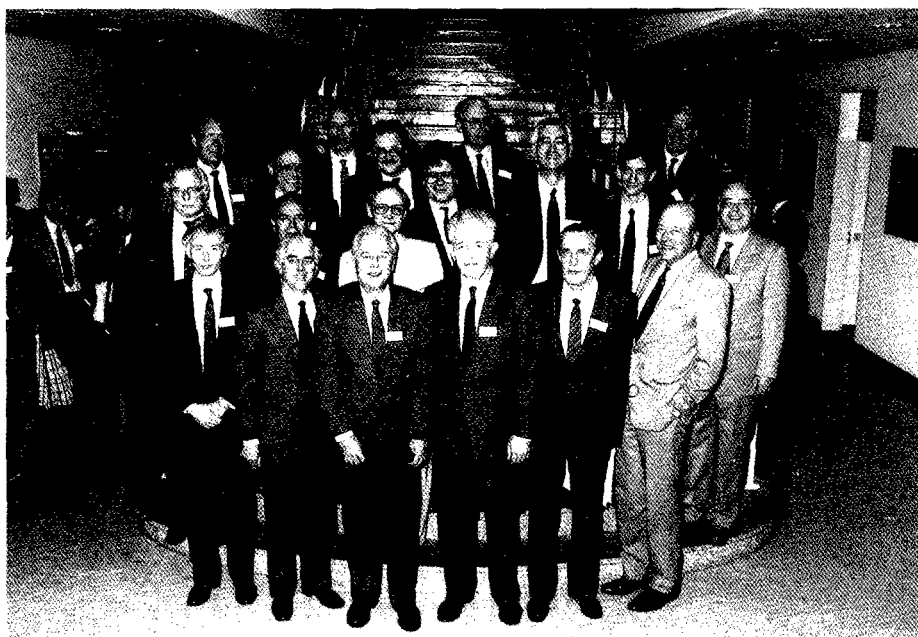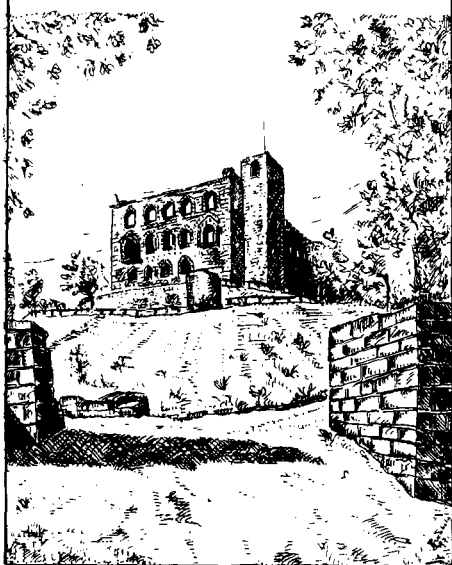

Some important delegates at the meeting

The secretariat

Hambach Castle

monument of german democracy

Castle of Bad Dürkheim - county

ing services this will result in a built up of spent fuel storage to some 15,000 t heavy metal. The total reprocessing capacity in EC-Countries is presently dominated by GGR reprocessing. In the course of the next decade there will be a shift to thermal recycling in Light Water Reactors, which will increase up to 70% of the total capacity in the year 2000 while the total capacity itself will be doubled up to 4800 t heavy metal per year. Consequently the quantity of annually separated plutonium will increase by the factor 4. Moving on to mixed oxide (MOX) fuel fabrication it was noted that the production capacity will increase by a factor of 6 and arrive at a level of 360 t MOX/y in the year 2000, most of which is foreseen for thermal recycling.

The next step of the study consisted of the identification of safeguards relevant nuclear fuel cycle characteristics which might be subject to change as a consequence of the described evolution. For each facility type such as power reactors, long term storage of spent fuel, reprocessing facilities and MOX fuel fabrication plants and LEU conversion and fabrication, quantitative and qualitative parameters were identified in a structured way, which might make necessary adaptation or further development of existing safeguards techniques. However there was a limiting boundary condition in so far as the application of specific safeguards techniques are determined by future safeguards approaches. Therefore conclusions drawn from the study are to be understood more or less as speculations on todays knowledge.

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 Convenor 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 authentification 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 number of samples to be taken will require a higher frequency of Regular Interlaboratory Measurement Evaluation Programmes. Furthermore the increasing number of sample transports will raise practical problems which might be solved by making use of the on site laboratory or by mobile DA stations.

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 focussed 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 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 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 collar for the measurement of assemblies and the photoneutron interrogating device (PHONID) developed at the JRC-Ispra for measurements of input and process materials;
- statistical accountacy, essentially based on the practical use of NUMSAS (a sta-

tistical tool for the calculation of material balance uncertainties).

Besides that, expected changes in the design of LEU-fuel such as use of mixed oxide, 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, radiolysis; 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.

6) **6th Annual Symposium**, Venice, Italy, 14-18 May 1984.

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.

9) **9th Annual Symposium**, London, England, 12-14 May 1987.

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:

- **International Meeting on Non-destructive Measurement and Identification Techniques in Nuclear Safeguards**, JRC Ispra, Italy, 20-22 September 1971.
- **Symposium on Practical Application of R&D in the Field of Safeguards**, Rome, Italy, 7-8 March 1974.
- **Symposium on Isotopic Correlation and its Application to the Nuclear Fuel Cycle**, Stresa, Italy, 9-11 May 1978.
- **1st Seminar on Containment and Surveillance Techniques for International Safeguards**, JRC Ispra, Italy, 17-19 September 1980.
- **ESARDA/INMM Joint Specialist Meeting on NDA Statistical Problems**, JRC Ispra, Italy, 12-14 September 1984.

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 material balancing is considered, then a multiple balance model is introduced. The next two chapters explain the computer program PROSA and the sequential test procedures contained in PROSA. After this the capability of the NRTA measures to detect a loss is shown in an example. Furthermore, two examples demonstrate how the NRTA tests can value the size of the assumed measurement uncertainties.

The Material Balance Concept

Let us consider a well-defined box /1/ that contains at a given time t_o some material into which material enters and from which material leaves during a given interval of time (t_o, 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_o is called the physical inventory I_o. The algebraic sum of the amounts of material that enter or leave the material balance area in the interval of time (t_o, t_N) — which in the case of an industrial plant are called receipts and shipments — is called the net transfer T. The physical inventory at t_o plus the net transfer in (t_o, 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 :

$$B := I_o + T.$$

The amount of material actually contained in the material balance area at time t_N is called physical inventory I_N.

If all material contained in, and passing through, the material balance area in the interval of time (t_o, 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_N and the physical inventory I_N must be zero. This difference is called MUF (Material Unaccounted For) :

$$MUF := I_o + T - I_N.$$

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 switches over to the concept of sequential balancing (Near-real-time accountancy, NRTA). In order to follow that idea, the reference-time period (t_o, t_N) is subdivided into N balance periods.

With the definitions

I_i : physical inventory at time t_i,
$\quad$ i = 0,...,N

T_i : net transfer during (t_{i-1}, t_i)
$\quad$ i = 1,...,N

and

$$MUF_i := I_{i-1} + T_i - I_i$$

we obtain a sequence of MUF values $(MUF_1,...,MUF_N)$. At the end of the i-th balance period, statements can be made based on all i balance results $MUF(j)$, $j \leqslant i$, 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/, see Table I.

Multiple Balance Model

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

$$MUF(k) = I(k-1) + T(k) - I(k).$$

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 I - Material balance as usual compared to sequential balancing

Material balance	Scheme		Decision is possible	Decision is based on
conventional	┝──────────┥	t_o $\quad\quad\quad$ t_N	only at the end of the reference time	only 1 balance (total balance)
sequential (NRTA)	┝─┝─┝......┝─┝ ─ ┝ ─┥	t_o $\quad$ t_i $\quad\quad$ 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

$$I(k) = E(I(k)) + ZI(k) + SI(k), k = 0,...,N$$

with

E(I(k)) : true value of the inventory
ZI(k) : random error of the measurement
SI(k) : systematic error of the measurement

and analogously

$$T(k) = E(T(k)) + ZT(k) + ST(k), k = 1,...,N.$$

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

$$var(I(k)) = var(ZI(k)) + var(SI(k))$$ and
$$var(T(k)) = var(ZT(k)) + var(ST(k)).$$

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

$$\sigma_{ij} = cov(MUF(i), MUF(j)).$$

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

$$\Sigma = \begin{pmatrix} \sigma_{11} & \bullet & \bullet & \bullet & \sigma_{1N} \\ & & \bullet & & \\ & & & \bullet & \\ & & & \bullet & \\ \sigma_{N1} & \bullet & \bullet & \bullet & \sigma_{NN} \end{pmatrix}$$

The matrix Σ 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 hypothesis 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 :

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

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

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

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 α (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 (**Pro**gram for **S**tatistical **A**nalysis 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 /3/. PROSA is a decision tool to determine on the basis of statistical considerations if in 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 choosen false alarm proibability α. 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(i) values and give a decision between the two hypotheses :

$$H_0: E(MUF(k)) = 0 \text{ for all } k = 1,...,N$$
$$H_1: E(MUF(k)) = M(k)$$
$$\text{and } M = \Sigma M(k) > 0.$$

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 α.

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) :

$$CUMUF(i) = MUF(1) + ... + MUF(i) \text{ for all } i = 1,...,N$$

The test is performed as follows /4/ :

for i = 1,...,N-1 :

$$CUMUF(i) \begin{cases} > s(i) & \text{reject } H_0 \\ \\ \leqslant s(i) & \text{no decision and go to the next period} \end{cases}$$

for i = N :

$$CUMUF(N) \begin{cases} > s(N) & \text{reject } H_0 \\ \\ \leqslant s(N) & \text{reject } H_1. \end{cases}$$

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

GEMUF test

Testing the single hypothesis H_0 against a simple alternative

$$H_2: E(MUF(k)) = M(k) \text{ and } M = \Sigma M(k) > 0$$

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 :

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

$$MUF_i = (MUF(1),...,MUF(i))^T \text{ and}$$
$$ZG(i) = MUF_i^T * (\Sigma(i))^{-1} * MUF_i.$$

The test is performed as follows :

for i = 1,...,N-1 :

$$ZG(i) \begin{cases} > s(i) & \text{reject } H_o \\ \\ \leqslant s(i) & \text{no decision and go} \\ & \text{to the next period} \end{cases}$$

for i = N :

$$ZG(N) \begin{cases} > s(N) & \text{reject } H_o \\ \\ \leqslant s(N) & \text{reject } H_1. \end{cases}$$

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

Pages test

The materials balance results MUF(i) are stochastically dependent random variables. With a linear transformation it is possible to transform the sequence MUF(1),...,MUF(N) to a sequence of stochastically independent random variables MUFR(1),...,MUFR(N).

The Pages test uses the following statistics :

$S_o = 0$
$T_o = 0$
$S_i = \max(0, S_{i-1} + \text{MUFR}(i) - k$
$T_i = \min(0, T_{i-1} + \text{MUFR}(i) + k$

for i = 1,...,N where k is a fixed number /7/.

The test is performed as follows :

for i = 1,...,N-1 :

$S_i > h$ or $T_i < -h$ reject H_o
$S_i \leqslant h$ or $T_i \geqslant -h$ no decision and go to the next period

for i = N :

$S_N > h$ or $T_N < -h$ reject H_o
$S_N \leqslant$ or $T_N \geqslant -h$ reject H_1.

The parameters h and k are determined by simulation to guarantee a false alarm probability α for the N balance periods. In our case we have selected k = 0.

Examples for Valuation of Measurement Models

As mentioned earlier the condensed measurement model Σ 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 Σ can be computed and material balances according to this dispersion matrix

$$\text{MUF}_N = (\text{MUF}(1),...,\text{MUF}(N))$$

can be simulated.
In order to test the capability of the NRTA measures, various loss pattern

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

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 Σ, which is the exact picture of the based measurement model. According to Σ a balance series $\text{MUF}_{20}^{(1)}$ is simulated :

$$\text{MUF}_{20}^{(1)} = (\text{MUF}^{(1)}(1),...,\text{MUF}^{(1)}(20))$$

(see Fig. 1).

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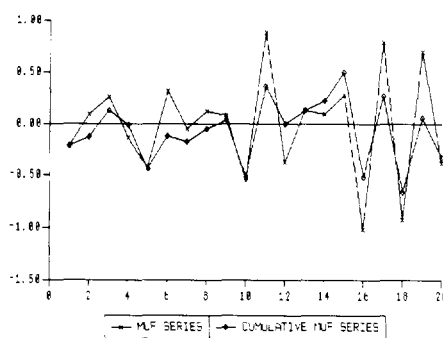

Fig. 1 - Simulated MUF series without loss according to the exact dispersion matrix

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 accordint to a loss :

$$\text{MUF}_{20}^{(2)} = \text{MUF}_{20}^{(2)} + M_{20}$$
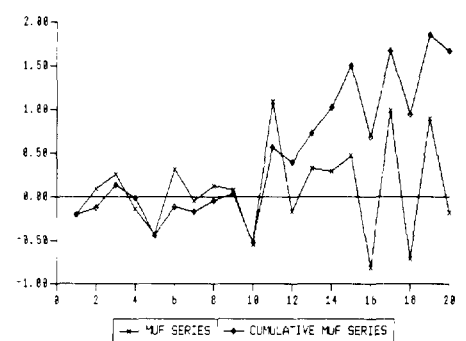
(see Fig. 2).

Fig. 2 - Simulated MUF series with loss according to the exact dispersion matrix

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 Σ. The NRTA measures, however, value these balances according to a dispersion matrix Σ_1 computed from the estimated variances, which is only an approximation of matrix Σ.

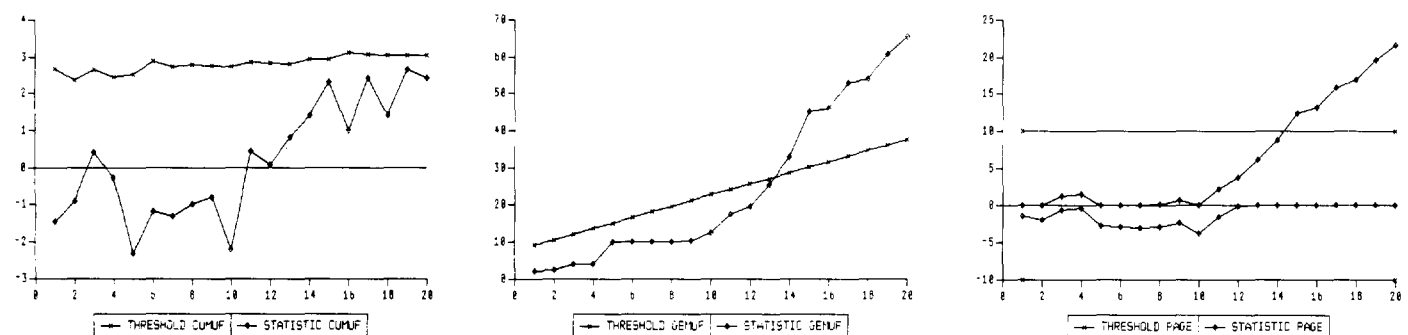If the variances were estimated too

Fig. 3 - Results of the NRTA tests based on the exact dispersion matrix and on the simulated MUF series with loss

conservative, too pessimistic, the sensitivity of the NRTA measures deteriorate. The reason is that the obtained balance series is considered as a realisation according to the estimated measurement model Σ_1 instead to the "true" model Σ. This means that larger fluctuation are accpeted in the material balance. This is shown in example 2.

Example 2 :

By increasing the variances of the inventory measurements we maintain a new dispersion matrix Σ_1. The MUF series $MUF_{20}^{(2)}$ of example 1 (with loss) is considered as a realisation of a random vector according to this "worse" matrix Σ_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 Σ_2 only accepts lower fluctuations in the balance data than the true model Σ. This will be demonstrated in the next example.

Example 3 :

Reducing the variances of the inventory measurements, we obtain a further measurement model Σ_2. Valueing the MUF series $MUF_{20}^{(1)}$ (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 Σ_2. The consequence of this alarm is that the measurement model Σ_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.

Conclusions

For application in practice, the estimate of the "true" measurment model is of great importance. Too "pressimistic" 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 uncertain-

ties. 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.

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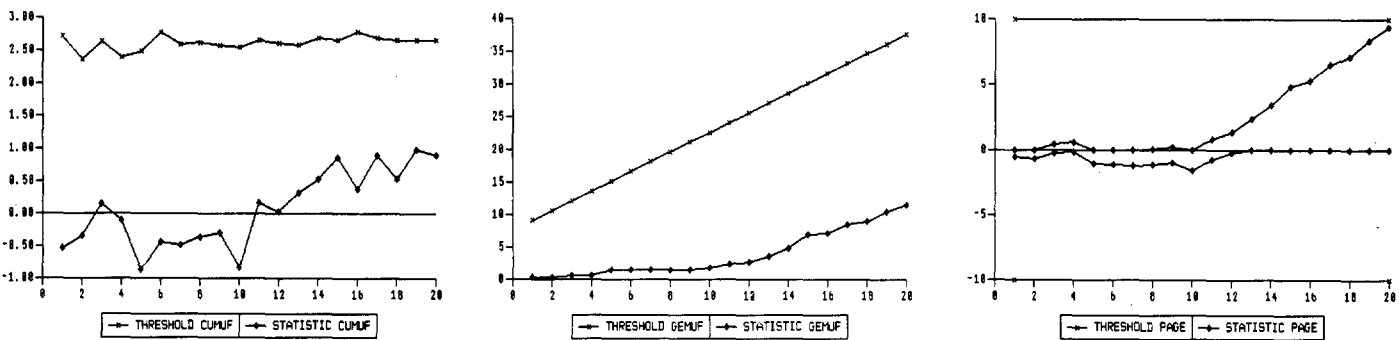
Fig. 4 - Results of the NRTA tests based on the too pessimistic dispersion matrix and on the simulated MUF series with loss
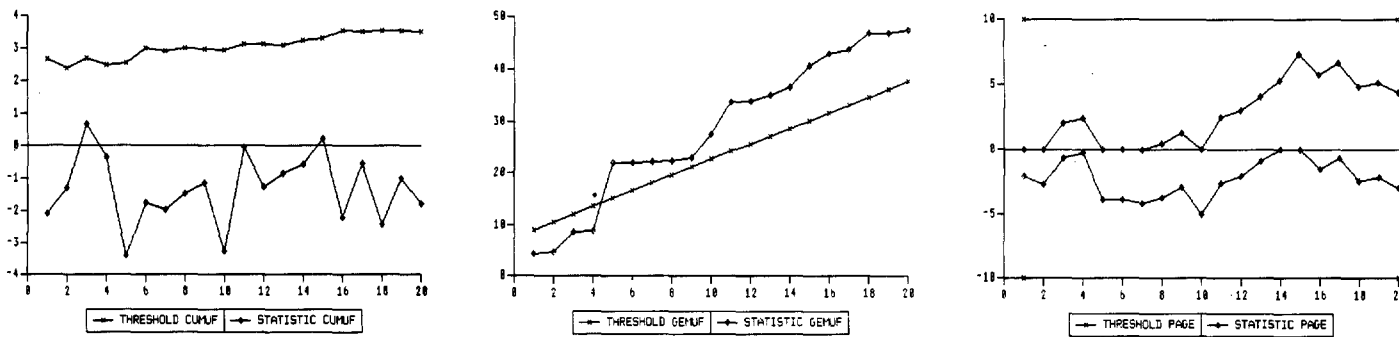

Fig. 5 - Results of the NRTA tests based in the too optimistic dispersion matrix and on the simulated MUF series without loss

Inspection Randomization for Pedestrians

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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 leaving the operators uncertain as to whether an inspection will take place or not (inspection randomization), 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 sacrifycing 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 $P_A \leqslant P_B$ and, of course, $0 \leqslant P_{A(B)} \leqslant 1$.

The probabilities of inspection we define to be I_A and I_B with

$$I_A + I_B = I \leqslant 2. \qquad (1)$$

I is the parameter which defines the degree of randomization. If $I = 2$ there is no randomization, while if $I = 0$ 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

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

These two probabilities must sum to unity since we assume that diversion will take place with certainty (no affront to Ruritanian intended). Again, $0 \leqslant I_{A(B)} \leqslant 1$ and $0 \leqslant D_{A(B)} \leqslant 1$.

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

$$P(I_A, I_B, D_A, D_B) = I_A D_A P_A + I_B D_B P_B \qquad (3a)$$

or, equivalently,

$$P(I_A, D_A) = I_A D_A P_A + (1 - I_A)(1 - D_A) P_B. \qquad (3b)$$

Let us call I_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**

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

But what precisely do we mean by an optimal strategy ? Simply this : If the inspector were to inspect facilities A or B with optimal probabilities I_A^* and $I_B^* = 1 - I_A^*$, 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

$$P(I_A, D_A^*) \leqslant P(I_A^*, D_A^*) \leqslant P(I_A^*, D_A) \qquad (4)$$

which are called the **saddle point conditions**.

Now we can write down the solution to the game, that is the values of I_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 $0 \leqslant I \leqslant 1 + (P_A/P_B)$ the solution is

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

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

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

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

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

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

$$I_A(P_B/(P_A + P_B))P_A + (I - I_A)(1 - (P_B/(P_A + P_B)))P_B$$
$$\leqslant (IP_AP_B/(P_A + P_B))$$

which is equivalent to $I \leqslant I$.

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 $I_A^* = 1$ and $I =$ $1 + (P_A/P_B)$ or $I_B^* = (P_A/P_B)$. 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)

$$P^* = 0.5, \quad I_A^* = 1.0, \quad I_B^* = 0.5.$$

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 $I_B^* = 0.556$ rather than 0.5.

Finally, if we have $P_B = 0.9$ and $I_A + I_B = 1.3$, then we get according to (5b)

$$P^* = (1.3 \times 0.5 \times 0.9)/(0.5 + 0.9) = 0.42$$

and the optimal inspection strategy

$$I_A^* = (1.3 \times 0.9)/1.4 = 0.84,$$
$$I_B^* = 1.3 - 0.84 = 0.46.$$

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.

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/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 Coexistence.

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 I - Active Tasks

Containment and Surveillance

C/S 1-a	Underwater Ultrasonic Seals for Containers and Spent Fuel Stacks
C/S 2	General Purpose Seals
C/S 4-a	Identification of Items by Means of Surface Topography
C/S 9	Feasibility Study of a PWR Fuel Assembly Sealing System
C/S 10	Image Processing System for Film and Video Tape Review
C/S 11	Modular Laser Surveillance System for Safeguarding Spent Fuel Storage Pools / Plutonium Dry Storage Facilities

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	UF$_6$ 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 dimention.

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
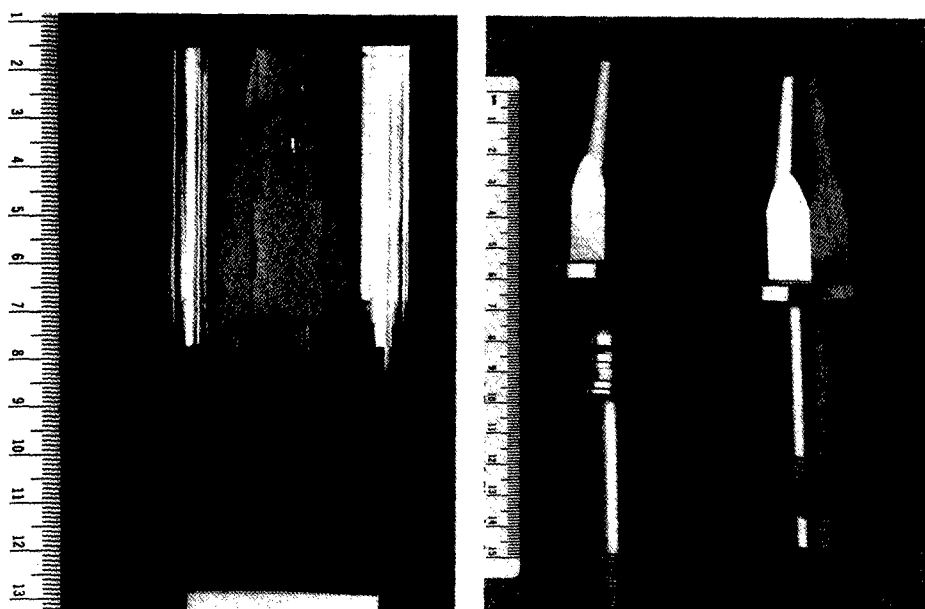

Fig.1 - Section of a model of the ultrasonic sealing bolt (sunk in plexiglas resin) and two complete bolts ready for use
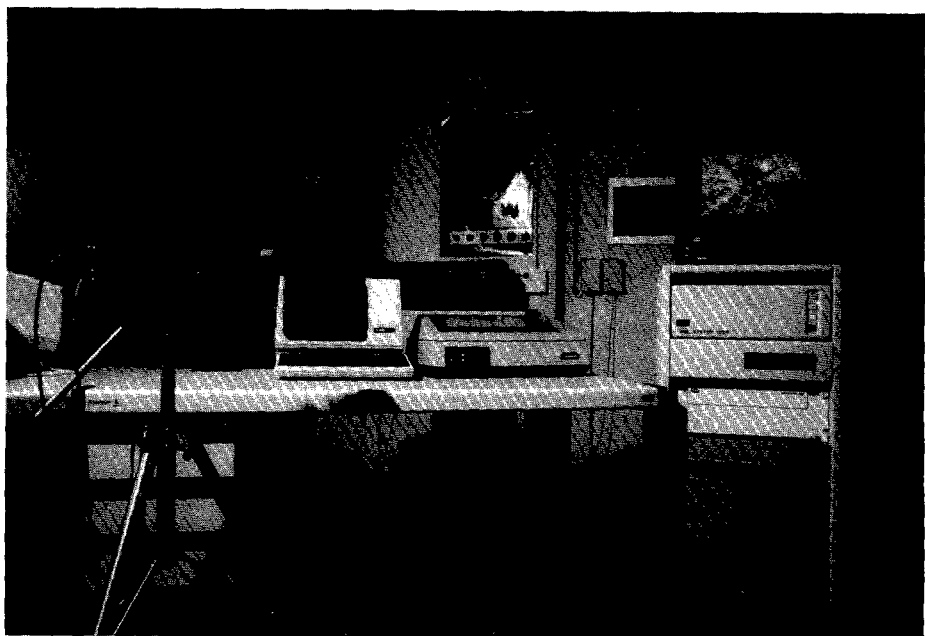

Fig. 2 - The computer vision system which performs the reviewing of video pictures both from tape (off line) and from TV camera (on line)

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) is based on the input method using metallic spikes. It is used to assay directly undiluted input samples for U and Pu concentration and improve the accuracy under routine conditions. The metallic spikes were prepared and characterized at the JRC-Geel. A measurement campaign is planned in the F.R. Germany.

The work on the UF_6 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 UO_2 (powders and pellets), PuO_2, 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-Geel 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
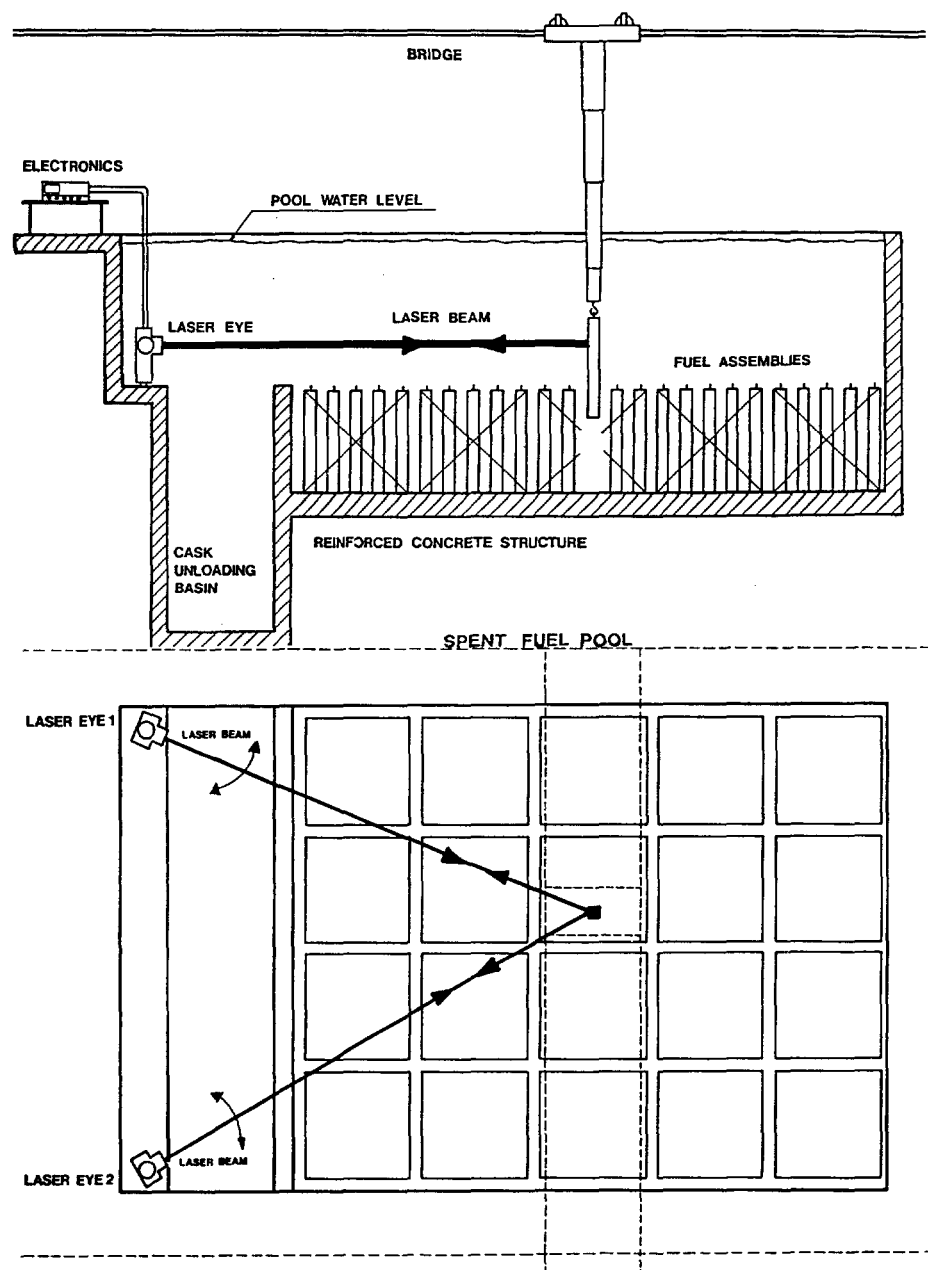

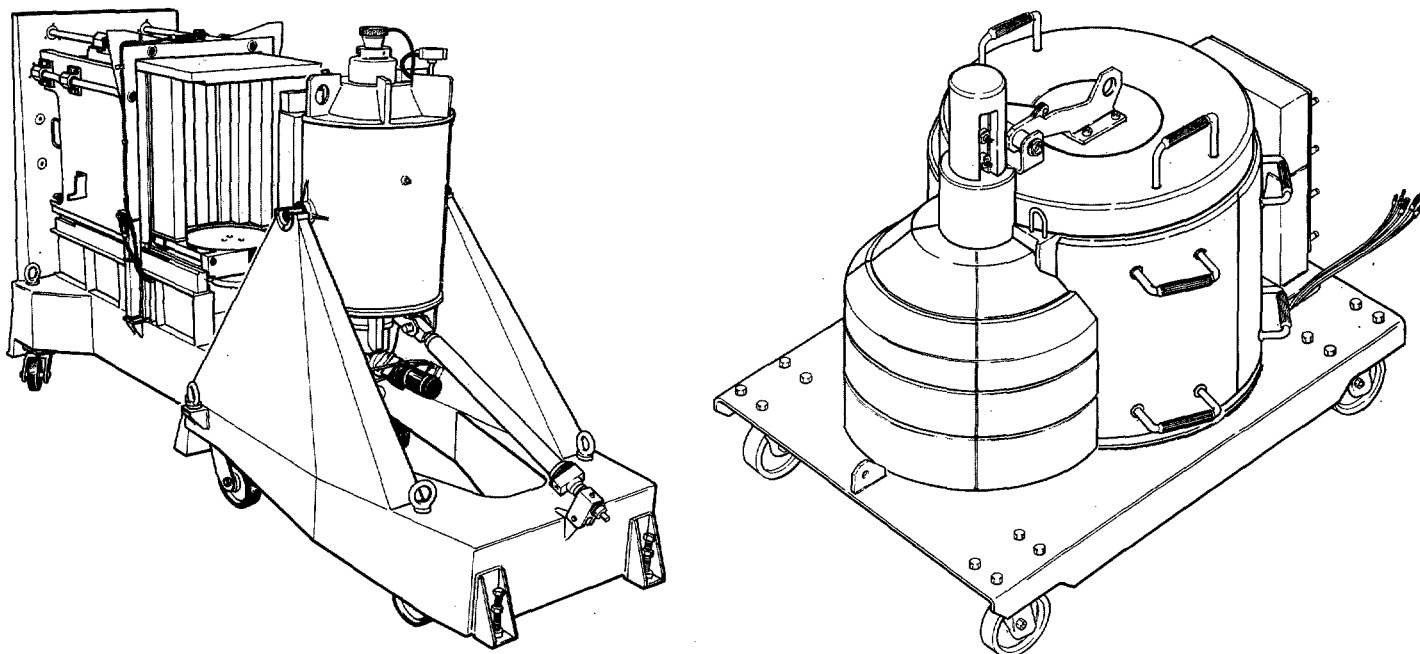Fig. 3 - View of the laser surveillance system (vertical section and top view)

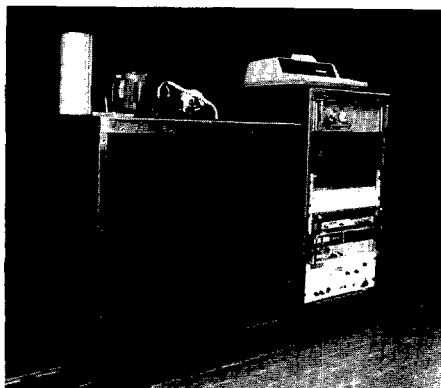Fig. 4 - View of PHONID 3 *(left)* and PHONID 4 *(right)*

Fig. 5 - View of the Mound calorimeter installed in PERLA

Fig. 6 - Picture of Spike Isotopic Reference Materials (^{233}U - ^{242}Pu - ^{233}U/^{242}Pu mixed) as delivered to the IAEA

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
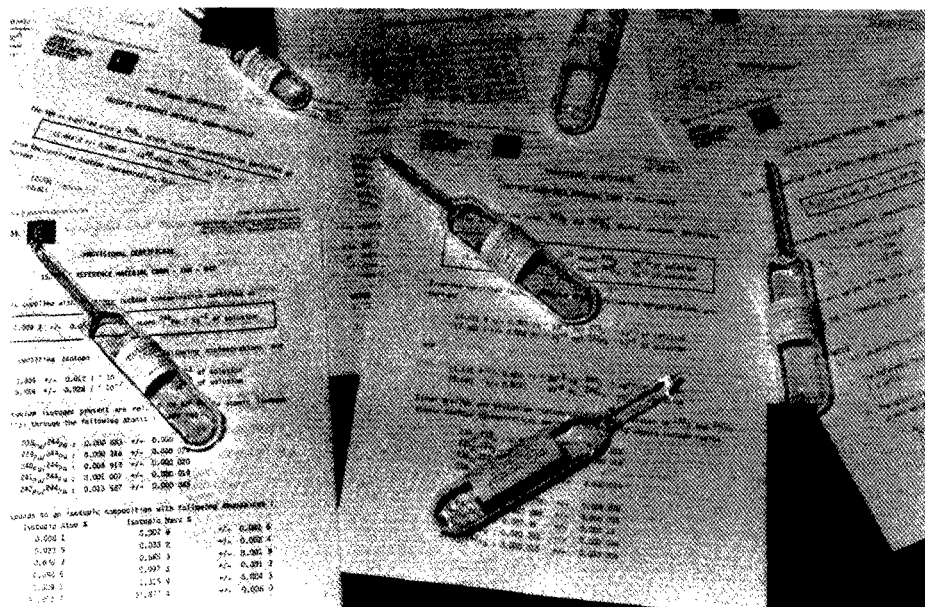
for the large number of analyses performed by the SAL (Seibersdorf Analytical Lab.) on samples from reprocessing facilities. The benefits of such an automated system include higher throughput, more reproducible processing of samples and lower radiation exposure of the personnel. The installation of such 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.
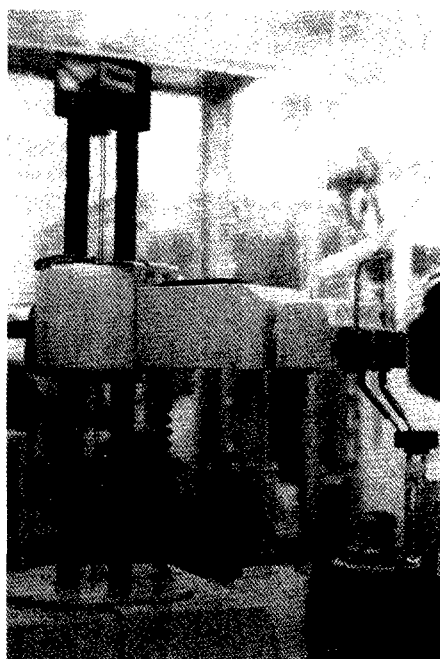
A second task carried out at the JRC-

Fig. 7 - View of the robot developed at the JRC-Karlsruhe

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.

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 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 /13/.

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. The prototype system was also used during the physical inventory exercise (see Training tasks below) held in July 1987 at PERLA.

The last task of this area concerns the design and evaluation of a knowledge based system for transit matching (Fig. 8). The correct matching of shipments and receipts can be reconciled by standard matching algorithms. The rest must still be reconciled with normal procedures utilizing the knowledge of the expert staff. The first release of a knowledge based system has been made, is now being tested and IAEA staff are starting to use it.

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 (PIV).
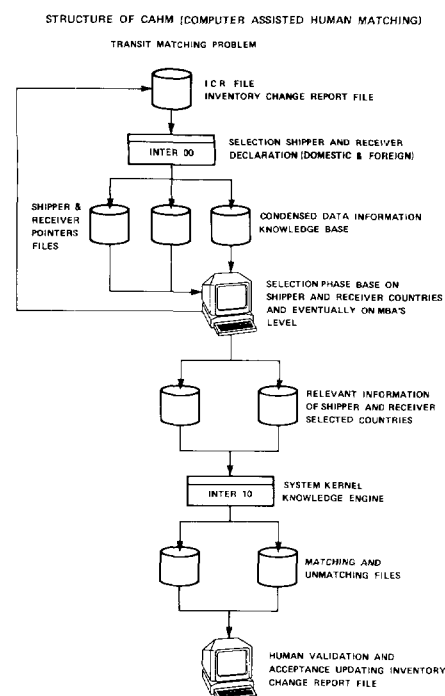
The first task aims to provide courses for

Fig. 8 - Flow chart for the transit matching

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 (ISPO). 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.

Description of Conventional Accountancy

The paper uses the same data to compare a variety of NRTMA procedures which make use of different test statistics. However, to evaluate the test procedures, it is important to first quantify what can be achieved by conventional accountancy using the single MUF test.

Conventional accountancy means:

1 Start by measuring the opening physical inventory;

2 Record all materials transfers for a campaign;

3 Finish by measuring the closing physical inventory;

4 Calculate MUF (book inventory - physical inventory);

5 Interpret MUF value.

Interpreting the MUF value consists of checking whether, when divided by its standard deviation, it has reached a significance threshold (z) chosen such that the false alarm probability (FAP) is controlled at some nominal value, α. In other words,

$$z = U_{1-\alpha}$$

where U is the inverse standard normal distribution function.

With a standard deviation of 6.325 kg the expected distribution of MUF, for the plant in control, is shown in Figure 1. The significance threshold, in order to give a 5% FAP, is set at 1.6449 standard deviations, or 10.403 kg. The effect of a loss of 10.403 kg is shown in Figure 2; the centre of the MUF distribution now coincides with the significance threshold or, in other words, the detection probability is 50%. Loss of twice this amount, 20.807 kg, is shown in Figure 3 and the detection probability has risen to 95%. The complete sigmoid power curve is shown in Figure 4, with particular attention drawn to the three points illustrated in Figures 1-3. It is particularly important to note that, once the significance threshold has been set in accordance with the required FAP, the response of conventional accountancy to a loss depends only on the total size of the loss and not in any way on its form.
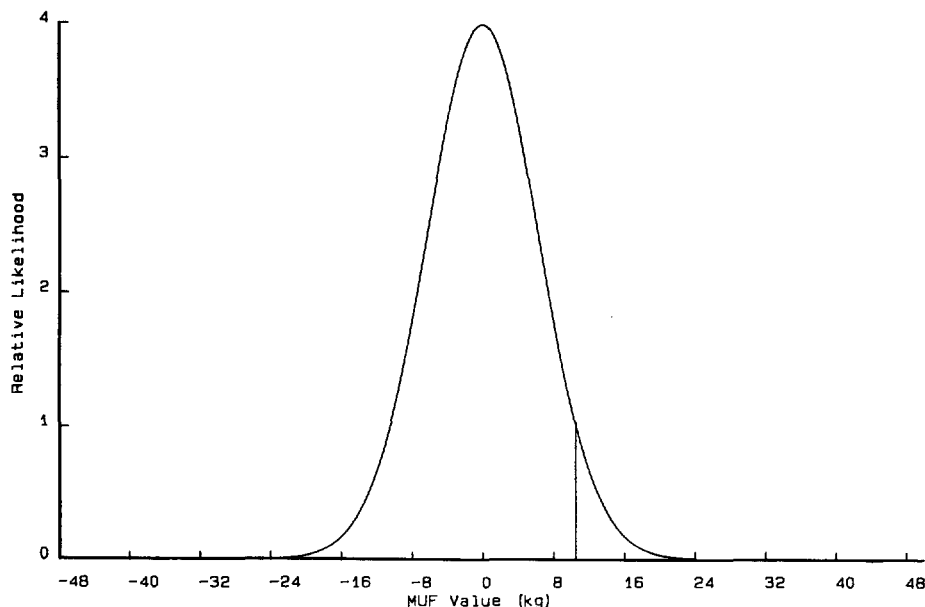

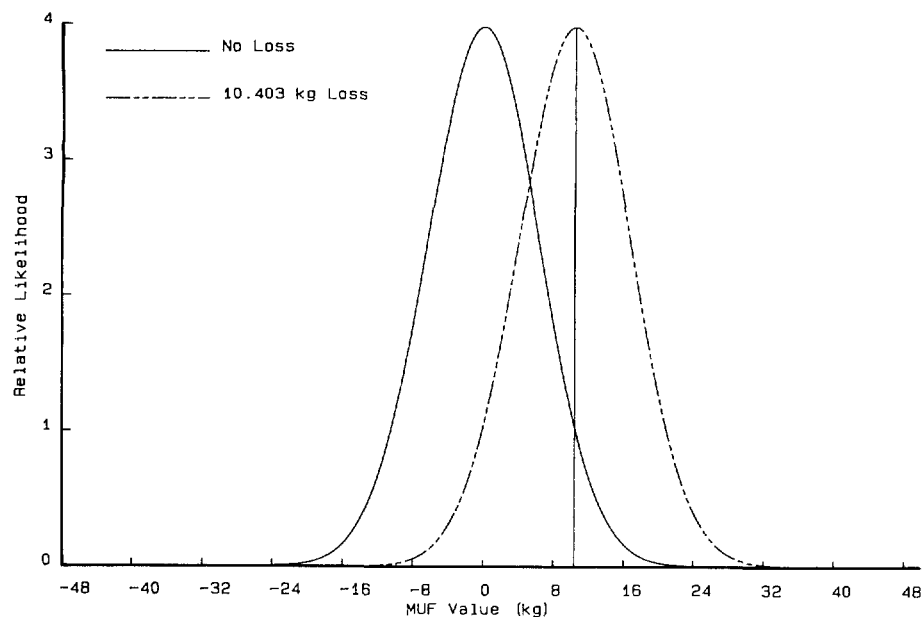Fig. 1 - Distribution of MUF Values (No Loss)
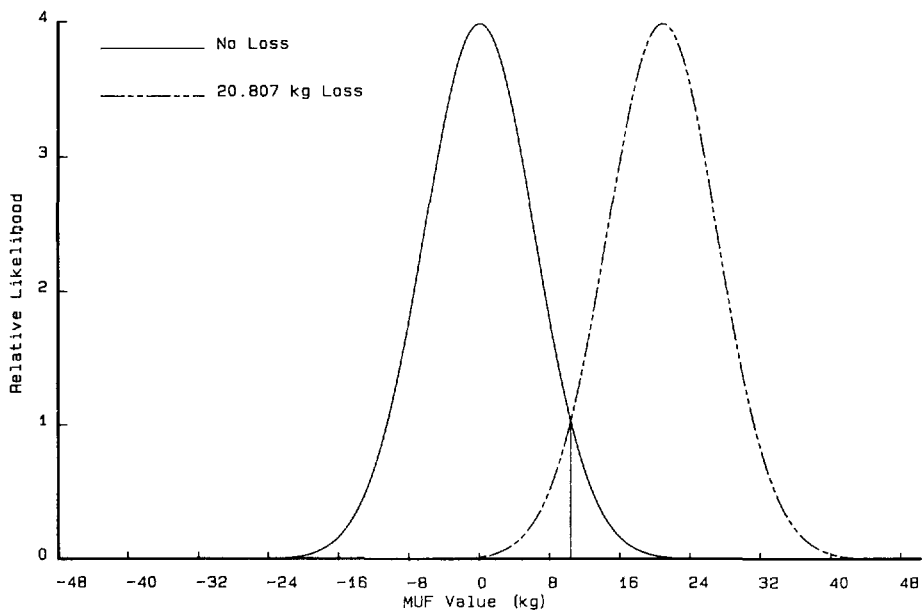
Fig. 2 - Distribution of MUF Values

Fig. 3 - Distribution of MUF Values

Data Generation for NRTMA

Data was simulated for 10,000 campaigns of 40 periods. Since the model assumes a zero beginning and ending inventory, no errors are associated with these values. For each of the intermediate inventories, and for the transfers during each balance period, the associated random measurement errors are obtained by multiplying values obtained from the Box-Muller algorithm with I and T respectively. The simulated measurement errors for inventories and throughputs are used to derive MUF_1 ... MUF_{40}. The same 10,000 streams of data were used throughout. When response to losses was examined the 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 SITMUF; 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

$$Z_i = \frac{MUF_i}{\sigma MUF_i} \qquad i = 1 \ldots 40$$

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 $MUF_1 \ldots MUF_{40}$, 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:

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

This is true only if the values $MUF_1 \ldots MUF_{40}$ 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
Significance Threshold = 1.6449
(10,000 Simulated Data Streams)

I (kg)	False Alarms
0.0	8,734
0.5	8,822
1.0	8,823
1.5	8,845
2.0	8,867
2.5	8,872
3.0	8,853
3.5	8,842
4.0	8,836
4.5	8,833
5.0	8,842
10.0	8,865

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
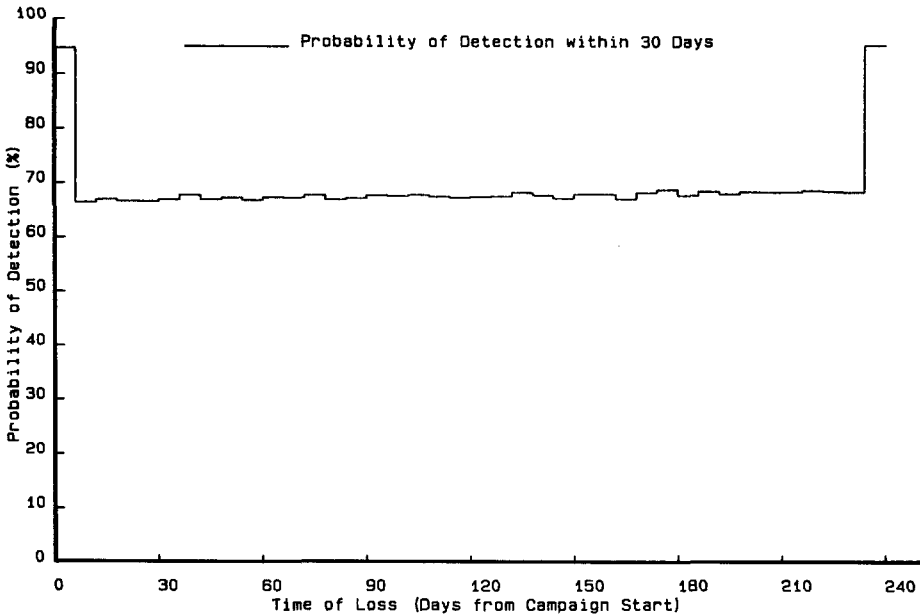
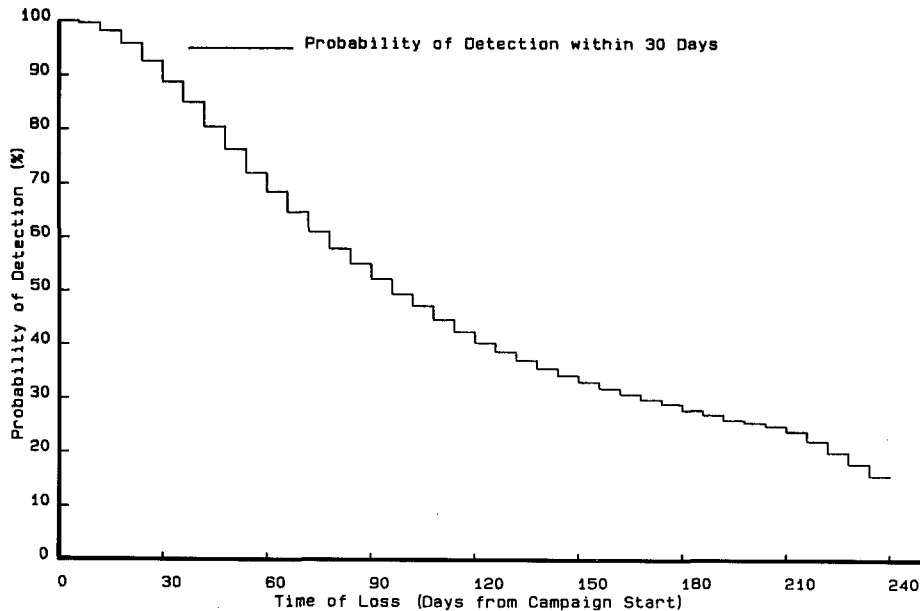Fig. 5 - Detection of Abrupt Loss of 10.403 Kg (MUF)

Fig. 6 - Detection of Abrupt Loss of 10.403 Kg (CUMUF)

- 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:

$$E(L) = \sum_{i=1}^{40} (L_i \cdot (p_i - p_{i-1})) = L_{40} \cdot (1 - p_{40})$$

where L_i is the cumulative loss and p_i the cumulative detection probability by period i.

The performance of the test with règard 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;

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, S2, 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

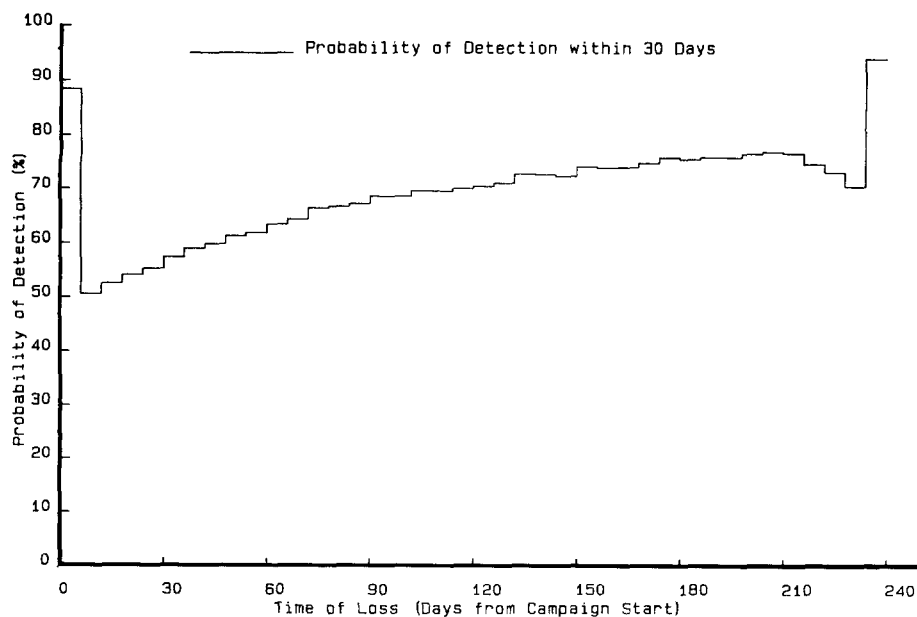Criteria have been proposed previously /3,4/. **Any** testing procedure aimed at detecting **abrupt loss** should:

Fig. 7 - Detection of Abrupt Loss of 10.403 Kg (MUF & Page)

Fig. 8 - Detection of Abrupt Loss of 10.403 Kg (SITMUF & Page)

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).

- have an ultimate response which is comparable with conventional accountancy. When comparing tests, the aim should be to select the test which minimizes the max-imum 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 VII: Comparative Response to Abrupt Loss of 10.403 kg
(10,000 Simulated Data Streams)

Test	Minimum Number of Campaigns Ending in Alarm
MUF	6,600
CUMUF	1,565
Joint Page / MUF	5,055
Joint Page / SITMUF	7,838

Table VIII: Average Loss per Campaign (kg)
MUF Test (10,000 Simulated Data Streams)

Starting Period	Ending Period			
	10	20	30	40
1	19.793	20.088	20.036	19.943
11	—	19.671	19.850	19.775
21	—	—	19.387	19.554
31	—	—	—	19.170

Table IX: Average Loss per Campaign (kg)
CUMUF Test (10,000 Simulated Data Streams)

Starting Period	Ending Period			
	10	20	30	40
1	8.021	8.881	10.152	11.348
11	—	12.463	12.987	13.731
21	—	—	14.874	15.018
31	—	—	—	16.242

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

Starting Period	Ending Period			
	10	20	30	40
1	17.109	15.999	15.170	14.528
11	—	14.570	13.551	12.978
21	—	—	13.365	12.390
31	—	—	—	12.428

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

Starting Period	Ending Period			
	10	20	30	40
1	14.792	14.562	14.006	13.559
11	—	14.682	13.503	12.821
21	—	—	13.788	12.546
31	—	—	—	13.012

Table XII: Comparative Control of Protracted Loss of 20.807 kg

Test	Maximum Average Loss (kg)
MUF	20.09
CUMUF	16.24
Joint Page / MUF	17.11
Joint Page / SITMUF	14.79

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.

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/4/ BARRY J JONES, "Near Real Time Materials Accountancy Using SITMUF and a Joint Page's Test: Dependence of Response on Balance Frequency", Proceedings of the Third American Nuclear Society Conference on Facility Operations - Safeguards Interface, 242, (1987)

/5/ W E BENNETT, R W FOULKES & R D MARSH, "Effective Safeguards in a Commercial Reprocessing Plant", Proceedings of the Third American Nuclear Society Conference on Facility Operations - Safeguards Interface, 44, (1987)

CORRIGENDUM

The ESARDA WGDA ashed 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