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INSPECT - A PACKAGE OF COMPUTER PROGRAMS
FOR PLANNING AND EVALUATING SAFEGUARDS INSPECTIONS

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ABSTRACT

As part of the U. S. Program of Technical Assistance to IAEA Safeguards, PNL has developed a package of computer programs, called INSPECT, that can be used in planning and evaluating safeguards inspections of various types of nuclear facilities. The programs are based on the statistical methods described in Part F of the IAEA Safeguards Technical Manual and can be used to calculate the variance components of the MUF (Material Unaccounted For) statistic, the variance components of the \hat{D} (difference) statistic, attribute and variables sampling plans, and a measure of the effectiveness of the inspection plan.

The paper describes the programs, reviews a number of applications, and indicates areas for future work.

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INTRODUCTION

Mathematical and statistical methods have long played an important role in nuclear material safeguards, as a large body of theoretical and applied work in the literature demonstrates. But because the methods are complex and sometimes involve burdensome computations, widespread practical application has tended to lag behind theoretical developments.

Quantitative methods occupy an especially important place in international safeguards. Safeguards agreements negotiated in connection with the Non-Proliferation Treaty specifically provide that in implementing safeguards the IAEA "shall take full account of technological developments in the field of safeguards", including "statistical techniques and random sampling."⁽¹⁾ And the desirability of basing the safeguards system on objective or quantitative criteria has often been stressed.

From this point of view, it is of interest to consider ways of facilitating the application of mathematical and statistical methods in international safeguards, as well as ways of enhancing the usefulness of such techniques. As part of the U.S. Program of Technical Assistance to IAEA Safeguards, Pacific Northwest Laboratory has developed a package of computer programs, called INSPECT, that can help to further these objectives.

DESCRIPTION OF THE PROGRAMS

In Part F of the IAEA Safeguards Technical Manual⁽²⁾, some basic statistical concepts and techniques for international safeguards applications have been documented. The INSPECT programs are based mainly on the methods described in Part F, and in particular on Chapters 6-9, which deal with the inspection and verification of material balances.

THE MATERIAL BALANCE MODEL

The starting point for the analysis is a material balance model. The material balance consists of four components: beginning inventory(BI), receipts(R), shipments(S), and ending inventory(EI). Material unaccounted for (MUF) is defined as

$$MUF = BI + R - S - EI$$

Each of the components of the material balance is divided into strata. Each stratum is subdivided into batches. Each batch consists of a number of discrete items.

Amounts of nuclear material are estimated on the basis of three basic kinds of measurement operations: bulk measurement (i.e., weight or volume), sampling, and analysis. In general, the uncertainty in an item amount can be expressed in terms of random and systematic components of variance associated with these basic operations. A relative error model is used.

An important index of material balance performance is the uncertainty of MUF. This is calculated by propagating over the complete material balance the uncertainties associated with each basic measurement operation. The result is the standard deviation of MUF due to measurement uncertainties. The components of the variance of MUF are also calculated so that one can see the contributions of each measurement operation to the overall uncertainty.

INSPECTION AND VERIFICATION OF A MATERIAL BALANCE

The central role of material balance verification in international safeguards is reflected in the statement of the objective of safeguards given in Paragraphs 28-30 of INFCIRC/153⁽¹⁾. In Paragraph 29, material accountancy is defined "as a safeguards measure of fundamental importance." Paragraph 30 specifies that "the technical conclusion of the Agency's verification activities shall be a statement, in respect of each material balance area, of the amount of material unaccounted for over a specific period, giving the limits of accuracy of the amounts stated."

The process of verifying a material balance begins with an analysis of the ways in which a diversion might show up in the material accounting system. The argument can be presented in terms of a diversion tree (see Figure 1). Given the diversion of an amount M of nuclear material, there are two basic possibilities that must be factored into the analysis. Either the accounting system accurately reflects the status of nuclear material, or it does not. If it does give an accurate picture, then the diversion will tend to show up in material unaccounted for (MUF). If the accounting system does not give an accurate picture of the status of material, then all or part of the diversion may fail to be reflected in MUF. It will instead manifest itself in the form of discrepancies between the stated (recorded) contents of individual items and the true contents of those items.

These item discrepancies can arise in several ways. For example, for an item in the receipts component of the material balance, the diverter can understate the weight and/or concentration. For an item in the shipments component, the diverter can overstate the amount. For an item in ending inventory, the diverter can either falsify the data or remove material from the item in such a way that the content is overstated. In any case, it should be noted that the important thing is not how the discrepancy arises (data falsification or removal of material after recording of the amount) but rather the fact that a discrepancy exists that tends to prevent the diversion from showing up in the MUF.

The next step in the analysis depends on the assumption that the inspector makes two kinds of measurements:

- Variables-type measurements
- Attributes-type measurements

Variables-type measurements usually involve relatively accurate weighing and destructive chemical analysis. Attributes-type measurements usually involve a relatively quick, non-destructive technique that can be used to detect easily discrepancies that constitute a significant fraction of the content of an item.

These two kinds of measurements furnish the basis for classifying item discrepancies into three groups:

- discrepancies large enough to be detected by a single attributes measurement. Such discrepancies may be referred to as gross defects.
- discrepancies that are too small to be detected with non-destructive measurements, but which are large enough to be detected with a single variables measurement. These are called partial defects.
- discrepancies that are too small to be detected with a single measurement of either type. These are called bias defects.

In summary, the analysis yields four basic diversion paths:

- gross defects
- partial defects
- bias defects
- diversion into MUF

The inspection strategy for covering these diversion paths consists of sampling plans for attributes and variables and a battery of statistical tests based on the information collected during the inspection. The principal statistical tests that have been defined are:

- tests for gross defects. These involve analysis of the data collected with the attributes test instruments.
- tests for partial defects. These tests make use of variables measurement data, but the analysis is essentially an attributes-type analysis, i.e., the items are classified either as defective or not defective.
- tests for bias defects and diversion into MUF. A single test called the MUF- \hat{D} test can be used. It is based on the operator's MUF and the inspector's variables measurements. MUF- \hat{D} is essentially the operator's MUF adjusted for bias; it has sometimes been referred to as the inspector's estimate of MUF.

The a priori effectiveness of the verification may be expressed in terms of the probability of detecting the diversion of a specified amount of material. A quantity called Q_{MAX} has been defined as the probability of non-detection assuming the diverter chooses his optimal strategy (i.e., maximizes the probability of non-detection). The probability of detection is then $1-Q_{MAX}$.

The details of the analysis described above are quite complicated, and the calculations required to carry out the analysis are laborious. In order to facilitate these calculations, the INSPECT computer programs were written.

THE INSPECT PROGRAMS. - AN OVERVIEW

The INSPECT package⁽³⁾ is a set of five interactive FORTRAN programs which can be used to calculate:

- the variance components of the MUF statistic
- the variance components of the \hat{D} (difference) statistic
- attributes and variables sampling plans
- a measure of the a priori effectiveness of the material balance verification

The purpose of the programs is to facilitate the application of the material balance verification methodology described in Part F of the IAEA Safeguards Technical Manual.⁽²⁾

The programs were originally developed as part of a system study conducted under the auspices of the U.S. Program for Technical Assistance to IAEA Safeguards. Initial implementation was on a PDP 11/70 minicomputer at PNL, where the programs were used extensively in both interactive and batch modes as tools for system studies. Later, the programs were converted to the IBM computer at IAEA headquarters for use in batch mode. Since that time, the programs have been used at IAEA headquarters by members of the System Studies Section and the Section for Data Evaluation Services.

Five basic steps are involved in using INSPECT:

- the necessary input data are assembled and organized
- data files are set up on the computer
- the data files are converted to direct access files
- variance calculations are performed
- sample sizes and detection probabilities are computed

There are two kinds of inputs to the programs: a) information on the facility and the safeguards approach and b) verification parameters. The information on the facility and the safeguards approach consists of the stratified material balance along with information about measurement methods used by the operator and inspector. The verification parameters consist of such things as the goal quantity, the false alarm probability, and the goal probability of non-detection.

To assist in organizing the input data, a set of forms has been drawn up, one form for each of the five data files that are to be input to the computer. The five data files are:

- stratum description file. This file contains data on the amounts of material and the measurement methods in each stratum in the material balance.
- bulk measurement error file. This file contains random and systematic error relative standard deviations associated with weight or volume measurements.
- material sampling error file. This file contains random and systematic error relative standard deviations associated with material sampling.
- analytical measurement error file. This file contains random and systematic error relative standard deviations associated with analysis for element concentration.
- between-laboratory error components file. This file contains a between-laboratory error component associated with each analytical method.

Once the necessary data files have been set up, two programs are used to convert these to direct access files. Direct access files are stored outside of the core of the computer on remote memory (disk). The chief advantage of this arrangement is that the requirements for in-core storage capacity can be reduced to the point where all of the programs can run easily on a minicomputer. If all of the data were stored in core, a full-size computer would be needed.

After the direct access files are set up, one program computes the components of the variance of MUF. Another program computes the variance components of the \hat{D} statistic. The fifth and final program calculates sampling plans and computes the a priori effectiveness of the verification activities.

APPLICATIONS OF THE INSPECT PROGRAMS

To date, the programs have been used in a variety of projects, which fall into two broad categories: a) system studies and b) analysis and evaluation of actual IAEA safeguards data.

SYSTEM STUDIES

The programs were originally designed with system studies in mind and systems studies constitute the principal field of application so far. The programs are well-suited to investigations of such topics as:

- the impacts of changes in measurement techniques
- the impacts of safeguards parameters such as goal quantity, false alarm probability, etc.

- the tradeoffs between alternative inspection strategies
- the assessment of the effectiveness of material balance verification systems

The first application was in Task C.5 of the U.S. Program of Technical Assistance⁽⁴⁾. The objective there was to develop and demonstrate a method of estimating the inspection effort required to implement IAEA safeguards as a function of varying safeguards goal parameters and inspection procedures. The INSPECT programs were useful in performing this task because the output from the program, namely, sampling plans and the probability of detection assuming the diverter's optimal strategy, are responsive to changes in parameters such as goal quantity and to changes in inspection strategy. In order to estimate inspection effort, other considerations must be factored in as well (costs of records examination, planning and preparation, report writing and so forth) so the computer programs were supplemented by other analyses. The method was illustrated by application to a 200 ton per year low-enriched uranium conversion and fuel fabrication plant.

In another task carried out under the auspices of the U. S. Assistance Program--Task C.19--the objective was to analyze the impact of safeguards criteria. The idea was to assess the impact on safeguards efficiency and effectiveness of variations in certain key parameters such as goal quantity, false alarm probability and plant size. The technical approach taken was to perform a sensitivity analysis using the INSPECT programs. Low-enriched uranium conversion and fuel fabrication was again taken as an illustrative case. Seven key parameters were selected for detailed analysis. An experimental design was used to systematically vary the parameters, and a large number of cases were run. Graphical and statistical (response surface) methods were used to analyze the data and reach conclusions about the impacts of the various parameters.

The IAEA's Section for System Studies has performed a study of various aspects of safeguards at mixed oxide fuel fabrication facilities.⁽⁵⁾ The results have recently been reported in a Safeguards Technical Report. The analysis included a number of case studies performed using the INSPECT programs, which have been made available on the IBM machine at IAEA headquarters. Among the parameters studied were:

- the inspector's random error
- the inspector's systematic error
- the inspector's combined random and systematic error
- goal quantity
- sample sizes
- detection probabilities

Some additional work along these lines is currently underway as part of Task C.35 of the ISPO program.

The programs have also been used to explore the implications of various inspection strategies for U. S. domestic safeguards. Among the topics considered in that study were:

- tradeoffs between the use of NDA and chemical analysis for inspection measurements
- sample sizes and inspection effort required for inspecting a number of facilities
- the need for and the impact of improved measurements for certain kinds of material

In another study performed for the NRC, the programs were used to help assess the material accountancy capabilities and resources needed to achieve specified IAEA safeguards technical objectives. Both low-enriched uranium and mixed oxide fuel fabrication facilities were modeled.

DATA EVALUATION

The IAEA's Section for Data Evaluation Services has arranged to make the INSPECT programs available to inspectors both for inspection planning purposes and for post-inspection evaluations, using actual inspection data. A safeguards technical report entitled "Inspection Planning and Evaluation Services" has been prepared and distributed to inspectors.⁽⁶⁾ The report provides a set of instructions and procedures that inspectors can use to request calculations of the variance of MUF, the variance of \hat{D} , sampling plans and detection probabilities. To date, the programs have been applied to several fuel fabrication facilities currently under IAEA safeguards.

AREAS FOR FUTURE WORK

Based on the experience gained from using the programs, a number of areas for additional work have been identified.

SHORT TERM SYSTEMATIC ERRORS

In Volumes 1 and 2 of Part F of the IAEA Safeguards Technical Manual⁽²⁾, the basic error models allow for three kinds of errors: random, systematic (within laboratory) and systematic (between laboratories). The INSPECT programs are based on the same models.

In some applications, it is desirable to use a different error model that includes short term systematic errors. Essentially, the idea is that measurement processes tend to undergo shifts from time to time for a variety of reasons. To account for this behavior, short term systematic errors can be included in the model. This topic is discussed in Volume 3 of Part F⁽²⁾.

The short term systematic error model will be included in future revisions of the INSPECT programs.

TREATMENT OF ISOTOPIC MATERIAL BALANCES

The programs as currently implemented are intended to be used for element material balances (uranium or plutonium) rather than for isotope balances (^{235}U). For some applications, isotope balances are of interest. It is planned to modify the programs to handle isotopics in the near future. Again, the methodology described in Part F of the IAEA Safeguards Technical Manual⁽²⁾ will be used.

A POSTERIORI EVALUATION

The programs were originally designed primarily for inspection planning purposes. The technical objectives for the inspection are input, and the program calculates the sampling plans needed to achieve the objectives. The program, as currently implemented, cannot take arbitrarily selected sample sizes as input and then calculate the achieved probability of detection. For evaluating the results of actual inspections, it would be useful to introduce this as an option.

ABSOLUTE ERROR MODEL VS. RELATIVE ERROR MODEL

The basic error model in Volumes 1 and 2 of Part F⁽²⁾ is the relative error model. Specifically, the model has the following form:

$$x = \mu(1 + \delta + \epsilon)$$

where x = measured value

μ = true value

δ = relative systematic error (expressed as a decimal fraction)

ϵ = relative error (expressed as a decimal fraction)

In some applications, an absolute error model is preferred:

$$y = \mu + \delta' + \epsilon'$$

where y = measured value.

μ = true value

δ' = absolute systematic error (expressed in absolute units, grams or kilograms, say)

ϵ' = absolute random error (in absolute units)

The programs will be updated in the near future to allow both absolute and relative error models.

INPUT FORMATS

In order to make the programs as easy to use as possible, it is desirable to make the input requirements for the programs closely compatible with the actual data that become available from inspection working papers and other sources of data. The way the programs operate currently, it is necessary to process some data by hand calculations in order to put it in the proper form.

The programs will be revised in the near future so that they can draw the necessary input information directly from inspection working papers with a minimum of handling.

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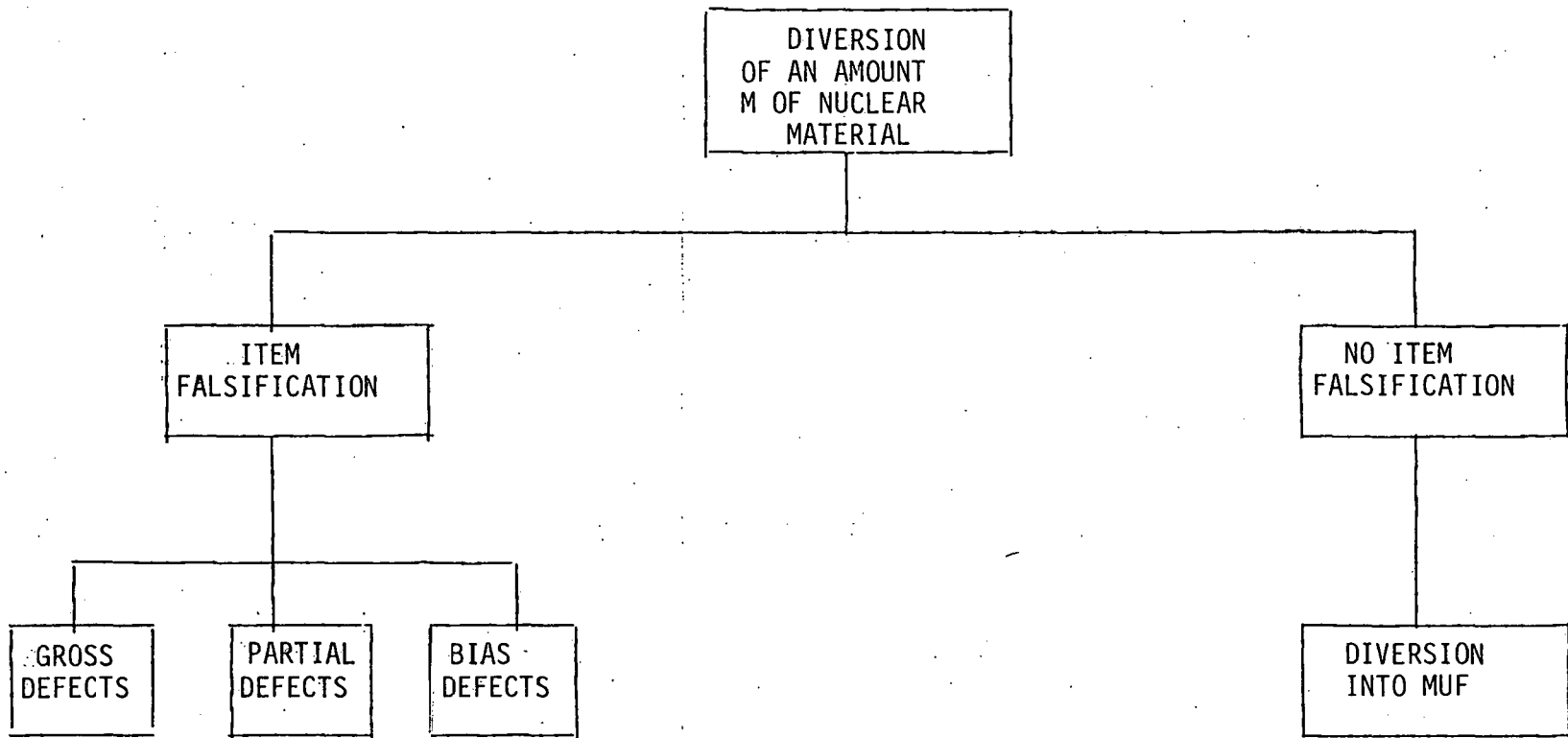


FIGURE 1. DIVERSION TREE