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APPLICATION OF THE BASIC CONCEPTS OF DYNAMIC MATERIALS ACCOUNTANCY TO THE TOKAI SPENT FUEL REPROCESSING FACILITY,

—— A FEASIBILITY STUDY ——

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Application of the Basic Concepts of Dynamic Materials Accountancy to the Tokai Spent Fuel Reprocessing Facility

——— A Feasibility Study ———

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During 1978 and 1979 individuals from the International Atomic Energy Agency, the Los Alamos Scientific Laboratory, and the Japan Atomic Energy Research Institute investigated the feasibility of applying the basic concepts of dynamic materials accountancy to PNC-Tokai reprocessing facility in Japan. The study concluded that such a system would be feasible, and recommended that an actual field test should be conducted as soon as feasible.

Conventional materials accountancy is based on cleanout physical inventories which are taken at intervals of six or twelve months. Such material balances are less than completely satisfactory, both because the 6 - 12 month material balance period is too long and because the accumulated systematic uncertainty over such a period reduces the sensitivity of the analysis. Dynamic or near-real-time materials accountancy argues that _if_ physical inventories could be taken at frequent intervals on an in-process basis, then various multiple-period statistical techniques (briefly described in the report) could be used to reduce the effect of systematic uncertainties and to provide both sensitive and timely detection capabilities. The statistical techniques are reasonably well developed; the major problem in implementing dynamic materials accountancy in actual facilities is the development of the necessary measurement procedures which permit in-process transfer and physical inventory measurements.

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The system developed for Tokai requires weekly in-process physical inventories for the process MBA, and allows 2-3 additional days for completion of measurements and for data reduction and evaluation. More rapid systems are discussed briefly, but are not considered necessary to achieve IAEA detection goals at Tokai.

Virtually the entire plutonium inventory at Tokai is in (a) a series of four buffer storage tanks, (b) three banks of mixer-settler solvent extraction contactors, or (c) the plutonium product evaporator. Residual inventory not in one of these locations varies according to process variations, but is less than 3-400 grams Pu, and should under stable operating conditions be constant to within 50-100 grams. No suitable measurement technique was found for the product evaporator, but the evaporator is discharged once every 24 hours, and it should be possible to schedule in-process physical inventories to coincide with evaporator discharge. The buffer storage tanks are sampled daily for process control, and these data can be used for materials accountancy. Plutonium in the mixer-settlers should be determinable from computer model calculations, using a program termed SEPHIS.

Since the objective of dynamic materials accountancy is the production of data which satisfy IAEA safeguards goals, the question of data verification is given considerable study in the report. It is shown that in a dynamic system verification should be thought of as a continuum, with varying degrees of "approximately verified", "partially verified", "more precisely verified", etc., rather than as a dichotomy. Since considerable process information is routinely available, it is possible to ask questions such as "What is the maximum credible falsification in a single batch?" and obtain a meaningful and useful answer.

Application of the verification philosophy discussed in the report leads to the conclusion that roughly 17% of the batches must be partially verified each week, the definition of "partial verification" being sufficient to reduce the maximum credible diversion from one batch to the 1-200 grams Pu range. It is also shown that the minimum credible diversion, extended over every batch for an entire year, is 10 grams Pu. This is about 0.16 - 0.30% for a typical batch, depending on the type of batch, and does not appear to be unachievable. Multiple-period statistic techniques would again be used to evaluate operator--inspector verification data. Specific verification techniques are reviewed for the major material flows. Since the partial verifications eliminate the possibility of abrupt diversion, these more precise verifications need not be completed with great rapidity.

Ikawa, at JAERI, has performed extensive computer simulations of the proposed system, and data are summarized to show that the ten day detection time model would detect the diversion of 8 kgs Pu over a twelve month period, whereas the same measurement techniques applied in a conventional manner would not.

Several problems requiring further study are identified. The first and most important is an actual field test of the ten day detection time approach. Others include the validation of the dynamic computer model for mixer-settler contactors and the extrapolation of the results to larger facilities.

Keywords; Dynamic Materials Accountancy, MUF, Tokai Reprocessing Facility, Safeguards, Statistical Analysis, Feasibility Study, Plutonium Inventory, Nuclear Material Management

東海再処理施設に対する動的計量管理思想の適用研究

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１９７８年から１９７９年の間，国際原子力機関（ＩＡＥＡ），ロスアラモス科学研究所及び日本原子力研究所の研究者達は，東海再処理施設に対して，動的計量管理の基本思想が適用可能なのかどうかについて研究を実施した。結論として得られたことは，そのようなシステムの適用は実現可能であるということである。この結論に基づき，そのようなシステムの現実プラントに於けるフィールドテストを早急に開始すべきであると勧告した。

在来型計量管理は６ケ月から１２ケ月の間隔で実施されるクリーンアウト実在庫測定を基礎としている。このような物質収支は，６～１２ケ月の物質収支期間が長過ぎるということ，およびそのように長い期間に亘り累積された系統的不確かさが解析の感度を低下せしめるという２つの理由から完全に満足出来るものとは言い難い。ダイナミックないしはnear-real timeな計量管理が主張するところは，実在庫測定がプラント操業中に頻繁に実行できさえすれば，多期間のデータを総合的に分析する多様な統計技術（本文中で簡単に述べる）を用いて前述の系統的不確かさの影響を減らし，かつ，感度が良くタイムリィな検知能力を確保することが出来るということにある。この統計技術はかなりの程度まで充分に開発されている。したがって，動的計量管理を現実の施設で実施する上での主な問題とは，操業中の物質の移動ならびに実在庫測定を可能ならしめるのに必要な測定手続きを開発することである。

東海再処理施設に対して開発した動的計量管理システムでは，プロセスＭＢＡに対して週毎の操業下実在庫測定を必要とし，（分析を含めて）測定を完結し，かつデータの整理ならびに解析をするのに２～３日間の猶予期間を認めている。もっと早く処理するシステムも簡単に検討したが，これはＩＡＥＡの東海における検知目標を達成するのに必要なシステムとは考えていない。

東海プラントのプルトニウム在庫が実質的に存在するところは，(a)４個のバッファー貯蔵タンク，(b)ミキサー，セトラ溶媒抽出器の３箇のバンク，あるは(c)プルトニウム蒸発塔

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の中である。これらの部分にない他の在庫は工程の変動に応じて変化するが，しかし，その量は３～４００グラム以下であり，定常運転状態の下では５０～１００グラムの範囲内で一定であろうと考えている。製品蒸発塔については適当な測定技術が見つからなかったが，蒸発塔は２４時間毎に内容物の放出をすることになっており，従って，この放出の時点に合わせて操業下実在庫測定を実施するように計画することで蒸発塔の実在庫測定を実質的に避けることが可能である。バッファ貯蔵タンクは工程管理の目的から毎日サンプルされており，それらのデータは計量管理にも使用可能である。ミキサー．セトラー内のプルトニウムはコンピュータ・コード・ＳＥＰＨＩＳを用いた計算から決める。

動的計量管理の目標はＩＡＥＡの保障措置目標を満足するデータを作り出すことにあるのであるから，そのデータの検認の問題については本報告書で充分の考察を実施した。これにより，ダイナミック・システムの場合，検認というものは，「近似的に検認出来た」，「部分的に検認出来た」，「より精密に検認出来た」などのようにその程度が変わるような時空間にわたる連続性のあるもの（Continuum）であるべきであって，一刀両断的なもの（Dichotomy）であると考えてはならないことが判った。プロセスからの情報は常時大量に入手可能なのであるから，「ひとつのバッチについて，想定可能な最大の偽造は何か？」という類の質問を考えることは可能であり，かつ，それに対して意味のある，そして有用な回答を得ることが可能である。

この報告書で検討した検認思想を適用すれば，おおよそ１７％のバッチが毎週“部分的に検認”されなくてはならないことになる。この“部分的検認”の定義は，最大想定転用を１バッチから１～２００グラムPu に減らすのに充分なだけの検認というものである。同様にしてこの思想を適用すれば，１年間に処理するすべてのバッチに対して想定されうる最小転用量はPu で１０ｇであることも判った。これは典型的バッチに対して，バッチのタイプに依存して0.１６～0.３０％に相当するものである。多期間統計技術を施設者－査察者データの評価に際しても利用することになる。工程内の核物質の主な流れのそれぞれについて，検認のやり方を再検討している。この部分的検認によって突然転用（abrupt diversion）の可能性は無くなるので，「より精密な検認」は，そう大急ぎで完了しなくてはならないというものではなくなる。

著者の１人，猪川は，提唱する動的計量管理システムの大規模なコンピューター・シミュレーションを実施した。そのデータをまとめると，この計量管理モデル「１０－day－detection－time model」は，１２ケ月間にわたって転用した８ kgsのプルトニウムを検知することが出来るものであることを示している。同じ測定技術でも，これを在来型の計量管理で使った場合には，この検知は出来ない。

今後検討すべきいくつかの問題点を指摘している。まず最初の，そして最も重要な問題は，１０－day－detection－time model の現実プラントにおけるフィールドテストをする事である。他にも，ミキサー・セトラーに対するダイナミック・コンピューター・モデルの妥当性の検討ならびに，本研究成果を大型施設に拡張する検討などがある。

Contents

1. Introduction 1
   - A. Background 1
   - B. Objectives and Scope 2
   - C. Acknowledgements 3
2. Dynamic Materials Accountancy 4
   - A. Conventional Materials Accountancy - The Single Period Model 4
   - B. Dynamic Materials Accountancy 6
   - C. Multiple Period Statistical Analysis 8
     - 1. Cumulative Sum Statistics 8
     - 2. Linear Filtering Statistics 9
     - 3. Interpretation of Multiple Period Statistics 10
3. The Short Time Detection Model 14
   - A. Basic Model Description 14
   - B. Measurements 16
   - C. Unmeasured In-Process Inventory 21
4. Verification for International Safeguards 22
   - A. The Verification Problem - General Discussion 22
   - B. Statistical Considerations 24
   - C. Specific Verification Possibilities 26
     - 1. Input Measurement Verification 26
     - 2. Output (Product) Measurement Verification 27
     - 3. Waste Discard Measurement Verification 29
     - 4. Inventory Measurement Verification 29
   - D. Outline Safeguards Approach 30
5. Evaluation and Discussion 32
   - A. Simulated Process Data 32
   - B. Cost - Benefit Evaluation 36
   - C. Shorter Material Balance Periods 37
6. Current Status and Future Needs 40
   - A. In-Plant Field Testing and Demonstration 40
   - B. Application to Larger Facilities 42
7. Process Monitoring 43

References 46

目　　次

1. 序　論 …… 1
A. 研究の背景 …… 1
B. 目的と範囲 …… 2
C. 謝　辞 …… 3
2. ダイナミック計量管理 …… 4
A. 在来計量管理―単一物質収支期間モデル …… 4
B. ダイナミック計量管理 …… 6
C. 多期間統計分析 …… 8
1. 累積和統計 …… 8
2. 線型フィルタリング統計 …… 9
3. 多期間統計の解説 …… 10
3. 短期間検出モデル …… 14
A. 基本モデル …… 14
B. 測　定 …… 16
C. 測定しない工程内在庫 …… 21
4. 国際保障措置のための検証 …… 22
A. 検証の問題―概論 …… 22
B. 統計的考察 …… 24
C. 特定箇所の検証の可能性 …… 26
1. 入量測定の検証 …… 26
2. 出量測定の検証 …… 27
3. 廃棄物測定の検証 …… 29
4. 在庫測定の検証 …… 29
D. 保障措置法の概要 …… 30
5. 評価と検討 …… 32
A. シミュレーションデータ …… 32
B. コスト／ベネフィット評価 …… 36
C. より短かい物質収支期間 …… 37
6. 現状と将来の必要性 …… 40
A. 現場におけるテストとデモンストレーション …… 40
B. 大規模施設への適用 …… 42
7. プロセス・モニタリング …… 43
参考文献 …… 46

APPLICATION OF THE BASIC CONCEPTS
OF
DYNAMIC MATERIALS ACCOUNTANCY
TO THE
TOKAI SPENT FUEL REPROCESSING FACILITY

A Feasibility Study

1. INTRODUCTION

A. Background

In the Spring of 1977 the Japanese government proposed to the IAEA a number of research agreements whereby the IAEA and Japan would cooperate in the development of improved international safeguards for the Tokai spent fuel reprocessing facility. Among those proposals the one directly pertinent to this report is titled, "Study of the Application of DYMAC Principles to Safeguarding Spent Fuel Reprocessing Plants." The reference research agreement number is 2063/CF. The agreement was signed in November 1977, and the project officially commenced on 1 December of that year.

When, in the Spring of 1978, the governments of France, Japan, and the U.S.A. agreed on a cooperative effort given the acronym TASTEX, for Tokai Advanced Safeguards Technology Exercise, and invited the IAEA to participate, a task similar to that envisaged in the research agreement was incorporated into that programme. This report thus constitutes both a report on task F of the TASTEX programme and a report on research agreement 2063/CF.

In July 1978 representatives from Japan visited the Los Alamos Scientific Laboratory (LASL) for the purpose of reviewing the work being done at that facility related to dynamic materials control, largely the installation and demonstration of a DYMAC system at the TA-55 plutonium and mixed-oxide recovery, conversion, and fabrication facility. There was also a review and discussion of the modelling techniques developed at LASL for evaluating the effectiveness of alternative materials control systems for hypothetical model facilities.

In August, 1978, the Japan Atomic Energy Research Institute, which had responsibility within Japan for task T-F of the TASTEX programme, invited

J.E. Lovett, System Studies Section, Department of Safeguards, IAEA, to Japan for consultations on the feasibility of applying the basic concepts of dynamic material control to spent fuel reprocessing facilities. Three way discussions subsequently occurred in Vienna in October 1978, at which time agreement was reached as to the specific tasks to be undertaken by each of the participating groups.

Informal discussions were held on various occasions in Vienna or Los Alamos, as the participants had occasion to be together for other reasons. A workshop was held in Los Alamos on 23-25 July 1979, at which time all aspects of the feasibility study were discussed, with particular attention to the separate reports prepared by Ikawa [1] and Lowry and Augustson [2].

One of the major topics discussed at the LASL workshop was the question of field testing, and this topic was further explored by Mr. Lovett in Japan during early August 1979. As this report is being prepared it is generally agreed at the technical level that a field test should be conducted but there is no final commitment to such a test.

B. Objectives and Scope

The first objective of TASTEX task F is to study the feasibility of "back-fitting" a dynamic materials accountancy system into the plutonium process line of the already existing Tokai facility. Assuming that such a system would be feasible, (and, as this paper shows, the conclusion is that it would be feasible) further objectives are to estimate the effort required and the system capability, both in terms of quantitative sensitivity and in terms of timeliness, and to evaluate the overall cost-benefit status of dynamic materials accountancy for reprocessing facilities.

The fundamental concepts of dynamic materials accountancy are poorly described in the published literature. Indeed, to some extent the concept is still evolving. As a secondary objective, the authors have taken advantage of the current study to include sections which describe and analyze the philosophy of dynamic materials accountancy.

This report presents the work of the authors in an area of potential future importance to international safeguards. Its publication does not necessarily reflect the current policy or position of any of the countries or organizations represented, either with respect to dynamic materials accountancy or with respect to the safeguards goals which the study attempts to satisfy.

C. Acknowledgements

This report has been prepared as a joint effort, involving a number of persons of differing nationalities and employed by different governments or organizations, not all of whom are listed as co-authors. Indeed, some of the persons actually listed as authors should be thought of more as co-ordinators within their respective organizations or countries. Any list of contributors is bound to be incomplete, but specific mention should be made of the following:

T. Canada (LASL), who evaluated various measurement techniques; D. Cobb (LASL), who "found" the dynamic modelling approach for measuring the in-process inventory in the mixer-settler; T. Koizumi and N. Suyama (PNC) , who provided answers to many questions concerning the detailed design of the Tokai facility; and J. Shipley (LASL), who organized the discussion of multiple-period statistical models.

One of the authors (J. Lovett) would also like to express his sincere thanks to the Japan Atomic Energy Research Institute and to M. Hirata and K. Ikawa for their cooperation in providing funds for two trips to Japan to organize the study and to discuss the feasibility report, and for their warm hospitality during those visits.

2. DYNAMIC MATERIALS ACCOUNTANCY

A. Conventional Materials Accountancy - The Single Period Model

The traditional or conventional concept of materials accountancy is based on the material balance equation (eq. 1).

$$BI + R - S - MD - EI = MUF \qquad \text{(eq. 1)}$$

where: BI = Beginning Inventory
R = Receipts, nuclear production, etc.
S = Shipments, nuclear loss, etc.
MD = Measured (i.e., not estimated) discards
EI = Ending Inventory

This equation is normally solved by measuring and recording all receipts, shipments, and discards for some significant period of time, typically 6 - 12 months, after which the facility is shut down and the physical inventory is measured. If the observed MUF is non-zero, which it presumably will be because of errors in measurement, then a statistical evaluation based on Gaussian error propagation theory is performed to determine whether the MUF is statistically significant (i.e., statistically different from zero). If the observed MUF is not statistically significant, it is presumed to have arisen solely from measurement errors, and no action is taken. If the observed MUF is statistically significant, it is assumed that an unknown loss of some kind occurred (with theft or diversion being examples of possible "unknown losses"), and further investigations are undertaken.

Although this concept of materials accountancy has been in use for almost thirty years, the model is by no means ideal. Most facilities measure receipts and shipments for reasons other than materials accountancy, but the measurement of discards (which obviously have little value, else why are they being discarded) has appeared to many as not being economically justifiable. The need for periodic cessations of operations, during which the process equipment is cleaned and the physical inventory is measured, also is a point of question, and inventory frequency very often is a compromise between what the safeguards or materials control expert would like to have and what the process engineer would like to give.

Nor are Gaussian error statistics the ideal statistical evaluation mechanism. The complete error propagation for a large bulk processing facility is a major undertaking, and requires the generation of a significant volume of component uncertainty data, much of which does not relate directly to the measurement of nuclear material quantities. The need for more (or better) measurements and the corresponding need for better measurement characteristics (uncertainty data) can strain available resources and the optimum balance can be difficult to establish either in theory or in practice.

The usual error propagation model is also a single period model, one which makes no use of data from prior material balance periods. There have been some attempts to incorporate other statistical techniques which do use historical data, but the existence of only 1 - 4 material balances per year results in an unacceptably slow rate of data accumulation.

Thus the history of conventional materials accountancy has been one of constant compromises. There have been compromises on the quality of the data used in preparing the material balance, leading to statistically significant MUFs when there was no actual loss. There have been compromises on the quality of the data used in the statistical evaluation, leading both to statistically significant MUFs when there was no loss and to such large apparent uncertainties that a significant loss could have occurred without detection. Most important, there have been compromises on the frequency of material balance closings, leading to a serious loss of both timeliness and sensitivity.

Some of these problems are solvable, some are not. Where process and material control personnel understand each other's problems and work cooperatively, meaningful material balances and material balance evaluations can be and have been prepared. So long as taking a physical inventory implies process shutdown, for periods ranging from a few days to two weeks or more it is unrealistic to think in terms of more than perhaps two material balances per year, and those who define timeliness in terms of days are correct when they conclude that conventional material balance accountancy is not capable of such rapid response.

The combined measurement uncertainty associated with MUF seldom is much less than 0.5% of total throughput*. For reprocessing facilities the Agency's "international standard" is 1.0%. Ikawa [1] calculates that the Tokai repro-

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* Unless stated otherwise, all uncertainty estimates are standard deviations.

cessing facility can do slightly better; his estimate for a six month material balance is ± 0.84% on the assumption that major calibrations are repeated monthly to reduce systematic uncertainty effects. Using $\alpha = \beta = 0.05$, he concludes that the reasonably achievable international safeguards goal using conventional accountancy techniques is 32.0 kgs Pu, with a timeliness of six months.

Major efforts are being devoted to the development and improvement of mesurement techniques, but significant improvement is not likely. What is needed is a breakthrough from 0.84% to 0.084%, not a refinement from 0.84% to 0.78% (which Ikawa suggests could be achieved at the expense of weekly recalibrations). Since much of the combined measurement uncertainty for a six or twelve month material balance is systematic uncertainty, such a breakthrough could be achieved only through order of magnitude improvements in calibration and standardization techniques. There is little reason for optimism.

B. Dynamic Materials Accountancy

If conventional materials accountancy, working alone, has limited capabilities with regard to IAEA safeguards goals, what are the alternatives? Basically two have been put forward, namely (a) an increased reliance on containment and surveillance measures as complementary measures to conventional materials accountancy, and (b) an extension of materials accountancy into the near-real--time domain, here termed dynamic materials accountancy.

The basic argument of dynamic materials accountancy is that the major limitations of conventional materials accountancy are related to the size of the material balance, both in space and in time. If the material balance could be closed and evaluated at short time intervals or for short series of process operations (or, especially for projected larger facilities, if both could be accomplished), then many of the problems with conventional materials accountancy should either be eliminated or be reduced to more acceptable levels.

Dynamic, or near-real-time, materials accountancy is designed to improve the timeliness and sensitivity obtainable by more conventional accountancy methods, primarily through the use of in-process measurements (i.e., measurements performed during normal process operations, with little or no disturbance of the materials and the operations being performed) to prepare material balances about a short time period (e.g. one day or one week) or about a short sequence of process operations. Sensitivity generally is improved for a single material balance because less material is processed, and the uncertainty added by less precise in-process inventory measurements is considerably less than the uncertainties which accumulate over a months long material balance period. In addition, since usually several material balances are available over a short period of time, the multiple-period statistics discussed in the next section provide added senstivity, both for individual balances and for the series, through taking greatest advantage of the correlations among the material balances.

Sometimes, especially for fabrication facilities, it is possible and desirable to divide the process MBA into sub-areas, often termed unit process accounting areas (UPAAs). These sub-areas may have several advantages. First, they may simplify the problem of developing in-process material balance procedures, through simplifying problems of coordination. Second, sensitivity may again improve, especially with regard to single period analysis.

The UPAA structure may also constrain a potential divertor's flexibility. Arguments are advanced in Section IV which suggest that dynamic materials accountancy may limit the maximum falsification which can be hidden in one batch measurement, forcing the divertor to multiple falsifications and simplifying the detection problem. If the UPAA structure is such that falsifications must be passed across the inter-UPAA boundary, the inspector's detection problem is yet further simplified.

There is no theoretical reason why physical inventories must be taken by shutting down and cleaning out the process. The practice has arisen largely because early facilities were not designed in such a way as to permit taking a physical inventory on any other basis. Thus the basic dynamic materials accountancy model for reprocessing facilities is one of preparing closed material balances, based on directly measured in-process inventories, at intervals ranging from one day to one week. Normally the physical inventory is not totally complete, some material usually is not in a form or location where it can be measured. During the first material balance period this "unmeasured inventory" appears as MUF; in all subsequent material balance periods only the variation in the unmeasured inventory appears as MUF. Clearly both the magnitude of the unmeasured inventory and the magnitude of its normal variation must be small if the dynamic model is to achieve its objectives.

Mixed-oxide conversion and fabrication facilities, on the other hand, operate more nearly as batch processes, and it is more convenient to develop dynamic materials balances on unit processes and unit batches. Each "batch materials balance" is closed when processing of the batch is completed, a period which may vary but which usually is only a few days. Special procedures are necessary where batch operations remain uncompleted for periods longer than the desired detection time.

Since the scope of this report extends only to the feasibility of dynamic materials accountancy for the Tokai reprocessing facility, the concept of dynamic accountancy for mixed-oxide facilities will not be pursued further.

C. Multiple Period Statistical Analysis

A single period statistical model uses data generated from clean-out physical inventories taken at six or twelve month intervals, and does not consider correlations between successive materials balances. What is needed is a multiple period statistical model which can use data derived from in-process (i.e., non-shutdown) physical inventories taken at intervals of a few days up to perhaps one week, and which does explicitly incorporate sequential correlations. There have been a number of significant advances in the field of multiple period statistical tests which are proposed for use in connection with the dynamic materials accountancy study of the Tokai facility.

1. Cumulative Sum Statistics [6, 7]. The cumulative sum or CUSUM statistic examines the cumulative sum of all observed deviations from some defined reference or standard value, or from the mean of observed deviations in some previous time period. (It cannot use the mean of current observations, else by definition the cumulative sum would be zero). The "no diversion" hypothesis is that the cumulative sum of observed MUF values should tend to zero; the alternative "diversion" hypothesis is that the cumulative sum is non-zero, with the value at any moment being an estimate of the total amount diverted to date, and with the slope of the CUSUM curve being an estimate of the average amount diverted per unit time period.

Aside from its simplicity and intuitive appeal, CUSUM has the distinct advantage that its statistical derivation includes no assumption as to the quantity diverted per material balance period. If diversion occurs in the form of a single large removal (the so-called abrupt diversion), and if only data taken during that materials balance period is considered all statistical techniques are essentially equal in their detection capabilities*. If diversion

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* This statement should be understood in terms of the length of the material balance period and its corresponding effect on the standard deviation of the material balance. If the material balance period is short, resulting in fewer batches being processed, resulting in reduced measurement uncertainties, the detection capability for abrupt diversion is correspondingly increased as compared with six month or one year material balance periods.

occurs in the form of a constant small removal of x grams per material balance period, the uniform diversion test described in the next section has a greater statistical detection power. In between there is a large class of semi-constant, semi-random, and other removal patterns, and one cannot hope to define every possible pattern and develop a "best" statistical test in each case. CUSUM, by being independent of any assumed diversion pattern, establishes a reference detection capability.

In conventional single period statistical analysis the exact specification of detection probability is straightforward. The parameters needed are the magnitude of the assumed diversion, the combined systematic and random uncertainty in the material balance, and the acceptable probability of a false positive. For multiple period statistics the problem is more complex. Systematic and random uncertainties must be stated separately, and the number of material balance periods (or time) before detection occurs becomes an additional parameter. Again, Shipley [6,7] has succeeded in reducing the problem to a three dimensional plot in which detection probability is given as a function of total loss and materials balance number, with the false-alarm probability fixed. These plots, called "performance surfaces", clearly show the nature of the relationship among the parameters for any materials accounting system and any operating condition.

The particular performance surface obtained depends on the statistical tests used to analyze the data. The time performance surface, a composite based on a battery of tests, is complicated to calculate. However, a performance surface based only on the CUSUM test statistic provides a conservative indication of the system's performance because, as discussed above, the CUSUM is independent of diversion patterns. The time performance surface will be at least as good as the CUSUM performance surface.

2. Linear Filtering Statistics. In 1960 R.E. Kalman reported the development of a linear filtering statistical model which has since come to be known as the Kalman filter [8]. The concept was originally developed for use in the aerospace industry; its adaption to materials accountancy was first suggested by Pike and Morrison in 1977 [9]. The adaptation discussed here is largely due to Shipley [7], who uses the term "uniform diversion test".

The Kalman filter uses the first two moments of the measurement error statistics and the calculations may be performed sequentially, which has computational advantages. The basic assumption is that diversion, if it occurs, occurs at a constant rate. That is, the null hypothesis is that the mean amount diverted per material balance period is zero, and the alternate or diversion hypothesis is that a constant amount is being diverted each material balance period. The result of the calculation is an estimate of this "bias". Figures 1a and 1b illustrate typical Kalman filter graphic displays, with and without an artificially introduced diversion.

One might hypothesize that a would-be diverter, in an effort to foil the uniform diversion test, could add a random or pseudo-random component to his otherwise constant diversions. Doing so, however, would be expected to lead to a larger material balance error variance than if there were no diversion. This in turn leads to the suggestion that one could use two Kalman filters, one based on the null hypothesis, the other based on the observed mean difference, taken as the best available estimate of the value of the alternative hypothesis. The result, termed the sequential variance test, is roughly equivalent to the traditional F test for comparing two variances, now applied sequentially.

Finally, the early work of Stewart [10] in attempting to obtain minimum variance estimates of material balance accountancy status can be incorporated into the linear filtering concept. In effect, two filters are used, one running forward in time, the other moving backward, to generate better estimates of the intermediate physical inventories. Clearly the test may result in some delay, since some number of additional materials balances are used in the "backward" filter. The object, however, is increased sensitivity to the detection of relatively small diversions that might otherwise escape notice; such diversions clearly cannot be of a magnitude requiring immediate detection.

3. Interpretation of Multiple Period Statistics. The preceding two sections have defined four statistical tests, all of them to be performed daily or weekly, and three of them involving iterative calculations. In addition, there is no *a priori* basis for knowing when a diversion might have begun, or when the diverter might have decided that he had enough, or for some other reason decided to terminate his diversion effort. The logical conclusion, accordingly, is that all four tests should be performed using all possible starting and ending material balance periods.

There is also another factor which assumes a much greater importance in multiple period statistical analysis, namely the possibility (probability) of false positives. Most statisticians who have any significant experience with practical applications have come to realize that the usual statement, 5% probability of false alarm, means exactly what it says. If a given statistical test is performed twenty times, there is a very high probability that at least one of the results will be positive, even though no discernable cause can be isolated. Where tests are performed at the rate of one or two per year, a

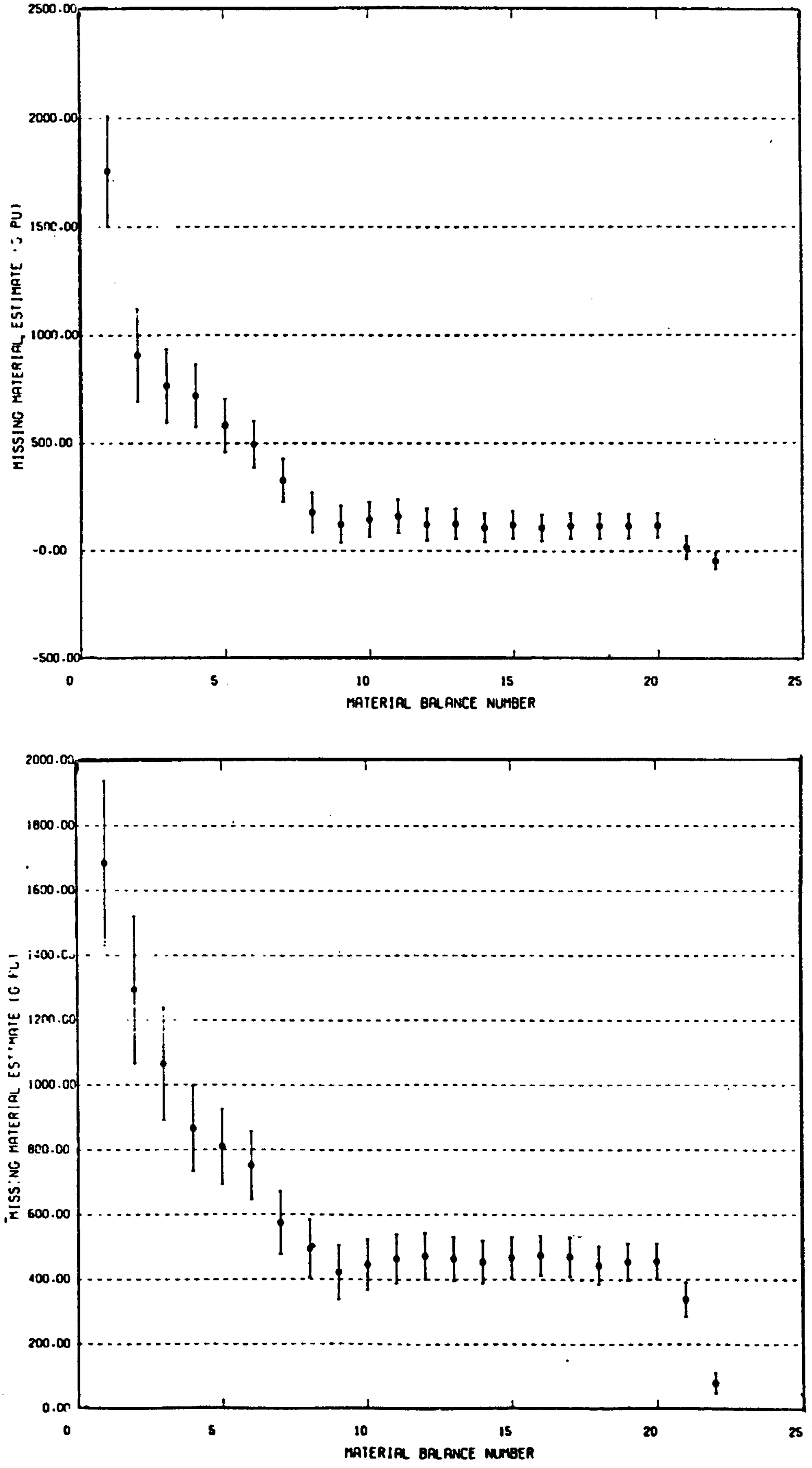


Figure 1a (top) showing a typical Kalman filter chart with no diversion, and figure 1b (bottom) showing the same data with an assumed diversion of 400 grams Pu per week (from[1]).

false alarm probability of once every ten years does not sound bad. Where four tests are performed once each week, the possibility of ten false alarms per year is intolerable.

On the other hand, simply adopting a false alarm probability of 0.001 or 0.0001, and taking no action until the test statistic at that level is violated, results in serious losses in detection sensitivity. The answer, as described by Shipley [7], is termed the "alarm sequence chart." Instead of performing each statistical test at one pre-defined level of significance, the question is asked, "At what level of significance is the test statistic significant?" If, for a given initial point, the estimated false alarm probability is 0.5 or greater, the sequence is defined as being of no significance and further calculations based on that initial point are terminated.

At the opposite extreme false alarm probabilities of 0.01 or less are considered as being of at least some significance, and in Shipley's terminology are coded with the letters A through G, A representing a false alarm probability of 0.01 - 0.005, and G representing a probability of less than 0.00001. The inspector thus is able to make his own judgements, giving little attention to an occasional A or B level alarm, giving an increased attention to groupings of B, C and D level alarms, especially when more than one test statistic is involved, but not "blowing the whistle" unless higher level alarms are involved or the test results are supported by his investigative results. Figure 2a shows an example of such an alarm sequence chart, taken from the simulation data published by Ikawa [1], in which no diversion occurred. Figure 2b shows the same material balance data, but with an assumed diversion equal to one standard deviation.

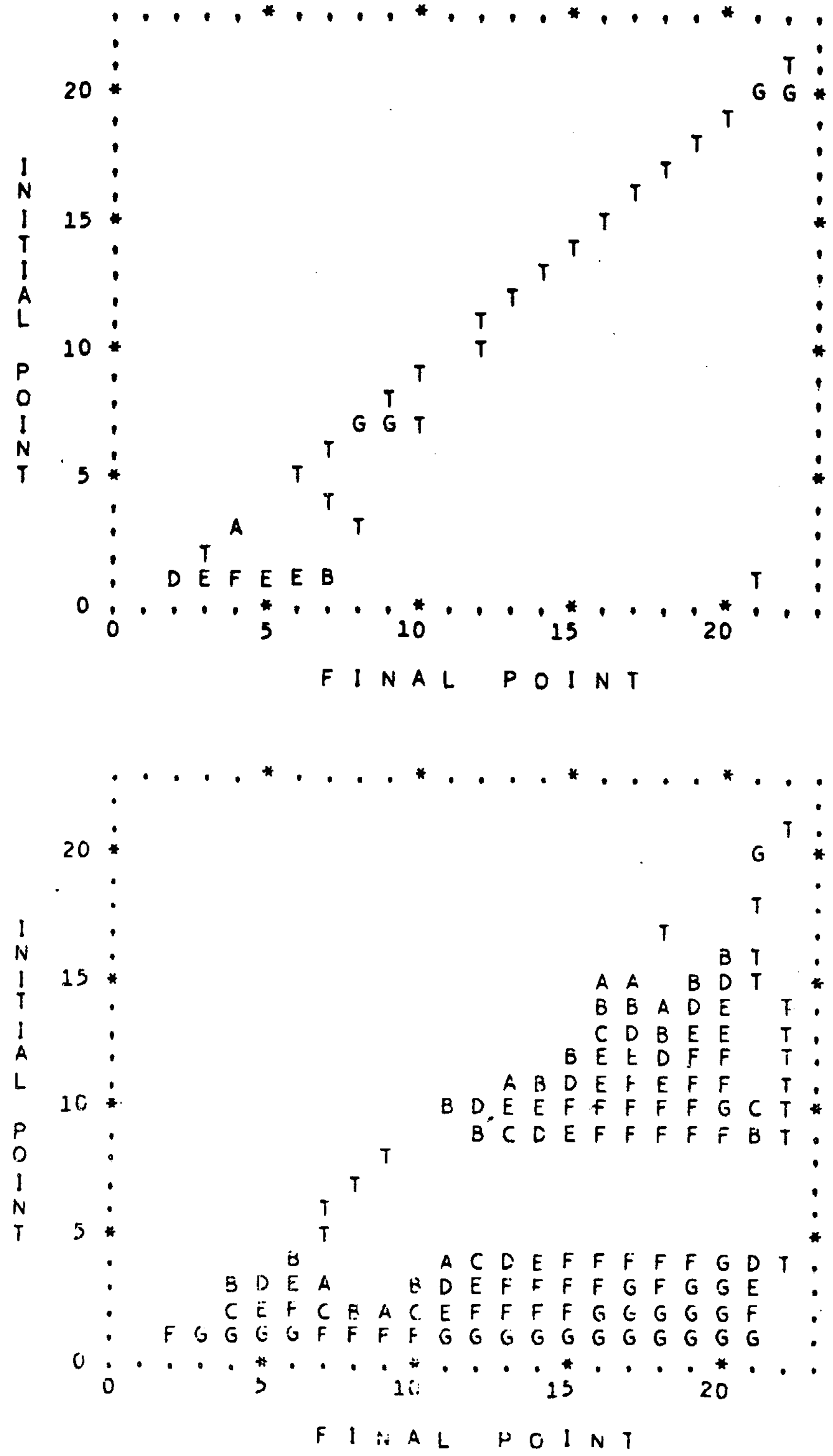


Figure 2a (top) and 2b (bottom) showing false alarm probabilities for the data shown in figures 1a and 1b. Since the first material balance period includes the unmeasured physical inventory, the bottom line in each chart should be ignored.

3. THE SHORT TIME DETECTION MODEL

A. Basic Model Description

It has been suggested that IAEA safeguards should be able to detect diversion of 8 kgs Pu, should it occur, within about ten days after the occurrence. This feasibility study accordingly has concentrated on what has come to be known as the "ten day detection time" model. The essence of that model is a weekly in-process physical inventory for the process MBA with the results to be available for evaluation and action no later than three days after the inventory cut-off point. That is, the material balance equation is to be solved once per week, and three days are allowed for the collection and evaluation of the data. It is perhaps stretching the definition to refer to such a system as "dynamic", but in actual fact essentially all of the problems associated with dynamic materials control exist in this "semi-dynamic" system. The ten day detection time system also serves as a benchmark against which the relative cost and relative effectiveness of more rapid and more timely systems can be evaluated.

It is not important exactly when during the week the dynamic material balance is prepared. For purposes of this study, however, it is assumed that the material balance cut-off point is Tuesday noon, and that the data collection and evaluation therefore is to be completed by Friday noon. Selection of Tuesday allows time on Monday for the resolution of any process difficulties which may have arisen over the week-end, yet still provides for evaluation of material balance data during the normal work week. As will be seen, the exact time of day is determined by the emptying of the product evaporator; the specification of noon here is for reference purposes only.

At or as near as possible to the agreed inventory point, the Pu product evaporator would be emptied into the product measurement tank (identified as Q_9 in reference 11). This product batch would be counted as having been removed prior to the inventory, and would appear on the weekly material balance as a product output (flow) batch. The determination as to when to discharge the product evaporator would be made by production personnel following their usual rules for making such a decision, with the added constraint that where possible the discharge would be scheduled to fall within the eight hour workday defined as the inventory cut-off time. In routine practice this may mean a somewhat greater attention, on the part of production personnel, to operations scheduling. Exceptionally, it might occasionally mean interrupting feed to the evaporator earlier than would otherwise be necessary, in order to allow the solution in the evaporator to reach the desired concentration prior to discharge.

As soon as possible after the discharge of the product evaporator, each of the four buffer storage tanks would be sampled for chemical analysis. The exact time of sampling would also be noted, and the volume in the tanks would be determined from the installed level recorders. Each of these tanks is normally sampled for process reasons once each day, so again the effect of this requirement is largely one of requiring production personnel to factor safeguards requirements into their operations scheduling. It is important, however, that these four tanks be sampled at the time of the evaporator discharge, and not just simply sometime during the day at the convenience of production personnel. (A delay of an hour or so, such as would be occasioned by assigning only one employee or team to take all four samples in sequence, is of no consequence).

Again taking the time of the discharge of product evaporator as the reference time, aqueous and organic flow rates to the three banks of solvent extraction mixer-settlers would be read from installed process instrumentation. These data, together with the measured Pu feed concentrations (from the buffer tanks) would be used to calculate the apparent Pu inventory in the mixer-settlers. This calculation is discussed in greater detail in section III.B.

Virtually the entire plutonium inventory in the Tokai facility is contained in one of the four buffer tanks or in the three mixer-settler contactors (a fourth set of mixer-settlers, concerned with the purification of separated uranium, contains no plutonium and is ignored in this feasibility study). The estimated remaining inventory, which in the ten day model would remain unmeasured, is in the order of 250 grams Pu, is widely scattered among many small process vessels, and has no safeguards significance. The normal variation in this remaining inventory has been estimated by Ikawa [1] as being as low as 28 grams when only one fuel type is processed. Ikawa obtained higher values, in excess of 1 kg, when the type and burnup level of fuels processed was changed drastically at frequent intervals, but this method of operation is considered highly unlikely for other reasons.

The ten day model allows a total of three days for completion of all measurements and evaluation of the resulting material balance data. It seems reasonable, assuming that the inventories are taken on Tuesdays, to ask that all measurement results be reported not later than Friday morning, allowing Friday for the necessary statistical data processing and evaluation.

B. Measurements

Figure 3 shows a schematic of the process MBA with the Key Measurement Points of interest identified as Q1, Q9, D1-D4. The parameters which govern the choice of measurement techniques are listed in Table 1 for these 6 KMP's. At present KMP Q1, Q9, D1-4 are sampled and sent for chemical analyses. As part of the TASTEX T-F study, alternative measurement methods relying on non-destructive assay have been examined and proposed for test and evaluation at the Tokai reprocessing facility.

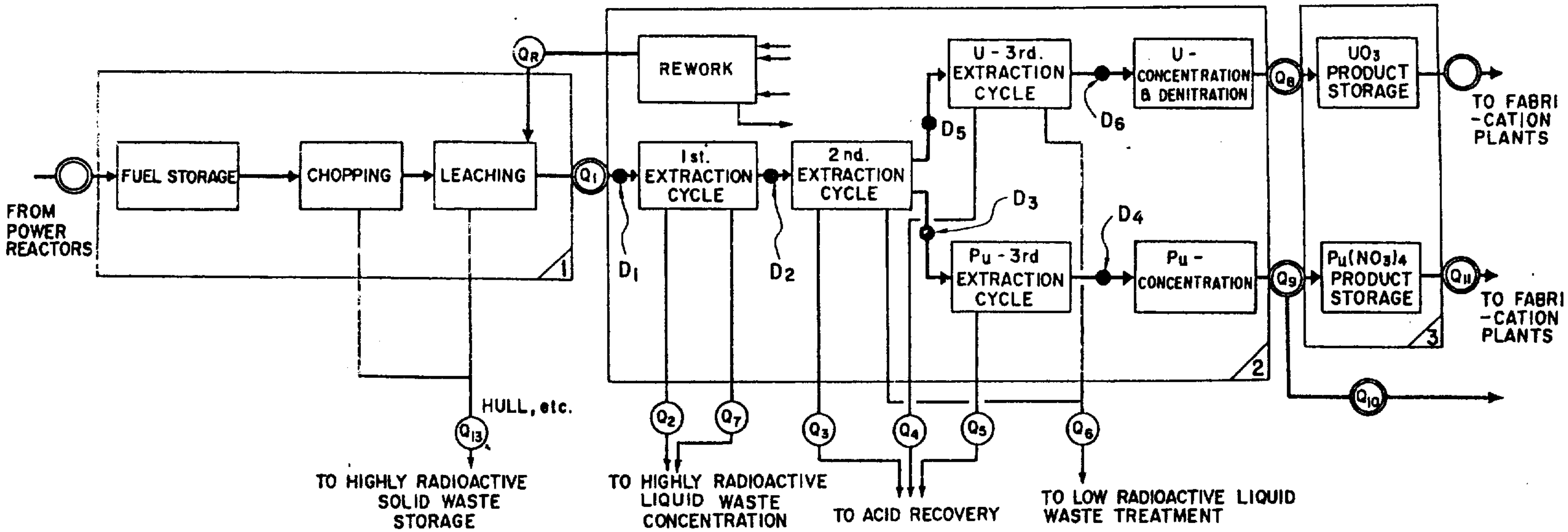
In addition, flow rate measurements at the inputs to the 1st, 2nd and 3rd extraction cycle are necessary to determine the in-process inventory contained in the mixer-settler contactors. These measurements of aqueous and organic flow rates as well as input plutonium concentrations do not directly measure the quantity of plutonium, instead they provide the input data to dynamic modeling calculations. These calculations, in turn, give quantitative estimates of the plutonium inventory in the contactors. The T-F study identified the need to compare the present modeling results with actual operational data and thus verify the validity of the calculations.

TABLE I

	Q 1/D1	D2	D3	D4	Q9
U Concent.	180 g/L	55	.8	0	-
Pu Concent.	2 g/L	.6	1.9	15	252
U/Pu	90	92	.42	0	0
GAMMA ACTIVITY	340 Ci/L	.3	.0034	00024	TRACE

Table I: Dynamic key measurement points and nominal concentrations of U, Pu, and fission products.

The measurement situation is summarized in Table I. Each measurement requires a sample to be taken and a determination of the corresponding total solution volume. There are also 3 in-line measurement techniques which have possible application to the assay of reprocessing plant samples, x-ray fluorescence, L-edge and K-edge absorption densitometry. The details of these tech-



	Q_1	Q_2	Q_3	Q_4	Q_5	Q_6	Q_7	Q_8	Q_9	Q_{10}	Q_{11}	Q_{12}	Q_{13}
	ADJUSTED FEED	Ist. CYCLE EFFLUENT	2nd. CYCLE EFFLUENT	U-3rd CYCLE EFFLUENT	Pu-3rd CYCLE EFFLUENT	SOLVENT WASH EFFLUENT	SOLVENT WASH EFFLUENTS	U-PRODUCT (UO_3)	Pu-PRODUCT ($Pu(NO_3)_4$)	Pu-PRODUCT SHIPPING OUT	Pu-PRODUCT SHIPPING OUT	REWORK EFFLUENT	HULLS
Batch/DAY	2	2	1	1	1	2	2	2	1	—	—	—	—

$D_1 \sim D_6$ = MEASUREMENT POINTS FOR DYNAMIC PHYSICAL INVENTORY TAKING

Material Balance Area 2 is defined as an Unit Process Accounting Area in the Semi-dynamic Material Accounting and Control system, i.e., "ten dey detection time model".

AREA No.

● BUFFER VESSEL .... DYNAMIC ACCOUNTABILITY POINTS

◎ MAIN ACCOUNTABILITY POINT

○ OTHER ACCOUNTABILITY POINT

Figure 3

niques and further references are presented in the LASL report [2]. The Tokai facility has the capability of performing x-ray fluorescence measurements, but PNC's experience to date with the quality of results is not as good as predicted by the research and development laboratories. Thus it would be useful to arrange closer communication between the R+D organizations and the analytical laboratory at Tokai if it is decided to utilize this technique as a safeguards measurement tool. An L-edge densitometry capability is not currently planned for Tokai but development and evaluation are being pursued at various R+D laboratories. An instrument based on the K-edge absorption principle will be installed at Tokai in the near future as part of TASTEX Task T-G. This instrument may be used to measure Pu product samples at KMP Q9.

The ten day detection model as proposed does not require the use of NDA measurements. Their advantage lies in the shorter times required to perform the assays and the automation possible with this type of instrumentation. They do require larger than normal samples (∼30 ml vs 1 ml)* and a significant capital equipment investment (∼ $ 100.000 - 150,000).

The plutonium content in the mixer-settler contactors of the 1st, 2nd and 3rd extraction cycles cannot be measured using sampling techniques because of the dynamic nature of these processes. At the present time, the approach which holds the most promise is to calculate the in-process inventory using measured flow rates of the aqueous and organic solutions and the input concentrations measured for the feed tanks. Dynamic model-type computer programmes have been written to calculate total plutonium and plutonium concentration profiles in mixer-settlers. These models are based on the programme SEPHIS ("Solvent Extraction Processing Having Interacting Solutes") or SEPHISJ for the Japanese version. A major problem with using the SEPHIS programme is the lack of experimental verification of the results. The Tokai facility could provide process data on the plutonium concentration profiles in their mixer-settlers and if the SEPHIS programme agrees with this empirical data, this would give credence to the in-process inventory estimates used in the ten day detection model. Because the SEPHIS code requires a large computer, a simpler model based on a model developed by LASL [6] has been proposed by Ikawa for the weekly material balances. This will help to improve the timeliness of results, but also has yet to be verified.

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* absorption-edge densitometry methods only.

TABLE II MEASUREMENT METHODS FOR KMPS ASSOCIATED WITH "TEN DAY DETECTION TIME" MODEL

KMP	PROCESS STEP	METHOD	NO. OF ANALYSES PER WEEK	TIME FOR ANALYSIS	ESTIMATED ACCURACY*
Q-1	Input accountability tank	Isotope dilution mass spectroscopy (I.D.M.S.)	14	8 - 12 hrs	
D-1	Feed tank for 1st extraction cycle	I.D.M.S.	1	4 hrs	
D-2	Feed tank for 2nd extraction cycle	Titration	1	4 hrs	
		X-ray fluorescence		1 - 2 hrs	1 %
D-3	Feed tank for Pu-3rd extraction cycle	Titration	1	8 - 24 hrs	
		X-ray fluorescence		1 - 2 hrs	0.5 - 1.0 %
D-4	Pu evaporator feed vessel	Titration	1	8 hrs	
		X-ray fluorescence or L-edge densitometry		1 - 2 hrs	0.5 - 1.0 %
Q-9	Pu solution product	I.D.M.S.	7	8 - 12 hrs	
		K-edge densitometry		1 hr	0.5 - 1.0 %

* does not include error in volume measurement

MODEL REPROCESSING PLANT

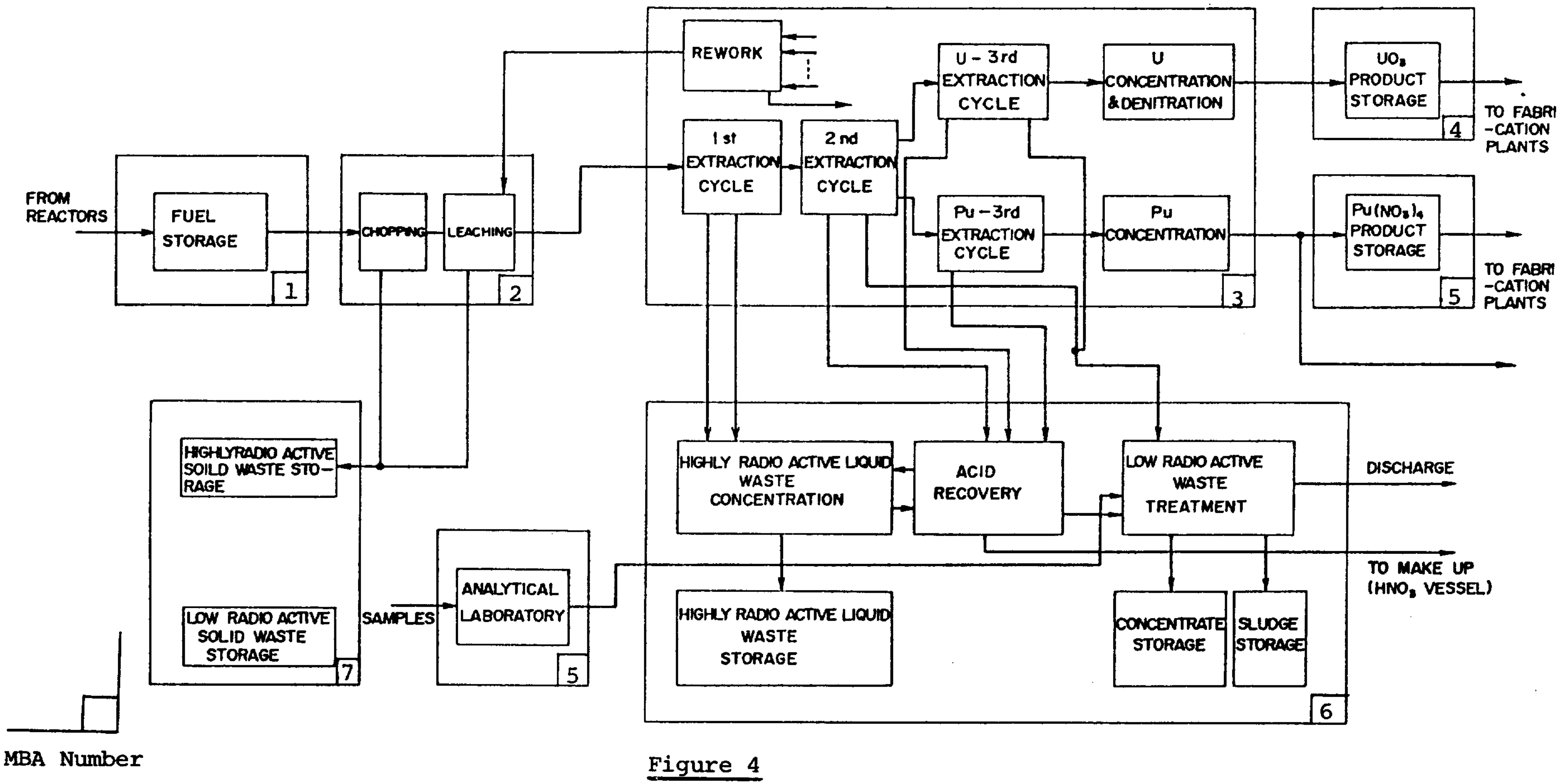

Figure 4

Table III

Plutonium Inventory Distribution

Location	Grams	Location	Grams
1st Feed Vessel	5300	Pu 3rd Extraction Cycle	760
1st Extraction Cycle	1770	Pu Evaporator Feed Vessel	3750
2nd Feed Vessel	2440	Evaporator	10600
2nd Extraction Cycle	1360	Product Receiving Vessel	10600
Pu 3rd Feed Vessel	1430		

C. Unmeasured In-Process Inventory

In the process of taking a dynamic physical inventory, there will usually be some in-process material that cannot be measured. This unmeasured component in the material balance equation can contribute significantly to the uncertainty in the material balance, depending on the amount of unmeasured material and its variation from batch to batch. In the ten day detection model, the effect on the ability to detect an 8 kg Pu diversion is two-fold. The amount of unmeasured in-process material shows up directly as MUF in the first material balance drawn. However, because this amount is now deleted from the beginning inventory for subsequent periods, the effect on these subsequent material balances is determined only by the week to week variation in the unmeasured physical inventory.

Using modelling techniques to simulate plant operations, Ikawa (1) studied the impact of these variations on the dynamic material balances. He assumed a worst case situation in which the mixer-settler inventories were unmeasured (whereas the feasibility study suggests that mixer-settler inventories can be effectively estimated using dynamic calculations). A number of process campaign sequences were studied (see chapter 5 for a more complete discussion), which would produce variations in the in-process inventory in excess of those likely to be encountered in actual operations. On the other hand, Ikawa's studies assume equilibrium plant operation for the fuel type being processed, a situation which cannot be depended on over long operating periods.

Since the simulation studies indicate that the unmeasured physical inventory varied only over very narrow ranges, even when the measured inventory was varying much more widely, it is concluded that variations in the unmeasured portion of the physical inventory are not likely to add sufficient uncertainty to the dynamic material balance to interfere with the detection of the protracted diversion of 8 kgs Pu.

4. VERIFICATION FOR INTERNATIONAL SAFEGUARDS

The ultimate usefulness of conventional materials accountancy data in international safeguards is dependent on several factors. Usefulness is dependent firstly on the existence of a suitable measurement technology, capable of performing the required measurements with the needed precision and accuracy and at acceptable costs. It is dependent secondly on the capabilities of the facility operator and his staff, who must implement the materials accountancy system. Finally, and no less important, it is dependent on the ability of IAEA inspectors to perform meaningful and timely data verifications. Verification cannot substitute for or improve the quality of poor measurements, but the best quality measurements are of little or no safeguards value if they cannot be verified in a meaningful and timely manner.

Similarly, the ultimate usefulness of dynamic materials accountancy data in international safeguards is dependent on exactly the same factors. The required measurement technology must exist, the facility operator must understand and be capable of implementing the dynamic materials accountancy system, and meaningful and timely data verifications by IAEA inspectors must be feasible. Previous chapters in this report have dealt exclusively with the problems of establishing a dynamic materials accountancy system at the level of the facility operator. This chapter addresses the question of independent IAEA verification.

A. The Verification Problem - General Discussion

The theory for the verification of conventional materials accountancy data at a reprocessing facility is reasonably well developed and understood. The practice, in implementation of that theory, is less well developed. Some of the problems result from the fact that the IAEA has limited actual experience in safeguarding reprocessing facilities. These problems, it may be supposed, can and will be resolved in due course. Other problems, however, appear to be more fundamental, and stem from the fact that verification theory was developed without taking into consideration current questions of short detection time. The paragraphs that follow accordingly examine some of the basic assumptions of verification theory, and in particular discuss areas in which this theory must be modified if it is to be applied to the verification of dynamic materials accountancy data.

In conventional materials accountancy the inspector usually has no definite knowledge as to how many batches there should be, nor as to how much material (i.e., general process range) should be in any given batch. Simple falsifications such as failing to report an input batch, or reporting an output batch as containing 16 kgs Pu when in fact it contains only 8 kgs Pu, are falsification possibilities which are, in conventional materials accountancy, at least superficially credible. Verification theory specifically recognizes this possibility of "gross defects", and indeed the sample size for "attribute"inspection (does the item or batch physically exist, and is its nuclear material content approximately correct) usually is the determining factor in the development of statistical sampling plans.

In dynamic materials accountancy the on-site inspector (the existence of one or more on-site inspectors is a working assumption in nearly all dynamic materials accountancy systems) has available an extensive body of corroborative information related to the number of batches and their typical content. This corroborative data, supplemented where necessary by specific attribute verifications, can be organized into an effective assurance against gross data falsifications. Sections IV C through F examine in detail the specific corroborative verifications proposed for the PNC-Tokai ten day detection model; the following paragraph gives one illustrative example.

The PNC-Tokai facility is designed to produce two input dissolution batches every twenty-four hours, each containing approximately 350 kgs of dissolved fuel, and therefore approximately 2.5 - 3.5 kgs Pu. The facility operator may, for a variety of reasons, interrupt dissolution temporarily, or produce a batch containing significantly less dissolved fuel than is normal. Both occurrences are in all cases known to the on-site inspector. Falsification of input measurement data is also constrained by:

a) Data supplied by the reactor operator
b) Comparison with other batches of the same fuel type during the same campaign
c) Isotope correlation calculations

The maximum falsification which conceivably could be incorporated into a single dissolver measurement batch requires more complex calculations than are attempted here, but is certainly less than 500 grams Pu. It may be as small as 100 grams Pu. If the diversion of 8 kgs Pu is to be concealed by the falsification of input measurement data, then the minimum number of batches which must be falsified is at least 16, and may be as high as 80.

In conventional materials accountancy, verification is largely a dichotomy. Any given item of data either is "verified" or "not verified", and intermediate possibilities are generally not recognised. The existence of extensive corroborative data, however, suggests that for dynamic materials accountancy verification should be thought of as a continuum, in which there are many degrees of partially verified, more precisely verified, accurately verified, etc. The question then is not, "How many batches should be verified in order to achieve a defined confidence level", but rather, "How much more verification, and at which levels, is needed in order to raise the existing confidence level to the level desired".

The consideration of verification as a continuum rather than as a dichotomy must also be applied with regard to the timeliness of verifications. If the assumed scenario is an abrupt diversion of 8 kgs Pu during one single seven day material balance, then (for PNC-Tokai) the total number of material balance line items is 35 (14 input, 7 output, and 7 each beginning and ending inventories), and the minimum falsification, assuming that all batches are falsified, is 228 grams. If rough verification procedures can be defined which would detect falsifications of 228 grams or larger, then abrupt diversion during one material balance period can be excluded, and more accurate verifications can be performed more slowly. If rough verification procedures exist which would detect falsifications of 100 grams Pu or larger, then "abrupt" diversion over a three week period can be excluded, giving even more time in which to perform accurate verifications.

B. Statistical Considerations

For the PNC-Tokai facility there are no flow or inventory batches which contain 8 kgs Pu. From this it follows that the concealment of a significant diversion through the falsification of a single measurement is not a credible possibility. Indeed, if the above arguments about corroborative evidence lead to the conclusion that the maximum credible single falsification is 500 grams Pu or less, then the minimum number of falsifications is 16. Since only one of these falsifications need be detected in order to claim that diversion has been detected, the fraction of the total "population" which must be verified (for 95% confidence) is 0.17. Ignoring adjustments for sampling without replacement from a finite population, this is only six batches, not an unreasonable number.

This result must be used with some care, however. The derivation assumes that all batches are nominally equal with regard to "probability of being falsified", a situation which may or may not exist. The batches clearly are not equal in general physical properties, but "probability of being falsified" implies a subjective analysis which is virtually impossible to quantify. The derivation also assumes that the six batches verified would be selected completely at random. There appear to be no serious obstacles to such a random selection, the inspector could make his selection secretly in advance, but there may be reasons why such a procedure might not be desirable. It could happen, for example, that the random selection would be completed during the first 19 batches, leaving the operator (who would know that the sample size was six) free to falsify the remaining 16 batches. Thus the discussion here is not meant to suggest that attribute verification should be performed on a random sample of 17% of the batches, but rather to demonstrate qualitatively that a high degree of confidence against gross falsifications will not require that all or nearly all batches be verified.

Moving from the subject of rapid approximate verifications to the ultimate problem of accurate verification against small measurement biases or pseudobiases, it should be recognized that the same advanced statistical techniques which were discussed in Chapter II in terms of the evaluation of material balance data are also equally applicable, and equally effective, for comparing a series of IAEA verifications with the corresponding operator measurements. CUSUM, for example, can be used to evaluate the cumulative difference, operator minus inspector, for any series of verification measurements. If "sigma" is defined as representing the combined uncertainty in the operator and inspector measurements, without here defining the precise manner in which sigma is to be calculated, the CUSUM should be expected to detect a non-random difference between the operator and the inspector measurements when the cumulative difference reaches about eight or ten sigma. Since comparative measurements will accumulate at a rate of more than one per week, the eventual detection power over a three month period may be as good as 0.2 - 0.5 sigma.

The other statistical techniques discussed in Chapter II are also applicable. If the operator minus inspector statistic is constant, then the uniform diversion test is superior to CUSUM, and detection should occur even sooner than indicated above. If a random component is deliberately introduced in order to confound the uniform diversion test, then the apparent "sigma" derived from the actual variations in the data will exceed the sigma calculated from known component uncertainties or from past data which did not include data falsifications, and this fact will be detected by the sequential variance test.

If 500 grams Pu represents the maximum single falsification which would not be immediately obvious, then approximately 10 grams Pu represents the minimum single falsification which, extended over every input and output batch for an entire twelve month period, would yield an ultimate diversion of 8 kgs

Pu within one year. (Diversion rates of less than 8 kgs Pu/year are discounted as being impractically slow, at least in terms of 95% detection probabilities). For a typical input batch, 10 grams is about 0.3%; for output batches it is about 0.16%. These are small percentages, but not necessarily hopelessly small. If "sigma" as previously defined can be kept to 1.0% or less, which seems reasonable, then these minimum credible diversion rates should be detected within three to six months using the advanced statistical techniques described in Chapter II. Even if sigma cannot be kept to 1.0%, it should be recognized that these are true minimum rates, achievable only if every single measurement is falsified. Any other strategy, designed to interfere with statistics such as the uniform diversion test, would increase the size of the bias and would in fact tend to make detection easier.

C. Specific Verification Possibilities

1. Input Measurement Verification. There are, as has been noted, 14 input dissolution measurement batches per week, or approximately one every twelve hours. Each batch normally contains one PWR or two BWR fuel assemblies, equal to about 350 kgs of dissolved fuel, and therefore contains about 2.5-3.5 kgs Pu, depending on the fuel's burnup history. Koch [12] has reviewed the status of input measurement technology, noting that a simple "volume x analysis" measurement usually is the method of choice for facility operators, but also noting that two alternative techniques, the Pu/U ratio or gravimetric method and the tracer addition method, are potentially available for IAEA verification use even where they are not used by the facility operator. Isotope dilution mass spectrometry is in all cases usually the analytical method of choice.

The ultimate verification of input dissolution measurement data must of necessity be based on independent IAEA analysis of samples (resin bead?), coupled with Pu/U ratio method extrapolation of analytical results to total quantities. This method does not free the inspector from dependence on samples taken by the facility operator (such dependence seems in general unavoidable, even in conventional accountancy), but it does make the inspector independent of tank volume calibrations. Further study and development is needed before inspectors can use independent tracer additions, but this development should be pursued. Since with tracer additions the operator would not know the correct dilution factor, falsification of his own measurement data would be difficult, possibly impossible. Statistical comparisons could be used to ensure that batches to which tracers were not added were identical (with regard to measurement differences) to batches that were spiked, giving the system considerable effectiveness.

It is assumed that current administrative difficulties can be resolved such that samples can be shipped to the IAEA's analytical laboratory and analyzed by it within a period of three to four weeks, but probably not much more rapidly. Pending receipt of the verified analytical result, the inspector must attempt to use a variety of consistency checks to protect against gross falsifications. A number of possibilities can be suggested; their actual effectiveness remains to be determined in any quantitative sense.

a) Simple comparison with the normal range within which such batches usually lie should be adequate to within 500 g Pu or less.

b) A more explicit comparison of a given batch with those immediately preceding and following it should be adequate to within 200 g Pu or less. This comparison is subject to a startup problem, in that until the first few batches have been accurately verified the inspector cannot be certain that his comparison standard has not been falsified. Data obtained from the reactor operator (or from the inspectors assigned to inspect the reactor operator) may be useful in overcoming this startup problem. The true effectiveness of these comparisons needs to be investigated carefully during early operations, since they will ultimately define the need for other rapid verifications or the time which can be allowed to complete the accurate verification.

c) Isotope correlation techniques, using isotopic data supplied by the facility operator. These isotopic data are not as easily falsified as might be supposed. The residence time for Pu in the Tokai facility is at most 2-4 days, and it will quickly become apparent, from product measurements, whether input isotopic data have been falsified to any significant extent. (See the next section for a discussion of verification possibilities for product measurements).

2. Output (Product) Measurement Verification. Under normal operations there should be seven product output batches per week, or approximately one every 24 hours. If the facility is operating at equilibrium, which of course is the assumption throughout this report, the Pu available for product output batches will vary in the range 5 - 7 kgs Pu per day, depending on the Pu concentration in the fuel being processed. Rather than discharge batches of varying concentration, however, the more common practice is to vary the time between discharges, maintaining a fairly consistent Pu concentration and volume across the batches. Thus the nominal 24 hour discharge cycle propably will, in actual practice, be a 20-28 hour cycle. This is not expected to create any problems in the dynamic accountancy system, although the potential exists, in

extraordinary circumstances, to ask that the operator interrupt evaporator feed, continue evaporating the solution in the evaporator until the desired concentration is reached, and discharge a short batch. With proper coordination and scheduling between the operating staff and the safeguards or accountancy staff, however, this eventuality should not be necessary.

Although the basic measurement method for output solutions, as described in Chapter III, is again a straightforward volume x concentration, a number of possibilities exist for the operator's analytical measurement and for the IAEA verification. These include potentiometric or coulometric titration, absorption edge densitometry, and isotope dilution gamma spectrometry. If titration is used by the facility operator (which it undoubtedly will be, at least until the PNC analytical laboratory has acquired a familiarity with the absorption edge densitometer), then it is likely that IAEA verification would have to be based on independent analysis of verification samples. If or when the absorption edge densitometer being developed and installed under TASTEX task G is adopted, a major part of the verification probably could consist simply of close observation of that measurement. This has distinct advantages, since it would eliminate the need for approximate verifications pending receipt of analytical results. The problems of making the absorption edge densitometer tamper-resistant or tamper-indicating are being examined under that project, and are not discussed here.

All proposed measurement and verification procedures appear to require a dependence on the operator's sampling technique. This dependence is not unique to dynamic materials accountancy; conventional materials accountancy is also dependent on the validity of the operator's product samples. The long range solution to this problem would appear to be an in-line instrument of some type, perhaps a high resolution gamma spectrometer. (Although the solution is flowing, so that any given molecule would be in front of the detector only a short time, the solution is presumably homogeneous and the total transit time should be long enough for a reasonably precise measurement.) One could also imagine that the absorption edge densitometer could be installed in line, not necessarily in the PNC-Tokai facility, but in future reprocessing facilities.

The volume of solution measured can be verified, at least approximately, by inter-comparison of the volume in the evaporator itself (from the strip chart recorder), the measured volume in the product measurement tank, and the increase in volume (again from continuously recording process instrumentation) in the product storage area. Consideration should also be given to an occasional (perhaps once per week) verification sample from the product storage area. The concentration, both Pu and isotopics, of this sample is a function of the volumes and concentrations of the individual batches added and removed during the period, and would be extremely difficult to falsify. The purification process is rarely so effective that one cannot, through high resolution gamma spectrometry, detect residual traces of some fission product, and the verification that these residual activities were consistent would add yet one more dimension to the falsification/verification process.

3. Waste Discard Measurement Verification. The quantity of plutonium in waste discards, a maximum of about 2% of the material processed, is such that abrupt diversion could not be concealed through the falsification of waste data. (The facility conceivably could claim process difficulties and record a fictitious 8 kg special discard, but such an event would be so grossly extraordinary as to invite special investigation by its very nature). Waste discard measurements still could be used to conceal a long term protracted diversion, but the absence of abrupt diversion possibilities eliminates the need for highly timely verifications. It is assumed here that waste discard measurements would be verified by observation and by the submission of randomly selected samples to an independent IAEA laboratory for analysis.

4. Inventory Measurement Verification. The falsification of inventory data is not an efficient means of concealing diversion, whether abrupt or protracted, since such falsifications only transfer the apparent loss to the next accounting period. In conventional materials accountancy, when the accounting period may be six or twelve months long, this transfer has some meaning. In dynamic materials accountancy, where the accounting period is only one week long, the falsification of inventory data might be given some credibility as a means of temporarily concealing an abrupt diversion, but the total in-process physical inventory at PNC-Tokai is so small that falsifications on the order of 4 - 8 kgs Pu are outside the range of normal operating parameters.

The first buffer storage tank, and therefore the first mixer-settler system, is easily verified, since the concentration is essentially determined by the last one or two batches dissolved, measured and transferred to the buffer tank. Since all four buffer tanks are sampled daily by the operator, and since the tank concentrations should be more or less smoothly varying "sinusoidal" functions of time, considerable verification can also be obtained by simply reviewing the operator's daily concentration data, and by comparing that data with process operating parameters. As a final check, it is probably desirable that randomly selected inventory samples be submitted to SAL for verification analysis.

D. Outline Safeguards Approach

This is a report of a feasibility study, not a specific definition of a safeguards approach for the PNC-Tokai reprocessing facility. If there is to be a field test, or if the concept studied in this report is to be utilized in any manner, there should be a detailed description of the proposed inspection procedures, defining not only exactly what verifications are to be performed, but also what they are expected to accomplish and under what circumstances they would be assumed to have detected diversion. Nevertheless, it does appear desirable to outline here, in general terms, how the authors believe the dynamic materials accountancy system studied might be integrated into a complete safeguards approach.

Without reviewing the merits (or lack of merit) of trying to seal spent fuel shipping casks at the reactor site, it is assumed that most or all casks will arrive unsealed. All such receipts would be verified, using 100% counting and identification, and perhaps random gamma scanning. C-S measures would be used to protect against the clandestine receipt of spent fuel, and to monitor the spent fuel storage area.

For all dissolver batches the inspector would verify the identity of the spent fuel assemblies dissolved, and would collect whatever data could be obtained regarding the supposed Pu content of those assemblies. Actual measurement of input accountability batches would also be verified on a 100% basis, and to the extent possible the inspector would attempt to monitor the transfer of the samples to the analytical laboratory and the subsequent treatment and preparation of IAEA samples.

A similar approach would be taken with regard to product batches. All product measurements would be observed and verified to the extent possible, and sample treatment would be controlled insofar as possible. The product measuring system would be controlled by C-S measures between declared measurements, to protect against possible undeclared transfers. The product storage area itself likewise would be controlled using C-S measures.

It is assumed that the inspector would be allowed more or less uncontrolled access to the control room and its instrumentation, and in particular would be allowed to read/copy a variety of volume or flow records. The exact manner in which these operating data would be inter-compared needs further consideration, but these inter-comparisons are an integral part of the verification of dynamic accountancy data.

Finally, it is assumed that the inspector would have available to him a small computing capability. For the purposes of the field test which hopefully will be performed in the near future, computing capabilities at JAERI-Tokai could be used. These facilities are not truly "independent" to the extent usually required for IAEA safeguards, but they are external to PNC, and would effectively simulate nearly all problems associated with IAEA operation of its own computing facility.

5. EVALUATION AND DISCUSSION

Previous chapters in this feasibility study have described the background which led to the study, the advanced "multiple period" statistical techniques which give dynamic materials accountnacy their sensitivity to small protracted diversions, the ten day detection time model which is proposed for the PNC-Tokai facility, the two-level verification philosophy which makes it possible to develop meaningful verification procedures for dynamic accountancy data, and the specific verification procedures which are proposed for the PNC-Tokai ten day model. This chapter reviews and evaluates the proposed ten day model, and considers possible variations in the model which have been proposed.

A. Simulated Process Data

Ikawa [1], starting from similar simulation models developed at the Los Alamos Scientific Laboratory, has developed and applied a computer simulation model for the PNC-Tokai Pu process area. Some twenty simulation runs have been published, covering a wide range of fuel types, operating conditions, and assumed diversion strategies. The simulations also include two levels of materials accountancy accuracy, one which is believed to be representative of current practice, and one which is believed to represent potentially achievable improvements. (Most of the supposed improvements either are in the process of being installed or still require development and demonstration; their absence in the existing facility should not be taken as a criticism).

Tables 4a and 4b, reproduced from [1], summarize the ten basic simulation runs and the results obtained. The first six cases assume a processing run of 150 days, followed by a shutdown inventory period of thirty days, the difference between the runs being the burnup level (and hence the Pu concentration) of the fuel. Case 7 assumes a ten day "flush-out" inventory mid-way in the 150 day processing run, and case 8 assumes three such flush-outs. Cases 9 and 10 assume a 90 day processing run followed by a thirty day cleanout inventory, with and without a ten day flush-out inventory mid-way in the campaign.

Case 5 was divided into two important sub-cases, discussed in a later paragraph. Eight additional cases were used to study variations in the level of measurement uncertainties (in the direction of improved measurements) or calibration frequency. Since the basic set of ten simulation runs demonstrates

Table IV a

Summary of the Simulation Studies

- In case of no diversion -

(these values are for plutonium)

		Dynamic Material Accounting				Traditional Material Accounting		
		Average			Kalman filter Estimate			
Case	Total feed (kg)	$\overline{MUF}_d$ (g/DMB)	$\sigma\overline{MUF}_d$ (g/DMB)	LEMUF $=2\sigma\overline{MUF}_d$ (g/DMB)	MUF_d (g/DMB)	MUF (kg/TMB)	σMUF (kg/TMB)	LEMUF $=2\sigma$MUF (kg/TMB)
S.S.1-1	414.00	99	224	448	32	2.171	3.358	6.796
S.S.1-2	532.00	112	294	588	-68	2.470	4.364	8.728
S.S.1-3	624.00	142	354	708	110	2.988	5.122	10.244
S.S.1-4	492.00	76	267	534	-58	1.662	4.036	8.072
S.S.1-5	760.00	152	417	834	137	3.352	6.234	12.468
S.S.1-6	894.00	256	506	1012	261	5.630	7.332	14.664
S.S.1-7	711.36	162	399	798	161	3.567	5.844	11.688
S.S.1-8	614.08	98	363	726	239	2.165	5.063	10.126
S.S.1-9	443.84	140	383	766	78	2.107	3.851	7.702
S.S.1-10	395.20	169	361	722	139	2.537	3.447	6.894

DMB : Dynamic Material Balance Period = 7 days

TMB : Traditional Material Balance Period = {6 months for S.S.1-1 ∼ S.S.1-8
{4 months for S.S.1-9, 10

Div : Diversion

Table IV b

Summary of the Simulation Studies

- In case of diversion -

(These values are for plutonium)

		Dynamic Material Accounting					Traditional Material Accounting			
			Average			Kalman Filter Estimate				
Case	Total feed (kg)	Div. rate (g/DMB)	$\overline{MUF}_d$ (g/DMB)	σ_{MUF_d} (g/DMB)	LEMUF $=2\sigma_{MUF_d}$ (g/DMB)	MUF_d (g/DMB)	Total Div. (kg/TMB)	MUF (kg/TMB)	σ_{MUF} (kg/TMB)	LEMUF $=2\sigma_{MUF}$ (kg/TMB)
S.S.1-1	414.00	226	325	226	452	228	4.742	7.153	3.381	6.762
S.S.1-2	532.00	292	416	290	580	324	6.133	9.154	4.341	8.682
S.S.1-3	624.00	343	483	348	696	492	7.205	10.136	5.096	10.192
S.S.1-4	492.00	268	361	263	526	281	5.637	7.984	4.017	8.034
S.S.1-5·1	760.00	418	577	420	840	625	8.780	12.695	6.204	12.408
S.S.1-5·2	760.00	100	267	419	838	269	2.107	5.881	6.229	12.458
S.S.1-6	894.00	492	700	496	992	689	10.332	15.400	7.300	14.600
S.S.1-7	711.36	391	526	403	806	538	8.217	11.579	5.820	11.640
S.S.1-8	614.08	355	372	365	730	255	7.096	8.187	5.039	10.078
S.S.1-9	443.84	614	652	376	752	791	7.978	9.778	3.813	7.626
S.S.1-10	395.20	560	590	365	730	376	7.274	8.843	3.417	6.834

DMB : Dynamic Material Balance Period = 7 days

TMB : Traditional Material Balance Period = $\begin{cases} 6 \text{ months for S.S.1-1} \sim \text{S.S.1-8} \\ 4 \text{ months for S.S.1-9, 10} \end{cases}$

Div : Diversion

an adequate detection capability, these additional runs are of little importance, and are not discussed here. One last run is important, however, and is discussed. Specifically, simulation run S.S.4 assumed that the facility operator changed fuel types at thirty day intervals, with ten day flush-outs between burnup levels. Since the effect is to introduce artificially large variations in the in-process inventory, and since no process operator is likely to operate in such a manner, the run demonstrates the capabilities of dynamic materials accountancy under conditions more adverse than those likely to occur.

In general, all simulation runs assumed that the divertor removed material at the rate of one standard deviation of the weekly dynamic material balance per week. A diversion rate of 1.5 std. dev. was assumed for runs 9 and 10, and a diversion rate of only 0.25 std. dev. was assumed for run S.S.1.5.2.

The first important fact to note from table 4b is that conventional materials accountancy detected diversion is only six of the ten cases, and that in all cases detection was somewhat marginal. In the two runs where 1.5 std. dev. were diverted, the ratio of MUF to its std. dev. was about 2.6, but in all cases where only 1.0 std. dev. per week was diverted the maximum ratio was 2.12, only slightly above the required factor of 2.0. Since most cases involved a diversion of 8 kgs Pu in about six months, and all cases except S.S.1.5.2 involved a diversion of over 8 kgs Pu per year, this record for conventional materials accountancy is not especially good.

In contrast, the Kalman filter calculation detected diversion in all ten cases, even in S.S.1.5.2 where the total diverted over a twelve month period is only a little over 4 kgs Pu. Table 4a suggests that the Kalman filter also detected "diversion" in two cases where none occurred. Examination of the alarm sequence charts, however (not reproduced here), shows that in fact the Kalman filter did not suspect diversion in one case, and gave a highly ambiguous record in the other. There is little question but that the latter case would have caused the inspector to conduct some sort of inquiry, but he could not have alleged diversion without more positive data than given in the alarm sequence chart.

Ikawa does not publish complete data for simulation run S.S.4, in which the assumed burnup levels were varied at thirty day intervals. He does publish a comparison between S.S.1.8 and S.S.4, however. Since the runs are identical in all aspects except the changing of burnup levels, the demonstration that the standard deviations of the two material balances are virtually identical indicates that attempts to foil dynamic accountancy by introducing wide swings in the in-process inventory would not be successful. This is not an unexpected result, since the bulk of the in-process inventory is physically measured, and it is only variations in the residual which might disturb the calculations.

B. Cost - Benefit Evaluation

No valid cost data was collected during the feasibility study, but the qualitative appearance is that the cost of implementing the dynamic materials accountancy system should be minimal for the facility operator and acceptable for the IAEA. The system does not require the facility operator to perform any additional measurements, but it does require that the timing of measurements be constrained by safeguards requirements. It also requires a more rapid completion of at least some analytical results. These costs cannot be neglected, but neither can they be estimated with any validity.

On the IAEA side, the system will require an on-site inspector, but this is current inspection practice already. Whether the inspection activities prove to be more than one man can handle remains to be determined, and probably will depend to a considerable extent on what current inspection activities can be dropped or reduced. If the answer is none, then a second on-site inspector probably would be required, because current inspection practices leave the inspector little free time.

As was noted in Chapter IV, the IAEA will have to have an on-site computing capability. If this computer is operated by the inspector himself, which should be possible, only the $100-200 000 initial investment should be a cost factor. If the inspector is too busy to take on yet one more activity, and it is decided to provide an IAEA computer operator in Japan, then the costs of that operator would clearly be a factor.

The level of IAEA analysis of input and output samples should not increase significantly (extensive verification of these samples, sometimes even 100% verification, is a significant part of virtually all proposals for reprocessing facility safeguards). If suitable approximate verifications are found, such that SAL can be given a reasonable time for its analyses, analytical costs should be identical across all proposals. If SAL is forced to speed its work in order to provide timeliness, this decreased analytical turn-around time may occasion some costs. The verification of inventory samples may also add 30-50 samples per year to the SAL workload.

The benefit, of course, is satisfaction of IAEA safeguards goals. The evidence of the feasibility study is that those goals can be completely satisfied, both with regard to the long term diversion of 8 kgs Pu over a period of one year, and with regard to the possible abrupt diversion of 8 kgs Pu within a short period of time. The system also completely satisfies INFCIRC/153. In particular, it:

a) avoids hampering the economic and technological development of the State....in the field of peaceful nuclear activities (section 4a);

b) takes full account of technological developments in the field of safeguards (section 6);

c) provides for the use of material accountancy as a safeguards measure of fundamental importance (section 28); and

d) permits the IAEA to make a statement...of the amount of material unaccounted for over a specific period, giving the limits of accuracy of the amounts stated (section 30).

On the negative side, the system requires at least one resident inspector, a requirement which was probably unavoidable in any case. The system requires that the on-site inspector be given considerable access to process operating information (e.g. level recorders, flow rates, etc.), and some of this information may be considered sensitive. The provision of an on-site computing capability, however, limits the extent to which this potentially sensitive data need leave the facility, and could be used to limit access within the Department of Safeguards.

The ability of dynamic materials accounting (i.e., Kalman filter type statistics) to distinguish between a diversion and a measurement bias is poor. (Fifty percent of the measurement biases, of course, should be in the wrong direction, and decision analysis can make that distinction). Since measurement biases are inevitable, the system must inevitably raise some "alarms" which are in fact false positives. The potential use of process monitoring techniques to separate measurement biases and potential diversions is discussed briefly in Chapter VII. If the safeguards community is not to become unduly alarmed over innocent measurement biases, and yet is to have confidence that a protracted diversion would be detected if it were attempted, the level of education, experience, and interest of the inspectors assigned to implement the system must be high. There can be no thought of leaving a "green" inspector alone at the facility with instructions to perform routine data collection and verification tasks, and to "yell diversion" if the alarm sequence chart prepared by the computer starts showing C or D level alarms.

C. Shorter Material Balance Periods

The initial outline of the feasibility study suggested that the study should consider, in addition to a ten day model based on weekly in-process inventories, a two day model based on daily inventories and a one day model based on in-process inventories at the end of every eight hour shift. As the feasibility study progressed it became apparent that these more nearly dynamic models were not necessary in terms of international safeguards criteria and objectives, and detailed consideration was dropped. This section reviews very briefly the question of the feasibility, and the corresponding benefit, of preparing material balances at intervals shorter than one week.

Daily in-process physical inventories appear to be feasible, with the major question being the ability of the analytical laboratory to deliver analytical results at the continuing rapid pace which would be required. The problem would relate primarily not to the four inventory measurements, which as was noted earlier are performed daily for process control reasons anyway, but to the input and product measurements. If these could be performed with two days analytical delay then a three or four day detection time model would be feasible. With installed NDA instrumentation which would permit accurate measurements in one day or less (such measurement alternatives were reviewed in Chapter III), even a two day model should be feasible. (Many writers on dynamic accountancy ignore data processing delays. Since diversion detection cannot be said to have occurred until data evaluation has been completed, these delays cannot be ignored).

Until the problem of inventorying an evaporator (other than by emptying it) is solved, in-process physical inventories more frequent than daily do not appear to be feasible. Indeed, the evaporator problem may be a limiting factor even in daily inventories, since the evaporator must be emptied in accord with process requirements rather than safeguards requirements. The evaporator is theoretically on a 24 hour schedule, but there is insufficient evidence to indicate whether, under long term routine conditions, it will in fact be discharged on a 20 hour schedule or a 28 hour schedule, or possibly will vary back and forth between those extremes. These variations could make adoption of a daily safeguards routine very difficult. They could also introduce variations of an unacceptable magnitude into the statistical calculations.

The possibility of inventories more frequently than daily also introduces other problems which have not been examined in detail. With eight hour material balances two-thirds of the material balances would not include any product removal, and one-third would include neither a fresh input batch nor a product removal. They would be, literally, repeat determinations of the same physical inventory which had been measured eight hours previously. The effect of these differences on the stability of the multiple period statistical analysis remains to be examined.

One must also ask the question, "Why?" Certainly not for more rapid detection of hypothesized abrupt diversion. The IAEA's detection goal for abrupt diversion is ten days, and all indications are that the ten day model based on weekly inventories achieves that goal. More rapid detection might be justified in terms of hypothesized theft scenarios, as an adjunct to physical protection systems, but not in terms of IAEA safeguards.

There is one logical reason for attempting in-process physical inventories more frequently than weekly, however. The discussion in Chapter II suggested that, in order to achieve a detection goal of 8 kgs Pu, the standard deviation of a single material balance should be no larger than about 800 grams Pu. For the PNC-Tokai facility this goal is achieved with weekly inventories, but for some other facility, especially a larger one, it might not be achieved so easily. In such cases one might logically resort to material balances every three days, or even every day, in order to reduce the number of input and output batches per material balance and thereby to reduce the standard deviation of a single material balance. The reason for the short material balance period, however, is reduction of systematic uncertainty effects, not timeliness.

6. CURRENT STATUS AND FUTURE NEEDS

A. In-Plant Field Testing and Demonstration

This feasibility study has shown, on paper, that it would be feasible to apply the concepts of dynamic materials accountancy to the PNC-Tokai facility, that doing so would fulfill IAEA objectives in terms of both detection quantities and detection timeliness, and that such a system would have a minimum impact on the facility operator. It has also shown, on paper, that it should be possible to develop and implement inspection procedures which would verify the dynamic accountancy data and make it useful for IAEA safeguards purposes. It remains, however, to demonstrate through actual field application that the assumptions made and the procedures developed can in fact be implemented on a routine basis. Such a field test was discussed in Japan during August, 1979, along the lines discussed in this section.

It is assumed that prior to such a field test there would be a detailed protocol specifying in advance exactly what was to be done and what was to be done with the resulting data. The procedures below are taken from an outline discussed during the August 1979 meetings, and are intended solely as an indication of the general nature of the needed protocol.

a) if there is any plutonium in the process area it should be inventoried (re-inventoried) just prior to the campaign;

b) during the campaign, and any flush-outs between fuel types, and extending for about 2 - 3 weeks after the end of the campaign, weekly in-process physical inventories would be taken by sampling the four buffer storage tanks simultaneously with the normal daily discharge of the product evaporator.

c) all samples would be analyzed by the usual procedures, and the laboratory would be asked to complete all analyses within two days. Alternatively, the LASL staff has proposed NDA measurement procedures which might be used, or both NDA and chemical analyses might be used in parallel. It seems preferable, however, not to confuse matters by changing procedures during the test;

d) the physical inventory in the mixer-settlers would be calculated using DYSAS-R, which appears to give inventory hold-up data very closely agreeing with the much more complex SEPHIS. (The validation that either SEPHIS or DYSAS-R truly agrees with physical reality is a separate problem which should be studied outside of the field test);

e) it is probably feasible to calculate the weekly material balances manually. However, if PNC has an interest and can get computer software ready in time, production of weekly material balances via electronic data processing should be considered as an additional part of the demonstration;

f) statistical evaluation calculations would be performed by JAERI, using the computer programs developed for the modelling and simulation studies. Although eventually the IAEA should have its own data evaluation capabilities, JAERI is sufficiently separated from PNC to be a valid demonstration of this aspect;

g) questions of IAEA verification require further study. If sample shipment problems can be resolved, the IAEA should try to field-test verification procedures by shipping samples to the safeguards analytical laboratory and requesting rapid analytical turn-arounds. Alternatively, consideration might be given to use of a "non-PNC" Japanese laboratory (JAERI or NMCC?) to generate quasi-verification data, so as to reveal any problems in the assumed verification concept (e.g., excessive false alarm rates).

As was noted in Chapter III, the proposed dynamic models for calculating the physical inventory in the mixer-settler contactor systems have never been validated by comparison with actual measured data. There are valid reasons for this lack of validation; no suitable operating facility has existed which could be used to generate validation data. Fortunately, the PNC-Tokai does have the capability to perform such a validation, and there have been several discussions or exchanges of letters relating to such a validation.

There are, unfortunately, significant questions of commercially sensitive data related to such a test. Even publication of the simple statement, "We have compared calculations to actual measurements and find agreement to within ± X%," might reveal commercially sensitive information, since it would enable others to use the calculations to better define their own process studies. Nevertheless, validation of the dynamic calculations is an ultimate requirement if the technique is to be useful for dynamic materials accountancy, and it is hoped that a suitable verification and validation can be accomplished.

The PNC-Tokai facility is perhaps uniquely suited for such a validation, since the process uses mixer-settlers, for which such parameters as stage volume or number of stages are known. Pulse columns and centrifugal contactors still obey the same theoretical laws of physical chemistry, but the definition of parametric values is difficult or impossible. The PNC-Tokai facility is also heavily instrumented, and the necessary analytical measurements at various stages are completely feasible.

B. Application to Larger Facilities

The application of the concepts explored in this feasibility study to larger reprocessing facilities should be reasonably straightforward. (The application of dynamic materials accountancy to other types of facilities should be feasible, but is a separate question not considered here). The biggest problem is the magnitude and variation in the unmeasured in-process inventory. If the magnitude of this inventory exceeds 8 kgs Pu it may be difficult to convince critics that the abrupt diversion of 8 kgs was not possible, even though in practice such a diversion might be achieved only at the expense of virtually destroying normal process operations. If the variation in the unmeasured inventory from material balance to material balance exceeds 800 g Pu (one standard deviation), then the goal of detecting a protracted diversion of 8 kgs Pu probably is not achievable. Thus the importance of devising, and incorporating, ways of reducing the magnitude of the unmeasured inventory. The total magnitude of the in-process inventory is not important, so long as it can be measured. The portion that cannot be measured is critical.

Since the statistical requirement is that the combination of the variation in the unmeasured inventory and the uncertainty in the measured material balance data not exceed 800 g Pu, larger facilities undoubtedly will require physical inventories on a frequency greater than weekly, up to a maximum of daily. (As was noted earlier, the purpose is not increased timeliness, but reduced uncertainty in a single material balance). If inventories are taken daily it still would be possible in theory to wait two or three days for the completion of analytical results, but a more acceptable approach undoubtedly would involve either at-line measurements or actual in- or on-line measurement equipment. There have been tremendous strides in this area in recent years, but it seems likely that significant further effort will be required before the stringent sample conditions existing in a spent fuel reprocessing facility can be handled effectively.

Measurement of the physical inventory in solution concentrators (evaporators) is an unresolved problem which could easily be by-passed in this study, but which may not be so easily treated in a larger facility. No specific suggestions are offered here, but if a suitable measurement system cannot be defined it may prove necessary to insist that the facility design provide for evaporator discharge on the frequency required for dynamic accountancy safeguards.

7. PROCESS MONITORING

One of the most commonly misunderstood concepts in statistics is the distinction between bias, or the extent which data deviates from some defined or assumed true value, and systematic uncertainty (or systematic error), the extent to which the operator/inspector/experimentor knows whether the data is biased. The value of multiple period statistical techniques such as CUSUM or the Kalman linear filter lies in their ability to distinguish between these two quantities, and to specify the magnitude of any bias which may be present more accurately and more rapidly than can be achieved with conventional statistical techniques. What these statistical techniques unfortunately cannot do, however, is distinguish between a bias caused by inadequately or improperly calibrated measurement equipment and an apparent bias caused by deliberate diversion of nuclear materials.

Measurement biases, of course, are inevitable. Even with most careful calibrations (and the frequency of calibration is statistically less important than the care used), small measurement biases cannot be assumed to be non-existent. Half of the measurement biases should be positive rather than negative. That is, at least from a statistical point of view, half of the measurement biases should contribute to an apparent nuclear material gain, not to an apparent loss. There is also a significant possibility that some of the biases will tend to cancel each other. (Remember, the question is the magnitude of the bias itself, not the degree of accuracy with which the inspector knows what the bias is). Nevertheless, it must be recognized that from time to time multiple period statistical techniques will detect biases or diversions, and will themselves give no indication as to which has been detected. Measurement control programmes, analytical comparisons, and other statistical evaluations will also help, but statistics alone will not always be able to distinguish between an honest measurement bias and a true diversion attempt.

To resolve this problem, it has been suggested that dynamic materials accountancy be combined with a form of dynamic surveillance, commonly referred to as process monitoring or dynamic operations monitoring. This feasibility study has limited itself to a study of dynamic materials accountancy, but it seems desirable to end the report with a brief note concerning process monitoring.

The basic premise of process monitoring is that diverted nuclear material cannot just be invented, but must come from somewhere, and must be removed via some physical process. This removal must also, at least in theory, leave its mark on the process. This leads to the suggestion of two detection possibilities; one that the removal process itself might be detected, and the other that the effect on the process might be detected. An example of the former might be the observation of radiation characteristic of plutonium in piping which should not contain plutonium. An example of the latter might be the observation that the concentration of Pu in a solvent extraction waste stream had increased significantly, indicative of non-equilibrium extraction conditions. Combined with other data that the apparent flow rate to the extraction system had not changed, this might indicate that a portion of the flow had been diverted elsewhere. It seems likely that in any practical situation both possibilities would be used together.

Although a number of investigators have discussed the potential feasibility of process monitoring, there has been very little practical work in the field. Most reprocessing facilities contain large numbers of process monitors, installed purely for operational reasons, and one might hypothesize that this already installed instrumentation might be adequate. This hypothesis does not appear to have been examined in terms of any real facility. At the opposite extreme, one might question whether any conceivable degree of instrumentation would be sufficient to cover all credible diversion scenarios. This question likewise does not appear to have been studied in any detail.

One can also question whether giving the inspector access to this process instrumentation would also give him access to sensitive commercial data. Since the degree of access required has not been defined, the acceptability of that access cannot be known. It has been suggested, however, that since the process monitoring data obviously would be fed to a small Agency computer, and since that computer would not need to know the calibration constants which convert electrical or pneumatic signals into meaningful technical information, the true degree of access might in fact be less than one might otherwise suppose.

Finally, it should be noted that process monitoring also has its limitations, even if one assumes that it can be made to function effectively. The facility operator clearly must be allowed to make operational changes, either in an effort to bring a process which is not quite under complete control under a more effective control, or possibly in an attempt to see if he can improve the process. Such changes cannot be treated as alarms, and the Agency's monitoring computer must somehow be able to distinguish between honest operational changes and changes indicative of potential diversion.

The usual suggestion, and the one accepted in this report, is that neither dynamic materials accountancy nor process monitoring should be used alone. Rather, each should be used as a secondary check on the other. If the dynamic accountancy statistics suggest that material might be missing, the first investigation should be to see if the process monitoring system gives any indication of possible removals. Conversely, if the process monitoring system indicates changes in process parameters which do not fit the established patterns, the first investigation should be to see if the dynamic accountancy statistics give any indication of missing material. Only if both systems give indications of possible diversion, or if one gives a clear positive signal which cannot be disregarded, would the inspector carry his investigations to the stage of reporting that diversion may be occurring.

There are too many unanswered questions to make any meaningful statement about the potential value of process monitoring at this time. It does appear to the authors, however, that answers should be sought for these questions.

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