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AN ADVANCED SAFEGUARDS APPROACH FOR A MODEL 200 t/a REPROCESSING FACILITY

PART I : DESCRIPTION AND DISCUSSION

October 1983

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This report describes an advanced safeguards approach which has been developed for a model 200 t/a reprocessing plant, using near-real-time materials accountancy in the process MBA, and borrowing advanced ideas from TASTEX, the IWG-RPS, or the authors own invention for the spent fuel storage and plutonium nitrate storage MBAs.

In the spent fuel storage MBA primary reliance is placed on 100% inspector observation and verification of all spent fuel receipts, and on surveillance measures to ensure that the inspector is aware of all receipts or other activities in the spent fuel cask receiving bay. The advanced safeguards approach gives more detailed consideration to the mechanical or chop-leach cell than most conventional approaches. Safeguards in the process MBA are based on n.r.t. accountancy. The n.r.t. accountancy model used assumes weekly in-process physical inventories of solution in some five buffer storage tanks. The safeguards approach suggested for the plutonium nitrate storage MBA is not significantly different from conventional approaches.

The use of sequential statistical techniques for the analysis of n.r.t. accountancy data requires a significantly different philosophical approach to anomalies and anomaly resolution. This report summarizes anomaly resolution procedures, at least through the earlier stages, and describes a summary estimate of inspection effort likely to be needed to implement the advanced safeguards approach.

Keywords: Advanced Safeguards Approach, Reprocessing, In-process Physical Inventory, Near-real-time Accountancy, TASTEX

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モデル200トン/年再処理施設に対する改良保障措置アプローチ
第1部：アプローチの説明と検討

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（1983年9月28日受理）

この報告書は，200トン/年の処理能力をもつモデル再処理施設に対して開発した改良保障措置アプローチについて記述したものである。このアプローチではプロセス物質収支区域(MBA)に対してはニア・リアル・タイム計量管理を用いると共に，TASTEXプロジェクトならびに「再処理保障措置に関する国際作業グループ」（IWG－RPS）にあらわれた進んだアイデアを取り込み，あるいはまた，使用済燃料貯蔵区域ならびに硝酸プルトニウム製品貯蔵区域に対しては著者自身の工夫によって導き出したものなどを用いている。

使用済燃料貯蔵区域におけるこのアプローチの基本は，査察官による全受入燃料に対する100％ベースの観察及び検認，ならびに燃料キャスク受入区域におけるすべての燃料受入活動について査察官が必ずこれを知っているようにするための監視手段の2つに置かれている。改良保障措置アプローチでは在来型アプローチに比べてメカニカル・セルに対して特段の配慮を行っている。また，プロセスMBAにおける保障措置アプローチとしてはニア・リアル・タイム計量管理をベースとしている。このニア・リアル・タイム計量管理では，5個のバッファー用貯蔵タンクに含まれる溶液について，毎週工程運転中の実在庫を測定することを仮定している。硝酸プルトニウム貯蔵MBAに対して提案している保障措置アプローチは在来のアプローチと大きくは違わないものとなっている。

ニア・リアル・タイム計量管理データの解析で逐次統計分析技術を用いるためには，アノマリーに対してもその解明に対しても，在来統計分析で用いられたものとは相当に異なった思想的アプローチをすることが要求される。本報告書では，このアノマリー解明の手続きで，その初期段階におけるものをまとめて記述すると共に，この改良保障措置アプローチを実施するのに必要な査察業務量の推定値について記述している。

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EXECUTIVE SUMMARY

The study of near-real-time materials accountancy as a potential advanced safeguards concept for the PNC-Tokai reprocessing facility began in 1978, under the TASTEX programme. Initial studies were based on computer modelling, but actual field test data were collected during 1980 and 1981. These studies clearly demonstrated that n.r.t. accountancy was feasible, and that it would produce meaningful safeguards accountancy data.

N.r.t. accountancy alone is not a complete safeguards approach, first because it is based on operator-generated measurement data, which data must be verified if it is to be used in IAEA safeguards, and second because it is generally applicable only in the process MBA, where bulk processing operations occur. This report describes an advanced safeguards approach which has been developed for a model 200 t/a reprocessing plant, using n.r.t. accountancy in the process MBA, and borrowing advanced ideas from TASTEX, the IWG-RPS, or the authors own invention for the spent fuel storage and plutonium nitrate storage MBAs. Chapters 2 through 6 discuss the basic diversion scenarios, describe the advanced approach and discuss the various ideas which have been incorporated into it. The authors acknowledge that not everything described has been constructed and tested in the specific form recommended, but they also argue that everything proposed has been developed and tested in sufficient detail to justify an assumption that the extrapolations required will also work as desired.

In the spent fuel storage MBA primary reliance is placed on 100% inspector observation and verification of all spent fuel receipts, and on surveillance measures to ensure that the inspector is aware of all receipts or shipments in the spent fuel cask receiving bay. Spent fuel assemblies, or pins removed from spent fuel assemblies, cannot be diverted except through the use of shielded casks which must move through the receiving bay. Thus control of this critical strategic point effectively ensures a high detection probability for a wide variety of diversion scenarios involving spent fuel assemblies or pins.

The advanced safeguards approach gives more detailed consideration to the mechanical or chop-leach cell than most conventional approaches. If both dissolvers (or all dissolvers in a more general model) are operating more or less in accordance with design, there are only limited diversion possibilities. If one or more dissolvers are declared to be temporarily out of service, however, then there are additional possibilities related to the unreported dissolution of fuel pins or assemblies diverted from the storage MBA, or to the unreported dissolution of chopped pieces accumulated from reported dissolutions. In all cases the intent of the unreported dissolution would be to transfer plutonium to the process MBA without the knowledge of the IAEA, in order to conceal a subsequent diversion of plutonium nitrate solution from the process MBA. To protect against these possibilities, the advanced approach suggests, among other things, the use of remotely verifiable electronic seals on dissolvers declared to be out of service.

Safeguards in the process MBA are based, as noted, on near-real-time materials accountancy. The n.r.t. accountancy model used assumes weekly in-process physical inventories of solution in four buffer storage tanks and one recycle tank. Inventories are timed to coincide with emptying of the product evaporator, eliminating the need to measure plutonium in the evaporator, and solvent extraction system inventory quantities are estimated based on a simplified model which assumes that a steady-state equilibrium exists.

Isotope correlations and other data comparisons are described which would detect any attempted gross data falsifications; conventional independent analysis of verification samples is used for the detection of small measurement biases. Data thus far available are not sufficient to permit a precise definition of detection sensitivity, but the simulation and field testing studies clearly indicate that the IAEA's goals of 8 kg Pu in 1-3 weeks (abrupt), or 8 kg Pu in one year (protracted) would be met or exceeded.

A reference system of conventional materials accountancy based on cleanout physical inventories at six month intervals is also included.

The safeguards approach suggested for the plutonium nitrate storage MBA is not significantly different from conventional approaches. Conventional materials accountancy based on six month physical inventories is used as a reference system, and a variety of seals, on-line volume monitoring systems, and occasional verification samples are used to ensure detection sensitivity and timeliness.

Safeguards for uranium are briefly discussed, largely because of the corroborative information such safeguards measures can provide.

Chapter 7 describes a summary estimate of inspection effort likely to be needed to implement the advanced safeguards approach, based on two alternative assumptions, one being full capacity operation, the other being operation for 200 days at 0.4 t/d, an approximation to 50% capacity operation. For full scale operation the estimate is 3594 man-hours per year, which the report translates into 599 man-days. For 50% capacity operation the comparable figures are 2126 man-hours, or 354 man-days. These estimates are generally comparable to current actual inspection practice at the PNC Tokai reprocessing plant, but the advanced safeguards approach is claimed to provide significantly increased detection sensitivity and timeliness.

Chapter 7 ends with a caveat which deserves repetition here. Many of the verification procedures depend significantly on "continuous inspector knowledge". It is doubtful if this continuous inspector knowledge can be satisfactorily achieved if inspection effort is rotated among a group of 20-30 inspectors, none of whom ever remains at the facility for longer than a week or so at one time.

The use of sequential statistical techniques for the analysis of n.r.t. accountancy data requires a significantly different philosophical approach to anomalies and anomaly resolution. Specifically, tests are first used in a manner which has a significant probability of responding not only to diversion but also to measurement biases and other "innocent" effects. If tests applied in this manner detect no anomalies, then a high degree of assurance can be given that diversion has not occurred. The converse, that anomaly detection suggests a high probability that diversion has occurred, cannot be accepted. Instead, procedures are described for the evaluation and resolution of anomalies, in particular those resulting from measurement biases. As these biases are identified and corrected the probability of their continuing to effect the statistics decreases, and the degree of assurance of non-diversion increases. Chapter 8 summarizes anomaly resolution procedures, at least through the earlier stages. Since anomaly resolution is highly dependent on the exact nature of the observed anomaly(ies), only general procedures can be given.

A companion report, STR-141 [17], assessing the effectiveness of the proposed advanced safeguards approach using the Safeguards Effectiveness Assessment Methodology described in STR-122 [18], is in preparation.

The authors are pleased to note that the report is being published jointly in Vienna, identified as IAEA report STR-140, and in Japan, identified as JAERI-M 83-160 or PNCT N141 83-02.

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Part I: Description and Discussion

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Part 1: Description and Discussion

1. INTRODUCTION

During the years 1978-1980 and early 1981 the governments of Japan, France and the United States of America mutually pursued a programme for the improvement of international safeguards techniques as applied to spent fuel reprocessing facilities, with particular emphasis on the applicability of those techniques to the PNC-Tokai facility. The International Atomic Energy Agency (IAEA) also participated in the programme, which was given the acronym TASTEX, for Tokai Advanced Safeguards Technology Exercise. The history and summary results of the TASTEX programme were jointly agreed and published by the IAEA [1].

Task F of the TASTEX programme called for an investigation of the feasibility of applying to the PNC-Tokai facility what has now come to be called near-real-time materials accountancy. Initial studies were based largely on computer modeling, but during 1980 and 1981 actual field test data were collected. The result, as described in detail in reference [2], was a clear demonstration that n.r.t. accountancy was feasible, and that it did produce meaningful safeguards accountancy data.

Near-real-time materials accountancy alone is not a complete safeguards approach. First, it is based on operator-generated measurement data, which data is of value in international safeguards only if it can be independently verified. Second, the technique is generally applicable only in bulk processing operations. There have been no proposals for the application of n.r.t. accountancy to spent fuel storage, and it is not immediately obvious that the technique could logically be used in that area. Thus the TASTEX task F effort, although highly successful, can only be considered as having reached an intermediate milestone in the eventual routine application of n.r.t. accountancy in international safeguards. This report is the result of an attempt to carry the work at least one step further, by showing how n.r.t. accountancy could be incorporated into an advanced safeguards approach for a model 200 t/a reprocessing facility such as PNC-Tokai.

The IAEA has adopted the following guidelines with regard to the safeguarding of plutonium and uranium at reprocessing facilities [adapted from 3].

a) for spent fuel, assurance that the diversion of sufficient fuel assemblies or fuel pins to permit the recovery of 8 kgs total plutonium would have a high probability of being detected within a period on the order of one to three months;

b) for separated plutonium, assurance that the "abrupt" diversion of 8 kgs Pu at one time, or over a short period of time, would have a high probability of being detected within a period on the order of one to three weeks;

c) also for separated plutonium, assurance that the "protracted" diversion of separated plutonium at an assumed minimum rate of 8 kgs per year would have a high probability of being detected before the total diverted equalled or exceeded 8 kgs Pu; and

d) for uranium, assurance that the diversion of separated uranium at any rate which results in the accumulation of at least 75 kgs contained ^{235}U over a period of one year would have a high probability of being detected within one year. (Note that for any burnup in excess of about 5000 MWD/t it requires more spent fuel to acquire 75 kgs ^{235}U than it does to acquire 8 kgs Pu, so that the definition of a safeguards goal for uranium in spent fuel has little meaning.)

The basic objective of this study, in its current form, is the development of an advanced safeguards approach capable of satisfying those guidelines. The study also evaluates inspector effort associated with the possible implementation of that advanced safeguards approach. The authors have made no attempt to define any alternative system, so a true cost comparison is not possible. The authors believe, however, that the safeguards approach described in this report is at least competitive with and probably significantly more economical than any other approach commonly discussed as potentially having the capability of satisfying IAEA safeguards goals.

The problem of developing an advanced safeguards approach based on n.r.t. accountancy for a reprocessing facility can be sub-divided into the following four sub-problems:

a) development of a mathematical model, and demonstration that if implemented that model would satisfy the IAEA's goals for detection sensitivity and timeliness;

b) development of practical procedures for implementing the mathematical model;

c) development of procedures whereby IAEA inspectors can be assured that data used in implementing the model are complete and correct (i.e. independent measurement or surveillance procedures); and

d) to the extent that the mathematical model admits of the possibility of false positives (commonly called anomalies or false alarms), development of practical procedures for resolving whether anomalous indications are an indication of possible diversion.

Previous reports [2,4-8] have dealt primarily with the first two subproblems. This report gives primary attention to the development of meaningful inspection (verification) procedures, and to the resolution of false positives. Attention also is not restricted to the process area, but is extended to cover all operations and activities from the receipt of spent fuel to the off-site shipment of uranium and plutonium.

This is a specific study of safeguards in the context of 200 t/a reprocessing facilities such as PNC-Tokai. There have been many discussions in recent years concerning safeguards for anticipated future large-scale reprocessing facilities. Many of the activities described in this report could be extended to larger facilities in a straightforward manner, others pos- sibly could not. These extensions to other facilities are not considered. The safeguards measures described also are to some extent design dependent.

The primary purpose of this report is the stimulation and coordination of development efforts in the field of advanced safeguards concepts and techniques for reprocessing facilities. The report has been prepared as a cooperative effort among several people from various organizations. Moreover, as noted below, the authors have drawn heavily on the work of a wide group of researchers in reprocessing plant safeguards, not only for their published work, but for helpful discussions. It should be expressly understood that the work is that of the authors, not of the organizations they represent.

A companion report, STR-141, examining the effectiveness of the advanced safeguards approach described here is under preparation. Although the reader is referred to that report for more detailed conclusions, the authors are pleased to note, based on initial drafts, that estimated detec- tion probabilities in general are very high, and that exceptions relate primarily to scenarios which are themselves technically complex, and which in most cases would have to be repeated many times in order to achieve assumed detection goals.

Many people contributed to this work, by providing detailed information concerning the PNC-Tokai facility, by discussing in detail various possible safeguards techniques, by commenting on various drafts of the report, or in

numerous other ways. The authors wish to specifically acknowledge assistance provided by the following individuals: Messrs. Y. Asakura, R. Augustson, D. Cobb, M. Hirata, H, Ihara, M. Iwanaga, K. Nakajima, H. Nishimura, H. Okashita, M. Rosenthal, J. Shipley, T. Sugiyama, N. Suyama, L. Thorne, H. Umezawa, O. Yamamura. The authors also acknowledge the assistance of the PNC Headquarters Safeguards Staff and the staff of the IAEA Department of Safeguards, and one of the authors (Jim Lovett) wishes to express his sincere appreciation for the hospitality and assistance afforded him during some six trips to Japan to coordinate and consult on the develop- ment of near-real-time materials accountancy and the advanced safegards approach.

The authors also acknowledge the assistance provided by the many discussions within the International Working Group on Reprocessing Plant Safeguards (IWG-RPS). Some of the ideas discussed in this report differ from safeguards possibilities suggested in the IWG-RPS Overview Report [9], but it was at least in part the discussions in IWG-RPS meetings and sub-group meetings which led the authors to look for alternatives which might be more effective or less manpower intensive. The IWG-RPS adopted a general cut-off on new technical information after about mid or late 1980, and this made it impossible to present these alternatives for IWG-RPS discussion.

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2. GENERAL CONSIDERATIONS

2.1 Facility Description

For a variety of reasons it is common practice to discuss safeguards in terms of model facilities. These "model" facilities, of course, must necessarily be based on real facilities (or on real proposals for future facilities). For reactors or low enriched uranium fabrication facilities, as two examples, the specification of an unidentified model presents few difficulties. There are numerous facilities to choose from, and features relevant to safeguards often are highly consistent from one facility to another.

The specification of an unidentified model facility for reprocessing is more difficult. Safeguards are currently being applied at very few reprocessing facilities, and many of the features of existing facilities are significantly different from one facility to another. Table I lists all reprocessing facilities where IAEA safeguards are currently being applied. Since it must in any case be obvious to the reader from context that the PNC-Tokai facility in Japan served as the reference model for the present study, this section acknowledges that fact, and presents a summary description of the PNC-Tokai facility.

A detailed description of the PNC-Tokai reprocessing plant has been published by Nakajima [10]; only a very general description will be given here. The basic process is the well-established Purex process, using tri-butyl phosphate (TBP) in a kerosine diluent to extract first uranium and plutonium and later (through a valence change for plutonium) only uranium. Mixer-settler contactors are used in all stages. Figure 1 shows the process flow diagram.

Table I

Reprocessing Facilities in NNWS Under IAEA Safeguards

WAK (Karlsruhe, FRG)	35 Mt/a
Eurex (Italy)	25 Mt/a (primarily used for MTR type fuels).
Itrec (Italy)	3 Mt/a
PNC-Tokai (Japan)	210 Mt/a
Prefre (India)	100 Mt/a

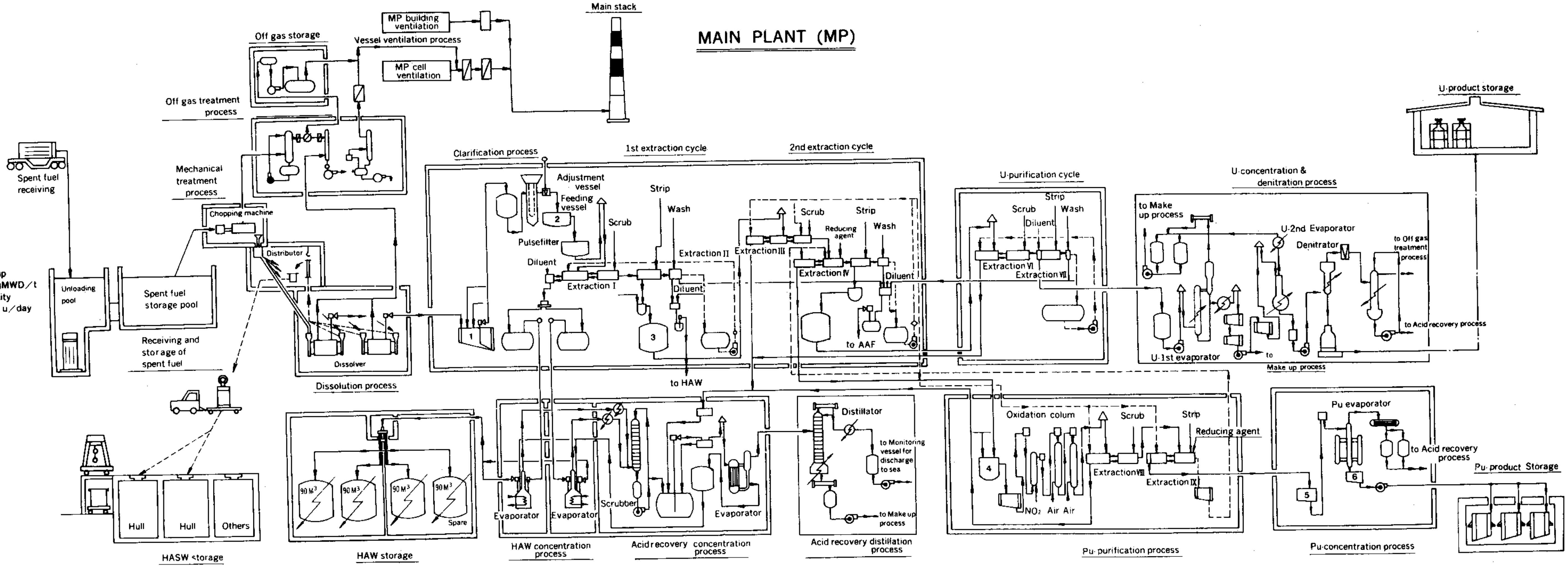
(INFCIRC/66/rev.2 safeguards apply)

Facilities with a rated capacity under 1000 kg/a have been omitted.

The nominal plant capacity is generally defined as being 210 MTHM/a, based on the use of two dissolvers, each of which has the capacity for one PWR or two BWR fuel assemblies, operating on a 24 hour dissolution cycle. Two thirty-day periods each year are assumed for inventory and general maintenance purposes.

After dissolution the input fuel solution is passed to the input accountancy tank, where the normal measurement procedure is based on conventional volume measurement plus sampling for isotope dilution mass spectrometric analysis. As discussed in the various referenced reports on the feasibility of n.r.t. accountancy, there are four buffer storage tanks, one each preceding the first, second and third extraction cycles, and one preceding the plutonium product evaporator. Evaporation is semi-continuous, with feed being interrupted about once every 24 hours while the evaporator is drained of product. As with the input, product plutonium nitrate solution is measured by a conventional volume measurement combined with chemical analysis. Plutonium nitrate solution is stored in a bank of three 700 litre plus four 500 litre storage tanks (annular geometry).

PNC REPROCESSING PLANT PROCESS FLOW DIAGRAM



Measurement tanks

1 Input Accountancy tank
2 First Buffer Storage tank
3 Second Buffer Storage tank
4 Third Buffer Storage tank
5 Evaporator Feed tank
6 Product Accountancy tank

Uranium is denitrated to UO_3 for final product sampling and storage.

The nominal in-process inventory, as given in [10], is about 14 kgs Pu, not including the input accountancy tank (5.3 kgs if full), the plutonium product accountancy tank (10.6 kgs if full), or the product evaporator (10.6 kgs if full). (Note that normally the product accountancy tank and the product evaporator would not both be full simultaneously.)

2.2 Legal Documents

IAEA safeguards are implemented pursuant to specific safeguards agreements between the government of the Member State (or the European Community) and the International Atomic Energy Agency, negotiated based on one of two model safeguards agreements, identified as INFCIRC/66/rev.2 and INFCIRC/153. The latter document applies to all agreements with States party to the Non-Proliferation Treaty (NPT); the former applies in States that have separately agreed to place some or all of their nuclear facilities under IAEA safeguards. In terms of practical safeguards measures the differences are minor, but since the PNC-Tokai model facility, and all other currently safeguarded reprocessing facilities with the exception of PREFRE in India, are safeguarded pursuant to INFCIRC/153, this report is limited to that agreement. The modifications necessary to apply the advanced safeguards approach to PREFRE, should it be decided to do so, would need to be developed in the course of specific negotiations.

INFCIRC/153 provides, in Section 1 and 2, that safeguards should be applied, "for the exclusive purpose of verifying that [nuclear] material is not diverted to nuclear weapons or other nuclear explosive devices". Section 28 further provides "that the objective of safeguards is the timely detection of diversion of significant quantities of nuclear material ..." The next section (section 29) further provides "for the use of material accountancy as a safeguards measure of fundamental importance, with containment and surveillance as important complementary measures". Finally, section 30 provides "that the technical conclusion of the Agency's verification activities shall be a statement ... of the amount of material unaccounted for over a specific period, giving the limits of accuracy of the amounts stated" [11].

This basic legal agreement is supplemented firstly by Subsidiary Arrangements and secondly by specific Facility Attachments for individual facilities at which safeguards are to be applied. Since specific facility attachments are considered confidential (because they contain sensitive propriety or technological information) it is necessary to refer to a model facility attachment for reprocessing facilities [12].

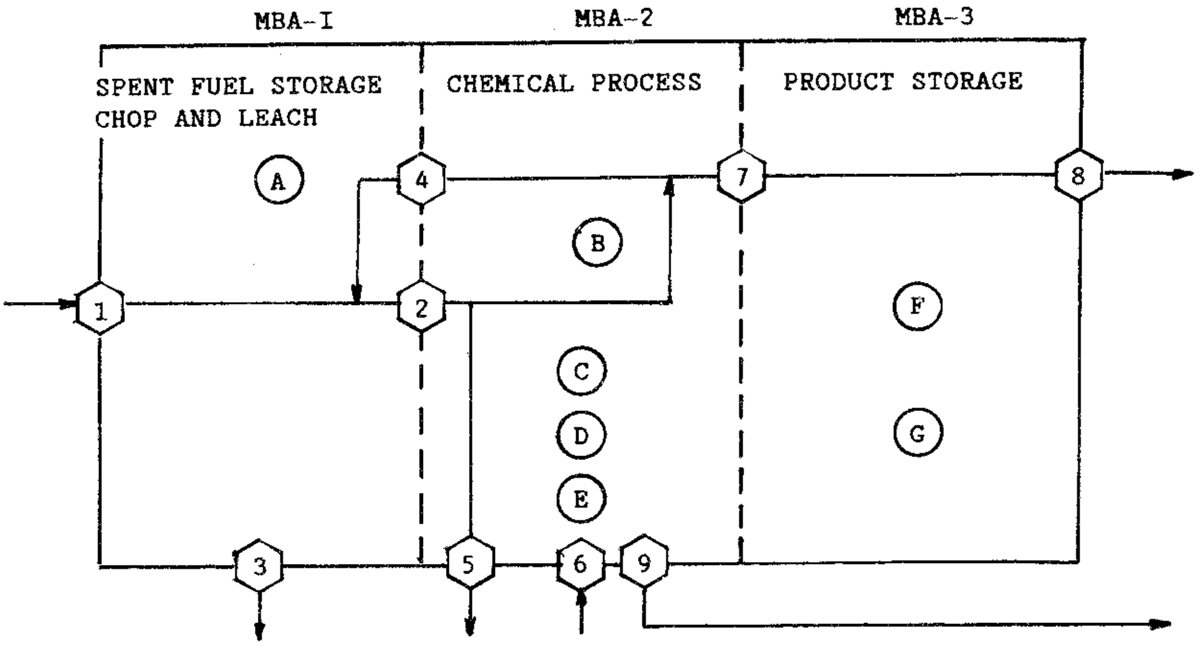
Consistent with INFCIRC/153 and the model facility attachment for reprocessing plants, the safeguards measures discussed in this report are for the most part materials oriented. Item accountancy is used in the spent fuel storage area, where all nuclear material is contained in identifiable fuel assemblies. Containment-surveillance measures are used throughout, but in a supportive role, to preserve the integrity of materials accountancy data. Process monitoring is also discussed as playing an important role, especially in the process and plutonium product storage areas, but that role is still primarily supportive of the materials accountancy system.

2.3 Material Balance Areas and Key Measurement Points

The facility is divided into three material balance areas, along conventional lines. The first MBA encompasses all activities from the receipt of spent fuel to the input accountancy measurement. Although this area is commonly called the spent fuel storage area, the various process operations in the chop-leach or mechanical cell form an important part of the MBA, and the terminology in this report uses spent fuel storage area and head-end area more or less interchangeably.

The second MBA, called the process area, includes all operations from the input accountancy measurement to the plutonium (and uranium) product output measurements. The third MBA covers uranium and plutonium product storage. Waste treatment, the analytical laboratory, and the Operation Testing Laboratory, none of which are specifically treated in this report, are considered to be part of the process MBA. The MBA structure and key measurement points as defined in the model facility attachment are shown in figure 2.

Figure 2: Material Balance Area Structure
and Key Measurement Points (from [12])



1 RECEIPT OF SPENT FUEL

2 TRANSFER TO MBA-2

3 MEASURED DISCARDS

4 TRANSFER OF REWORK SOLUTION

5 MEASURED DISCARDS

6 RECEIPT OF OTHER NUCLEAR MATERIAL

7 TRANSFER OF FINAL PRODUCT TO STORAGE

8 SHIPMENT OF FINAL PRODUCT TO OUTSIDE

9 SHIPMENT OF SMALL QUANTITIES AND
OTHER H.M. TO OUTSIDE

A STORAGE OF IRRADIATED FUEL ELEMENTS

B IN-PROCESS INVENTORY

C ANALYTICAL LAB.

D OPERATION TESTING LABORATORY

E VESSELS OF MAKE-UP LIQUID

F STORAGE OF URANIUM FINAL PROD.

G STORAGE OF PLUTONIUM FINAL PRODUCT

The model facility attachment provides for two clean-out physical inventories per year. The necessary frequency for clean-out physical inventories, given that n.r.t. accountancy is being implemented, has been the subject of considerable discussion. It is noted here that most existing reprocessing facilities perform "between campaign" clean-outs at least twice per year. Where this practice exists the use of these process shutdowns for inventory purposes seems to be logical, and to involve a minimal additional expense.

3. SPENT FUEL STORAGE (HEAD END OPERATIONS)

3.1 Spent Fuel Storage MBA

The spent fuel storage or head-end area is defined as encompassing all operations from the receipt of spent fuel through to the point at which the input accountancy measurement is performed. Once the dissolved fuel solution has been measured it is considered to be in the process area. The head-end area thus includes:

- spent fuel cask receiving and unloading;
- spent fuel storage;
- transfer of spent fuel to the chop-leach or mechanical cell;
- removal (and disposal) of fuel assembly end pieces not containing nuclear material;
- chopping or shearing of the spent fuel into short pieces suitable for leaching;
- dissolution (leaching) of uranium, plutonium and fission products from the chopped pieces;
- clarification (filtration) of the dissolver solution; transfer to the input accountancy tank; input accountancy measurement of uranium and plutonium in the clarified solution; and
- disposal of leached hulls and other solid wastes from clarification operations.

It is common to refer to the spent fuel storage MBA as being a shipper-receiver difference MBA, on the argument that any MUF observed in that area is the result of differences between the measurements (calculations) performed by reactor operators and those performed by the reprocessing facility operators. These differences, however, do not have the status usually accorded to S-R differences in IAEA safeguards. According to most commercial reprocessing contracts the receiver's plutonium measurement is taken as the "official" measurement, and any calculated data provided by the reactor operator is "corrected" to agree with the dissolution measurement. Even where this is not done, the difference between reactor calculations and dissolution measurements cannot be given the same status as is usually ascribed to S-R differences. Consistent patterns in these differences can be useful in the evaluation of anomalous accountancy information, but as a general statement cannot be taken as anomalies in their own right. In this report there is an expectation, but not an insistence, that the head-end area will observe MUF = 0 except for these S-R differences.

3.2 Diversion possibilities

Three diversion possibilities have been suggested with regard to spent fuel at reprocessing facilities. The first is that one or more previously received (i.e., safeguarded) fuel assemblies might be clandestinely removed for processing in an unsafeguarded facility. Such a removal might or might not be accompanied by the substitution of dummy assemblies in the storage pond for concealment purposes.

As a corollary to this diversion possibility, it has been suggested that the removal might involve only individual fuel pins, leaving the fuel assemblies apparently intact. If entire fuel assemblies are diverted a minimum of three PWR or about seven BWR assemblies would be required to contain the assumed minimum of 8 kgs Pu. Since detection of even one apparently missing fuel assembly would constitute an anomaly requiring serious investigation, it is common to define the inspection goal for spent fuel in terms of the detection of a single missing assembly. If individual fuel pins are removed, the minimum number to obtain 8 kgs Pu would be about 350 BWR pins or 450 PWR pins. (PWR fuel pins have a smaller diameter). Since leaking fuel pins are occasionally removed by reactor operators, one or a few missing pins would not necessarily be a significant anomaly.

Yet a second corollary to the possible diversion of spent fuel assemblies is the possibility that chopped pieces might be diverted from the mechanical cell. The diverted pieces could only be removed by charging them to a dissolver for a significantly shortened dissolution period. Since the maximum Pu concentration in spent fuel is on the order of 1%, the minimum total weight of chopped pieces which would have to be diverted is 800 kgs.

The second diversion possibility is that safeguarded fuel assemblies, or fuel pins removed from such assemblies, might be fed to the process without being reported, so that the recovered plutonium could be diverted from the process MBA. The third possibility is similar, but assumes that fuel assemblies or fuel pins which have been diverted elsewhere (e.g. assemblies previously diverted from a safeguarded reactor) might be processed. In all cases the discussions given above regarding the minimum number of assemblies or pins needed, and the safeguards significance of detecting a single anomaly, are equally applicable.

Given that near-real-time materials accountancy is used to maintain a continuous knowledge of nuclear material flows and inventories in the process MBA, the undeclared processing of either declared or undeclared spent fuel has a high probability of being detected in the process MBA. A similar argument suggests that if dummy assemblies, or assemblies from which fuel pins have been removed, are processed, the missing plutonium also has a high probability of being detected in the process MBA. Nevertheless, the safeguards approach outlined here recognizes all of the above diversion possibilities. As will be seen, very little effort is required beyond that needed to protect against the primary diversion possibility, the diversion of spent fuel for processing in an undeclared facility.

Spent fuel assemblies are intensely radioactive, even after several years cooling, and can only be moved with the aid of heavily shielded shipping casks. Cask sizes vary, with the smallest holding only two or three assemblies and the largest holding up to 30 (BWR). In all cases the cask weight is on the order of 20-100 MT. Inter-facility transfer of spent fuel rods is not common, and generalizations about shipping containers are not possible. A cask capable of holding 350 rods would be comparable to the smaller fuel assembly casks.

The diversion of chopped pieces would present even more serious shipping problems. The usual transport container for hulls is designed to handle three or four orders of magnitude less radioactivity and at least one or two orders of magnitude less weight. The containers are not designed for transport over public access roads, and also may not be critically safe for kilogram quantities of plutonium. An abrupt diversion of 800 kgs of unleached chopped pieces could be accepted as credible only if the physical design of the hull removal area would accommodate a 20 MT cask. (The design features which would be likely to preclude such a diversion include insufficient floor strength, lack of a crane capable of handling 20 MT, and spatial restrictions on cask movement.) A greater degree of credibility might be assigned to a protracted diversion scenario using available hull disposal containers and restricting their contents consistent with weight, radioactivity, and criticality considerations. Actual hull container designs would have to be considered individually, but the minimum number of removals probably would be in excess of one hundred.

Finally, it should be recognized that a diversion of spent fuel assemblies or pins might have occurred prior to receipt of the fuel at the reprocessing facility. Thus the number of assemblies received might not agree with the number shipped, one or more received fuel assemblies might be dummies intended to conceal an earlier diversion, or some fuel assemblies might have missing or dummy fuel pins, the removal or substitution having taken place prior to receipt at the reprocessing facility. These possibilities cannot be passed off as being outside the scope of reprocessing plant safeguards.

3.3 Safeguards for Spent Fuel Storage

3.3.1 Spent Fuel Receiving Bay. There is no feasible way for spent fuel to be introduced into or removed from the PNC-Tokai facility other than through the spent fuel receiving bay. When operating at capacity the facility will process either 14 PWR or 28 BWR fuel assemblies per week, so spent fuel receipts may be expected to occur about once every 3-5 days. Receiving a cask, lowering it into the receiving bay, transferring the assemblies to storage, and reassembling and removing a cask prior to shipment require on the order of a full day.

The safeguards approach suggested in this report assumes that the inspector will perform the following operations for all spent fuel receipts:

1. observe the cask prior to its being lowered into the spent fuel receiving bay, and remove the IAEA seal if one exists; (It is assumed that as a general rule IAEA seals on casks will not exist).
2. observe the removal of the cask cover, and compare the total number of contained assemblies with data supplied by the shipping reactor facility;
3. to the extent possible verify by observation of Cerenkov radiation that all fuel assemblies have been irradiated, and that there are no missing or dummy fuel pins;
4. to the extent possible compare fuel assembly identification numbers with data supplied by the shipping reactor facility;
5. observe the transfer of all fuel assemblies to storage baskets, and independently record the storage location assigned to each basket; and
6. observe the placing of the cask cover on the empty cask, and the subsequent removal of the cask from the spent fuel receiving bay.

To ensure that an undeclared removal of spent fuel could not occur without detection, and at the same time to ensure that spent fuel receipts could not occur without the inspector having had an opportunity to be present to perform the above verifications, a television camera connected to a video recorder should be used to maintain surveillance of the spent fuel receiving bay. Since spent fuel receiving (or shipping) operations require several hours, the television unit could be set to record sequences of perhaps ten seconds or one minute duration, with the interval between sequences being thirty minutes or one hour. Once each day, or once every few days, the inspector would review the video record, investigate any observed unexplained activities, and reset the unit.

Spent fuel casks can only be moved by using the installed heavy duty crane. This leads to the suggestion that a simple crane monitor designed to indicate whether the crane was used, or whether it was energized and could have been used, might logically serve as a backup surveillance unit. A somewhat different crane monitor was examined as part of TASTEX task A [1].

In that application the monitor was expected to record direction of crane travel and weight of crane load, and difficulties were experienced in trying to correlate the monitor record of crane movements with known spent fuel receipts.

If the steps outlined above are followed, that is, if the inspector personally observes and verifies all declared receipts of spent fuel and a television camera/recorder is used to verify that there are no undeclared receipts, the need to correlate crane movements with sensor records would exist only under special conditions. Crane movements not associated with movements of spent fuel casks could be ignored; so also could occasional failures of the video unit provided no crane movements occurred during the video outage. Only anomalies associated with crane movements during periods of video surveillance failure would require investigation.

These procedures should provide a high detection probability for any attempt either to remove declared spent fuel or to introduce undeclared spent fuel. Indeed, they should be effective against all defined diversion possibilities involving fuel assemblies or fuel rods with the exception of those relating to the possibility that diversion might have occurred prior to the reprocessing facility. The inspector's ability to detect the receipt of dummy fuel assemblies, or fuel assemblies with missing or dummy fuel pins, is largely dependent on step 3, related to verification of Cerenkov radiation. This verification is essentially qualitative, but it is suggested that the fabrication of dummy fuel pins with a characteristric Cerenkov radiation which is even qualitatively similar to that from spent fuel would be a complex problem.

Safeguards studies for PWR reactors often recognize the possibility that undeclared uranium rods might be inserted in guide tubes provided in such assemblies. It has been shown that a sufficient number of unused guide tubes is likely to be available, and that such insertions are not likely to have an adverse effect on the reactor's neutron economy. Detection of undeclared uranium rods is largely a problem for LWR reactor safeguards. It must also be recognized, however, that the rods may still be in place when the spent fuel is received at the reprocessing facility.

The possible existence of undeclared uranium rods does not in fact require any significant change in reprocessing plant safeguards procedures. Pin removal at PNC-Tokai is at best very difficult and could only be managed in the receiving bay or the transfer chute leading to the mechanical cell. Safeguards applied to the spent fuel receiving bay in order to provide an assurance against undeclared offsite shipments of diverted fuel assemblies or pins should be adequate to detect attempts to remove undeclared uranium rods from the facility. If the undeclared uranium rods are left with the fuel during chopping and dissolution, then the excess plutonium becomes part of the safeguarded material balance at that point, and any subsequent attempt at diversion is subject to the same detection probabilities as apply to declared plutonium. The final possibility is that the undeclared uranium rods might be removed and processed as an undeclared feed batch, but this too is only a variation of a more fundamental scenario involving declared fuel pins. Safeguards against by-passing the dissolver measurement tank are discussed in sections 3.4 (for the mechanical cell) and 4.4. (for the measurement tank itself).

Although step 4 requires a comparison of serial identification numbers with those stated by reactor operators, little importance is attached to this comparison. In particular, it is recognized that the serial numbers do not guarantee the identity or integrity of the assemblies themselves.

3.3.2 Spent Fuel Storage. Spent fuel storage at PNC-Tokai is in closed containers with top covers, referred to as baskets. Typical baskets hold four PWR assemblies or eight BWR assemblies (one design for each type). Baskets are loaded, stored, and taken to the transfer chute leading to process as a unit. This system permits easy handling with minimum risk of fuel damage, prevents the spread of contaminated water in the event of fuel leakage and ensures critically safe storage. The top covers, however, make meaningful verifications of spent fuel in the storage area virtually impossible. Optical surveillance of the PNC-Tokai spent fuel storage area has little meaning because there are logical reasons for moving the spent fuel pond bridges, on which the cranes are mounted, that do not involve the movement of spent fuel and because removal of spent fuel is only possible in the receiving bay or transfer chute area.

Existing safeguards practice in general requires the inspector to verify, by direct observation, both the serial number on the transferred fuel assemblies and the fact of all fuel transfers to the mechanical cell. Since as many as four fuel assemblies per day may be transferred, more or less at equally spaced intervals, this is a time-consuming inspection procedure, and in actual fact only a fraction of the transfers are normally verified.

Conceptually there are two possible alternatives. One is to replace the current human surveillance with some sort of instrumental surveillance; the other is to monitor the movements of the spent fuel handling cranes. Among the monitors examined in TASTEX task A the use of an underwater radiation monitor appears to offer promise as a useful instrumental surveillance device. Using three underwater G-M detectors, it was possible to determine the presence of a strong radiation source (a) in the area of the rocker arm used to rotate assemblies from vertical to horizontal, (b) actually being rotated on the rocker arm, or (c) moving on the conveyor leading to the mechanical cell. In the case of (b) and (c), direction of travel was also determined.

While this radiation monitoring system has useful features, a crane monitoring system is suggested as the preferred safeguards measure. Specifically it is suggested that the spent fuel cranes (i.e., the small bridge cranes used to handle individual baskets, not the heavy duty crane used for spent fuel casks) be fitted with a monitor capable of recording the position of the crane in terms of an X-Y grid of the entire spent fuel storage area.

In this alternative approach, the storage location of every fuel assembly would be recorded in an on-line micro-computer at the time the assembly was originally placed in storage. This on-line computer logically also would be given data supplied by the reactor operator as to residual uranium and plutonium composition. When the crane was moved to a location associated with that of a given storage basket, and then was moved from there to the location associated with the transfer chute to the mechanical cell, the on-line computer would assume that the fuel assemblies in question had been transferred to process. This would be confirmed by the radiation monitor described above.

On command, perhaps once per week, the computer would print a list of all assemblies transferred during the defined time period, together with the associated reactor data if available. The computer would also, on command, print a list of the fuel assemblies remaining on inventory and their locations.

Fuel assemblies are close to five metres long. Loading a fuel assembly into a basket, or removing it, thus requires a total water depth of about fifteen metres, ten in order to lift the assembly above the top of the basket plus an additional 3-5 metres for shielding. This necessary water depth exists in the spent fuel receiving bay and in the area leading to the transfer chute, but not in the spent fuel storage area itself.

It is not possible to move individual fuel assemblies manually once they have been placed in storage, first because the necessary tools do not exist (they presumably could be fabricated) and second because the necessary shielding does not exist. The complete "what if" consideration goes through a number of possibilities and is not repeated here. The 100 ton cask crane does not traverse the storage area. The normal fuel handling cranes are bridge mounted and cannot lift any object more than a few feet above the water level. Fuel assemblies could be diverted (i.e., removed from the storage baskets) only in the receiving bay and in the area leading to the mechanical cell. Since no baskets are stored in those areas and the crane position monitor would record any movement of a basket to those areas, diversion of spent fuel from the storage area effectively is not possible.

Process descriptions usually suggest that spent fuel would be allowed to cool a minimum of 120-180 days at the reactor, and then would be allowed to cool an additional 180 days minimum at the reprocessing plant. With current spent fuel backlogs, it is doubtful if there is any need to process fuel which has not cooled for several years at the reactor, so additional cooling at the reprocessing plant is not essential.

On the other hand, these same spent fuel backlogs can be used to suggest that reprocessing facility operators would not be acting without reason if they agreed to accept spent fuel up to the capacity of their storage, in order to help relieve storage problems at reactors. In the absence of any published data, the assumption here is that the nominal capacity of the spent fuel storage pond is on the order of 100 tons, and that under normal operating conditions this capacity will be more or less totally utilized.

It is usually suggested that, consistent with the defined safeguards goals, the IAEA inspector should verify the inventory of spent fuel in storage at intervals of one to three months by counting the total number of assemblies and by observing, probably on a random sampling basis, either the characteristic Cerenkov radiation or the engraved serial number. Since the fuel assemblies are stored in baskets, performing a meaningful inventory verification in this manner would require considerable effort.

If the spent fuel receiving area safeguards measures are operating properly, and if no anomalous indications result from the crane location monitoring system or the safeguards measures in the mechanical cell area, one may question whether inventory verification in the spent fuel storage area more frequently than once or maybe twice per year is truly necessary. The principle of surveillance is "that which is known to have entered an area, and is reliably known not to have left the area, may be assumed to be inside the area". If this principle has meaning, then frequent inventory verifications in the spent fuel pond are redundant. Some discussion of measures which might be adopted in the event there are anomalous indications from surveillance measures is given in section 8.3.

3.4 Mechanical Cell Operations

In the mechanical cell the fuel assembly end pieces are first removed, and the fuel rods are then sheared into short lengths for dissolution. Under normal circumstances one dissolver charge consists either of one PWR assembly or two BWR assemblies. A few sheared pieces may fall to the side and not be dissolved until some subsequent batch, but the usual dissolver charge consists either of one entire PWR assembly or of two entire BWR assemblies.

For official IAEA reporting purposes the model facility attachment provides for batching of up to ten consecutive dissolver charges into one accountancy batch. It is assumed here that the inspector can obtain relevant data on an individual charge basis from operating records. This would include, where necessary, an arbitrary pro rata division where fuel assemblies are split between two dissolver charges.

If both dissolvers are operating more or less in accordance with their design specifications, there are only limited diversion possibilities in the mechanical cell. Specifically, a would-be divertor could consider:

a. charging only perhaps 90-95% of a declared fuel assembly to the dissolver, removing the remaining chopped fuel pieces via the mechanism provided for the removal of end pieces and leached hulls; or

b. interrupting dissolution after only a few hours, such that the undissolved hulls still contained a significant fraction of the original plutonium.

Both of these possibilities require the undeclared removal from the facility of highly radioactive hulls, using either specially designed transport containers or containers which were not designed for that level of activity.

If one or both dissolvers are declared to be out of service, possibly because of maintenance difficulties or because of downstream problems requiring operation on significantly reduced feed rates, additional diversion possibilities may exist. For example,*

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* Note that the question here has no direct relation to the more political question of whether the IAEA should safeguard against the possible existence of undeclared spent fuel. All three scenarios described above can be implemented using declared spent fuel transferred from the spent fuel storage area, spent fuel diverted from some other safeguarded facility.

c. One or more entire fuel assemblies might be dissolved in the supposedly out-of-service dissolver, the resulting solution being transferred to the process MBA without being measured in the input accountancy tank;

d. Selected fuel pins, perhaps removed from declared assemblies in the mechanical cell prior to chopping, might be dissolved, the resulting solution again bypassing the input accountancy tank; or

e. Only 90-95% of the chopped fuel pieces might be transferred to the declared dissolver, the remaining 5-10% being clandestinely dissolved in the out-of-service dissolver, the solution again bypassing the input measurement tank.

3.4.1 Hull Monitoring. Hull monitoring was extensively studied under task C of the TASTEX programme. It is generally agreed that the plutonium content of hulls should represent a maximum of 1.0% of the initial value, with contents in the range of a few tenths of a percent being more typical of good operations. Various hull monitoring techniques have been proposed. In general claimed detection sensitivities are in the range of 0.1% (of initial Pu content before leaching), with uncertainties above 0.1% also being on the order of ± 0.1%. For the model 200 t/a facility these values would be equal to a detection sensitivity of better than 5 gms Pu per batch and a one standard deviation measurement uncertainty of about ± 5 gms Pu. Given other uncertainties elsewhere in the process, a detection sensitivity/uncertainty double the claimed values would still be fully acceptable. All proposed techniques have potential theoretical and practical problems, and most techniques have not been extensively tested. The quoted values may eventually be achievable, but it is doubtful if they can be achieved routinely at this time.

The economic value of hulls containing 5, 10 or even 20 grams Pu per batch is small, and most facility operators have little interest in time-consuming accurate measurements. There are really three questions, however.

a. to the facility operator, some indication of Pu content can be useful as an assurance that dissolution conditions do not require adjustment to stop the loss of valuable plutonium. The question is not one of returning a given batch of hulls for further dissolution, which is rarely warranted economically and may not even be physically possible, but of changing temperatures, acid concentrations, or other parameters on future batches in order to improve recovery.

b. isotope correlations, the gravimetric method, and other calculations related to dissolution input measurements assume that the residual Pu content in hulls is negligible. Where the correlations indicate lower input values than expected, assurance that hulls truly contain negligible Pu is important in order to focus attention on other alternative explanations.

c. there must in any case be some verification or assurance that all hull batches either are irretrievably discarded or are monitored to establish that they have marginal residual Pu contents. Where these conditions do not exist there is a possibility that chopped pieces might be diverted by charging them to a dissolver and then immediately discharging them, after minimum or no leaching, bypassing whatever hull monitor is used.

Very little attention has been given to the question of assuring that all hull batches are presented for monitoring, or, in the absence of any form of monitor, that all hull batches are irretrievably discarded. Most hulls in fact are not irretrievably discarded, but rather are stored on site pending later decisions as to the best method of discard.

Again, an important question is whether all dissolvers are operating more or less on a full schedule. If they are, and if the inspector has verified that a batch of hulls was monitored after each declared dissolution, then there is little room left for undeclared hull batches bypassing the monitor. If one or both dissolvers are declared to be out of service, then hull monitoring and monitor bypassing become parts of the broader question of undeclared use of a supposedly out of service dissolver.

In the reference model facility, hulls are monitored using a gamma detector, ^{144}Pr being the fission product of primary interest. The monitor is nominally installed in line, but there has been very little study of the possibilities for monitor bypassing.

Given that it can be established that all hulls are in fact discarded, i.e., are not themselves diverted, there is little advantage to a would-be divertor in under or overstating the plutonium content of hulls in order to conceal diversion elsewhere. The suggestion here is that safeguards inspections need give relatively little attention to verification of hull measurements so long as the reported values are negligibly small. The inspector might logically set a threshold (perhaps 1.0% of initial content), and ask that he be given the opportunity to verify all hull measurements exceeding that threshold. Measurements below the threshold would be verified on a relatively low level random sampling basis.

3.4.2 Dissolver Sealing. All of the scenarios listed above (i.e., under the assumption that one or both dissolvers might be misused while declared to be out of service) have the complication that the dissolved solution must bypass the input accountancy measurement and must subsequently be removed from the process MBA without its presence (or the removal process) having been detected. Detection possibilities related to bypassing the input measurement or to the presence of excess plutonium in the process MBA are discussed in Chapter 4. There is one other detection mechanism which deserves serious consideration, however. This is the possibility of sealing the dissolver, or some piece of auxiliary equipment critically related to it, in order to ensure that any attempt at undeclared use would be detected.

There are several places that might be considered for such a seal, but nearly all have problems of one type or another. The valve on the nitric acid inlet line is one possiblity. This valve, unlike some other possibilities, should be accessible for sealing, and there should be no logical reason to use the valve for purposes other than spent fuel dissolution. There are many pipes in the area, however, and a careful design review would be required in order to establish that the line could not be bypassed, or that an alternate line could not be used. It is not immediately obvious that an acceptable degree of assurance against undeclared extra lines could be established.

Sealing the transfer point between the dissolver and the input accountancy tank does not appear to be feasible. The entire transfer occurs behind shielding, and the transfer mechanism is a vacuum lift. An adequate assurance against an undeclared extra line is unlikely to be achievable.

The tops of transfer chutes leading from the mechanical cell to the dissolvers normally are capped during dissolution, in order to channel radioactive gases through the off-gas system rather than back up into the mechanical cell. This leads to the suggestion that an out-of-service dissolver might be sealed by sealing its cap in place. Seal design requires careful consideration, because once in the mechanical cell the seal could only be verified remotely. Remotely verifiable seals are discussed in section 4.4., however, and their adaptation to mechanical cell use should be given serious consideration.

4. CHEMICAL PROCESS OPERATIONS

4.1 Diversion Possibilities

In order to discuss diversion possibilities from the process MBA meaningfully, it is first necessary to recognize the distinction between diversion possibilities and concealment or falsification possibilities. The facility operator can remove (i.e., divert) any nuclear material which is physically present, at any time and at any rate. Thus to list diversion possibilities is to list the nuclear materials which are physically present, and possibly to note quantities, concentrations, or other physical constraints which might limit the operator's ability to remove the desired quantity in a safe manner. Such a list is given in Table II.

If the facility operator chooses to remove any of the materials listed in this table, the removal is subject to a probability of detection which is a function of the quantity removed, the uncertainty in accountancy measurements employed, and other variables. This probability of detection, it may be supposed, will normally be higher than the operator can tolerate. In this case the facility operator may be expected to resort to some form of deception, concealment or falsification, with the intent of decreasing the probability of detection to a more acceptable level. This then leads to a second and completely different safeguards consideration, namely that of concealment possibilities.

There are conceptually three ways in which a diversion from the process MBA might be detected. One is to detect, through materials accountancy, the fact that a quantity of plutonium appears to be missing. The second is to detect, through surveillance, either the removal process itself or some associated action. The third, not as commonly discussed, is to detect the effect of the missing material on process equipment or operations. In this chapter the emphasis is on the use of materials accountancy to detect the apparent absence of nuclear material. (More properly, materials accountancy is used to confirm the absence of diversion by confirming that there is no

TABLE II:

DIVERSION POSSIBILITIES IN THE PROCESS MBA

Location	Solution Volume Required		Remarks
	Abrupt Diversion	Protracted Diversion	
Any point in first two extraction cycles, including first three buffer tanks.	4-8000 litres	20 l/day	Shielded container mandatory, especially in first cycle. Even a 20 l container could not be lifted by one or two men.
Fourth buffer tank	5-600 litres	2 l/day	Critically safe container mandatory above about 30 litres.
Product evaporator	30 litres minimum	100 ml/day	Values given assume removal just prior to evaporator discharge. Time-averaged values range between values given here and those given for the fourth buffer tank. Critically safe container mandatory above 1-2 litres.
Product accountancy tank	30 litres	100 ml/day	Critically safe container needed above 1-2 litres.

apparent missing material.) Surveillance and process monitoring activities are discussed in supportive roles, to provide a measure of system redundancy and to assist in the resolution of observed anomalies.

Several comments are in order regarding Table II. In all operations involving plutonium solutions it is necessary for the process designer to choose between equipment which is critically safe by virtue of its geometry and a dilute process flow sheet which is critically safe in all geometries. Both restrictions are severe, and the choice is not necessarily an easy one. The evidence, however, is that designers of the smaller facilities considered here tend to choose a dilute process flow sheet. In the PNC-Tokai facility, for example, the concentration is less than 2.0 g/l through the first two extraction cycles, and rises only to about 15 g/l in the final purification cycle. Except in the product evaporator and the product accountancy tank truly concentrated (250 g/l) solutions are not to be found.

The result is that in general the diversion of 8 kgs Pu requires the removal of relatively large volumes of solution, volumes which do not necessarily exist at one time or place. The concept of abrupt diversion in the sense of a single large removal of the entire quantity to be diverted has meaning only in terms of the diversion of concentrated product solution. At any earlier stage the diversion would of necessity involve two or more removals over a period of time (but still within the assumed 1-3 week interval), with the time between removals being defined largely by the time required for the process to recover from the perturbations introduced by the first removal.

Attention should also be drawn to the remarks in Table II itself, regarding the need for shielded or critically safe containers. These remarks assume that for an abrupt diversion the normal rules of radiation or nuclear safety would be abandoned, but that some rational precautions would be taken to prevent gross personnel exposures and to preclude an accidental criticality. For protracted diversion, in view of the long time period involved, it is probably better to assume that the more restrictive rules universally in current practice would continue to apply.

Using materials accountancy (either conventional or near-real-time), it is not important to consider how such a plutonium removal might be effected. The effectiveness of materials accountancy, in the absence of data falsifications, is determined solely by the quantity diverted, the uncertainties in the measurements used to establish the material balance, and the statistical evaluation procedures adopted.

Since IAEA safeguards cannot be based on an assumption that materials accountancy data has not been falsified, it is important to consider what data falsifications might be used in an effort to decrease the effectiveness of the materials accountancy system. Fundamentally there are three possibilities, understate the plutonium in the input solution, overstate the plutonium in the product solution, or overstate the plutonium in the in-process or clean-out physical inventory. There are in each case numerous possibilities as to exactly which record is falsified, or as to the exact nature of the falsification.

Inventory falsifications are of limited credibility in reprocessing facilities, especially when n.r.t. accountancy is used. The total quantity on inventory usually is small, such that relatively large falsifications are required, percentage-wise, in order to conceal any significant diversion. Also, and most important in n.r.t. accountancy, the falsification of inventory data only postpones detection until the next material balance period. If detection is to be postponed further, that inventory too must be falsified, etc. Where weekly in-process inventories are taken, thirty or forty falsifications may be needed to postpone detection for a year. If additional quantities are diverted during that period, the required magnitude of the falsifications increases, usually reaching a level where detection is inevitable.

A few additional possibilities are introduced as a result of the possibility, discussed in section 3.4, that an out-of-service dissolver might be used to dissolve diverted spent fuel with the intent of subsequently removing the recovered plutonium from the process MBA. These possibilities relate primarily to understatement of the in-process physical inventory to conceal the presence of excess plutonium which has not yet been removed, but it might in some cases be necessary to understate declared removals if the excess plutonium could not otherwise be removed.

Where surveillance measures are used to detect actions associated with the removal process itself, it is necessary to consider the point in the process from which the assumed removal is to occur, and the path the removal is assumed to take. Different paths may involve order of magnitude differences in technical complexity, and it is usually necessary to make some judgment as to a level of complexity which no longer is credible. No attempt is made in this report to identify all credible diversion paths, since surveillance measures are in any case given only a secondary role.

There are, however, only a limited number of places in a 200 t/a reprocessing facility process MBA from which eight kilograms of plutonium could be removed. These include the input accountancy tank itself, the four buffer storage tanks, the recycle tank, the product evaporator, and the product accountancy tank. A diversion which is in any sense "abrupt" must come from one or more of these locations, for the simple reason that no other locations contain that much plutonium. As previously noted, except for the product evaporator or the product accountancy tank an abrupt diversion must also involve either two or more removals from the same tank over a period of some days, or removals from two or more tanks.

Even when one switches attention to protracted diversions there are limitations on where the solution could come from. Section 4.4 considers whether surveillance measures applied to a limited number of process points, notably the buffer storage tanks, could be used to provide an added assurance that any attempted diversion would have a high probability of detection. Such measures could also be used to assist in the resolution of anomalies in the n.r.t. accountancy data.

4.2 Conventional Materials Accountancy

It is universally agreed that a reference system of conventional materials accountancy, based on cleanout physical inventories at six to twelve month intervals, should be a fundamental safeguards measure even where n.r.t. accountancy and/or extended C-S measures are used to meet timeliness and detection sensitivity goals. Such a system is described in the previously referenced model facility attachment [12]. The basic measurements include the input accountancy measurement tank, the product accountancy tank, and various high, medium, and low level waste discards. The physical inventory, under cleanout conditions, normally involves only residual quantities of solution in the four buffer tanks.

4.2.1 Input Measurements. The input accountancy tank receives solution from one dissolution batch, consisting of either one PWR fuel assembly or two BWR assemblies. The total solution volume, after acid adjustment, is on the order of 2500 litres, and the uranium concentration is about 180 g/l. For high burnup fuels this translates into a Pu concentration of slightly less than 2.0 g/l. It is worth noting that the Pu concentration is not an independently determinable parameter, but is determined by the reactor history of the fuel assemblies in question and the achieved uranium concentration. For low burnup fuels the Pu concentration may be only 1.0 g/l, even though the design uranium concentration of 180 g/l is achieved.

Under task E of the TASTEX programme a Ruska precision electromanometer was installed and tested for the measurement of input accountancy tank solution volume. The resulting uncertainties, as determined by PNC during routine use, are not larger than ± 0.1% for either liquid level or density (one standard deviation).

Samples of the input accountancy solution are analyzed for Pu and U isotopes using isotope dilution mass spectrometry, and total U and Pu are calculated on a volume times concentration basis. Although these measurements are both time-consuming and expensive, they have long-term systematic uncertainties of less than 0.5%. Various possibilities, notably X-ray fluorescence, have been studied as alternative measurement procedures, but the prospects for a reasonably rapid non-destructive measurement method for input dissolver solutions do not appear good.

The advanced safeguards approach places a heavy reliance on isotope correlation techniques to ensure the validity of input accountancy tank samples. The first rough checks are made by comparing the reprocessing plant measured values with data supplied by the reactor operator. These checks are probably no better than ± 10% on individual batches, or perhaps ± 5% on a campaign basis, but they can be made immediately and can thus provide useful protection against falsification to conceal an abrupt diversion.

The first accurate verifications are made using isotope correlations calculated from the operator's analytical data. Finally, the validity of this analytical data is established through IAEA independent analysis of duplicate samples. It is doubtful if these verification analyses can ever be completed more timely than about 3-4 months, but this should be adequate for detection of the small falsifications associated with protracted diversion.

It is assumed that the inspector makes no attempt to control the integrity of input accountancy tank samples except on a random basis. There are two justifications for this. First, it is generally agreed that observation of the sampling and analysis process, including the taking of the sample and its subsequent treatment prior to aliquoting and analysis, does not provide an effective assurance against sample tampering. Sample preparation is a time-consuming process, there are ample opportunities for the operator to take advantage of momentary breaks in the chain of observation, and there are still further possibilities for sample tampering which do not assume any lack of diligence on the part of the inspector.

Second, within the accuracy of mass spectrometry measurements and isotope correlation verifications, 1-2% at most, there are believed to be no sample falsification possibilities that would not be detected by isotope correlation verifications. Most possibilities would be detected at the input accountancy measurement point itself; a few would only be detected by comparison of isotope data across the input and output measurements, but would nevertheless be detected with a high probability.

On the other hand, it is assumed that input accountancy tank samples are in due course verified by independent IAEA analysis. This means a significant analytical workload for the IAEA, but the actual cost should be comparable to the cost of inspector control of sample integrity, and the improvement in safeguards effectiveness should be significant.

If process MBA input measurements are to be falsified as part of a diversion concealment attempt, either the volume must be understated or the Pu concentration of the sample must be understated, or possibly both. The following safeguards measures are assumed to be used to assure a high probability that such falsifications, if attempted, would be detected.

a. The input accountancy tank volume calibration is established during cleanout physical inventory shutdown. An IAEA inspector should observe all such calibrations. Moreover, as calibration data accumulates the consistency of each calibration with past data should be verified, and the total data set should be used to produce a mean calibration with a lower uncertainty than any individual calibration.

b. The procedures developed under TASTEX task E for frequent on-line calibration checks should be followed, and their use should be verified by inspection.

c. For each input accountancy tank the inspector should compare the total plutonium calculated by the gravimetric or Pu/U ratio method with that reported by the facility operator.

d. A sample from each input accountancy batch, prepared either in accord with current practice or in accord with the resin bead technique, should be shipped to the Agency's safeguards analytical laboratory for verification analysis.

4.2.2 Output Measurements. The product evaporator is fed continuously, and is discharged when the Pu concentration reaches a desired range of at least 250 g/l. With high burnup fuels this is expected to occur about once every 24 hours. Since to a first approximation the lower Pu input concentration in low burnup fuels carries through the entire process, evaporator discharge in fact occurs only once every 1-2 days, even with nominally "capacity" operation, depending on the fuel being processed.

The nominal size of a product accountancy batch is 30 litres, at a concentration of about 250 g/l. As with the input accountancy tank, the solution volume is measured, the solution is sampled for chemical analysis, and the total plutonium is determined by volume times concentration. A Ruska electromanometer system is used to determine the solution volume to an accuracy of better than ± 0.1% (one standard deviation).

Whereas it was necessary to understate the plutonium content of input batches, it is necessary to overstate plutonium in product output batches if measurement falsification is to be used as part of a diversion concealment attempt. The following safeguards measures are assumed to be used to assure a high probability that such falsifications, if attempted, would be detected.

a. As with the input accountancy tank, the product accountancy tank volume calibration is established during cleanout physical inventory shutdown. An IAEA inspector should participate in all such calibrations, and as calibration data accumulates the total data set should be used to produce a mean calibration with a reduced uncertainty. Any significant change in the calibration should be investigated.

b. After each product transfer, the inspector should compare the increase in volume in the applicable product storage tank with the volume measured in the accountancy tank.

c. A sample from each product accountancy tank should be analyzed in a K-edge densitometer (or other NDA instrument) under IAEA inspector control, or in an instrument which has been calibrated and tamper-safed under IAEA inspector control.

d. A sample from each product accountancy tank should be analyzed isotopically in an independent IAEA laboratory. This sample need not be the same as the sample analyzed in the K-edge densitometer, but samples integrity should be verified by inspector observation.

e. Informal isotope material balances should be maintained on all higher isotopes of plutonium. Any failure of MUF data for individual isotopes to "track" each other or the total plutonium balance should be investigated as possibly indicative of input sample falsifications.

4.2.3 Physical Inventory Takings. At intervals of approximately six months, when the process is shut down between campaigns, cleanout physical inventories should be taken. Specific instructions for plant cleanout prior to these physical inventories are not discussed here, but it is assumed that the mixer-settlers as well as all other process lines or tanks which cannot be measured will be flushed with nitric acid such that the residual (unmeasurable) plutonium content is negligible. In the course of these flushing operations the total plutonium in measurable tanks usually drops to no more than a few kilograms, and no further materials accountancy requirement is necessary. It is assumed that the plutonium inventory during a cleanout physical inventory normally will be less than 5.0 kgs Pu.

4.3 Near-Real-Time Materials Accountancy

In addition to a system of conventional materials accountancy based on cleanout physical inventories at six month intervals, the advanced safeguards approach described here assumes that in-process physical inventories will be taken at weekly intervals, and that the resulting near-real-time materials accountancy data will be evaluated using statistical techniques which specifically recognize the sequential properties of the MUF data. This near-real-time materials accountancy system was extensively investigated as part of the TASTEX task F effort [1,2,4-8], and is expected to serve as the primary safeguards measure in the process MBA, both for "abrupt" and "protracted" diversion possibilities.

4.3.1 In-Process Physical Inventories. The nominal interval between in-process physical inventories is assumed to be seven days. There is a primary constraint, however, that each inventory must coincide with the emptying of the plutonium product evaporator. This occurs, or should occur, about once a day when the plant is operating at capacity on high burnup fuels. It may only occur every second or third day when low burnup fuels are being processed, and it may occur even less frequently if the plant is in a rinse-out mode. Exact scheduling is not critical so long as the inventory is taken between the time when flow to the evaporator is interrupted at the end of one evaporator batch and the time when flow is resumed at the start of the next batch. Since each batch is allowed to cool somewhat before being transferred, this time interval is large enough to allow some flexibility in scheduling.

At the designated inventory time, the volume in each of the four buffer storage tanks is read from the strip chart recorders in the process control room. It is also necessary to read solution temperatures from process control temperature indicators. Samples are taken, using installed sample lines feeding to the sample gallery, for analysis in the facility operator's analytical laboratory. From these data the plutonium inventory in the buffer storage tanks can be calculated.

It is assumed that the plutonium inventory in the solvent extraction systems will be estimated using a relation such as:

$$H = F_a \times C_f \times \frac{V}{F_a + F_o + F_s} \qquad \text{(eq. 2)}$$

where: H = total plutonium inventory in one cycle of solvent extraction

C_f = plutonium concentration in aqueous feed

F_a, F_o, F_s = flow rates of aqueous feed, organic feed, and scrub feed respectively

V = total system volume

Equation 2 is theoretically valid if the solvent extraction system is at steady-state and at equilibrium. It is assumed that the steady-state requirement can be satisfied by stipulating that inventory calculations be scheduled only a minimum of several hours subsequent to any significant change in flow rates or concentrations. The importance of the assumption of equilibrium is still under investigation. A non-equilibrium correction term can be theoretically defined, but there is some question whether the correction is of practical significance unless the system is far from equilibrium. Investigations in this area relative to possible application in future large scale facilities are still continuing.

4.3.2 Flow Measurements. The input and output flow measurements used for near-real-time materials accountancy are exactly the measurements previously discussed under conventional materials accountancy. In the TASTEX task F field test work it was assumed that conventional analytical methods could be used to produce analytical results within at most one week after the measurement date. No specific timeliness is assumed here. However, it seems likely that the K-edge densitometer can be used to provide interim measurement data on the needed time scale for the product accountancy measurement. Since no rapid NDA measurement for input solutions exists, the exact timeliness of the n.r.t. system will be determined by the achievable timeliness of conventional measurements. This should still be well within the 1-3 week guideline.

4.3.3 Data Evaluation. A variety of statistical tests have been suggested for the evaluation of near-real-time materials accountancy data. Nearly all have in common the fact that they are equally applicable to the detection of uncorrected measurement bias, unrecognized plutonium losses, and protracted diversion. (Reference [13] uses the term "constant effects" to refer to all three possibilities.) Some statistical tests include an estimate of the magnitude of possible uncorrected measurement biases, sacrificing detection sensitivity for a degree of assurance that what is eventually detected has a greater probability of being of real significance. Others place primary importance on detection sensitivity, and assume that subsequent assessment procedures can be used to identify the exact nature of the constant effect detected.

Statistical tests, and the evaluation and interpretation of the results of those tests, are discussed in greater detail in Chapter 8.

4.4 Surveillance and Process Monitoring

The advanced safeguards approach places primary emphasis on a combination of conventional and near-real-time materials accountancy to confirm that no significant quantity of nuclear material is unaccounted for, and therefore that none could have been diverted. This accountancy system, it was argued in section 4.3, is believed to be capable of satisfying IAEA goals regarding both abrupt and protracted diversion possibilities. Nevertheless, there are some areas in which it appears that surveillance measures could improve detection sensitivity, could assist in the resolution of false positives, or could provide a desirable degree of redundancy.

The conceptual purpose of all C-S measures is to preserve the integrity of (a) previously verified measurement data, (b) IAEA measurement equipment (or jointly used equipment on which the IAEA relies), or (c) IAEA surveillance equipment. In conventional C-S applications only individual items, containers, or equipment items, or collections of items, containers or equipment, are involved. There is presumed to be no movement of nuclear material within individual items or containers, or it is presumed that movements of identifiable items can be identified and resolved from examination of the surveillance record.

In extended C-S proposals a defined physical area comprising an entire material balance area (or even a group of MBAs) is controlled, and it is explicitly recognized that there will be legitimate (i.e., declared and verified) movements of nuclear material into and out of the MBA. The theoretical basis is still preservation of the integrity of verified measurement data, but the data in question relates to the material balance as a whole, not to individual items or containers within the material balance.

There are in fact very few potential applications of conventional C-S measures in the process MBA of the model reprocessing facility. It would be useful to be able to seal the transfer line from the input accountancy tank to the first buffer storage tank, but the transfer is by vacuum lift behind heavy shielding, and identification of a useful sealing technique does not appear possible. One might also consider sealing some or all of the sample lines in the sample gallery, but the number of points to be sealed and the need to take frequent samples for operational purposes makes such seals unattractive.

A seal on a valve in the transfer line from the product evaporator to the product accountancy tank would be highly useful. So also would a seal on a valve in the line from the product accountancy tank to the product storage MBA. Flow from the evaporator to the accountancy tank is by gravity through a valved line; the valve is operated manually inside a glove box. Flow from the accountancy tank to the product storage tanks is through a pump; again the necessary valves are operated manually inside glove boxes.

The glove box constraint is not a minor one. True laboratory verification of standard type E seals would be impossible. Some fibre optic seals also suffer from the same limitation. They are dependent on a photographic verification which could only be accomplished by creating a separate glove box with an optical path to a camera mounted outside the box.

One exception may be the VACOSS seal [14], or a seal developed in Japan under the general title of a remote monitoring system [15]. Conceptually the two sealing systems are highly similar. The seal wire is fibre optic; the "seal" itself is an electronic box roughly comparable in size to a package of cigarettes. The Japanese version is permanently connected to its remote monitor and therefore contains no internal power supply, making it somewhat smaller. The VACOSS seal is connected to an interrogating "adapter box" only when system interrogation is desired, making it independent of external power failures. Both systems have comparable abilities to respond to and record opening of the seal or seal wire, or various attempts at system tampering.

The suggestion in this report is that either VACOSS or the Japanese remote monitoring seals be used to seal (a) the valve leading from the product evaporator to the product accountancy tank, (b) the valve leading from the product accountancy tank to the product storage area, and (c) all other valves which might be used either to remove a plutonium-rich solution from the process MBA or to transfer such a solution between the process and the product storage MBAs in either direction. No specific attempt has been made to identify all valves in these latter categories. It is known that the PNC-Tokai facility has a rework tank and a transfer line leading from the product storage area to it; this would be one place for such a seal.

Whether other possibilities exist will depend on design characteristics of specific facilities. Given the radioactive nature of the solutions in question, the number of such lines should be very small and may well be zero.

One recognized problem inherent in near-real-time materials accountancy is that detection sensitivity is achieved at least partly at the expense of a higher probability of "false positives". Where a false positive is caused by some type of measurement problem (most typically a measurement bias), it may be assumed that the true nature of the situation can be established through investigation and measurement control. Where a false positive results from a chance combination of stochastic measurement errors, however, resolution may be more difficult. Since in this latter case there is no definable physical cause no amount of investigation and measurement control can assign a physical cause, leading inevitably to the suggestion that diversion may in fact have occurred.

Diverted nuclear material, however, cannot be invented. It must have been removed from some physical point in the facility, through some physical removal mechanism. This leads to the suggestion that a monitoring system designed to detect unusual movements of plutonium-rich solutions through lines not intended for such movements might be used as corroborative evidence in support of near-real-time materials accountancy. Anomalous MUF data in the n.r.t. accountancy system unsupported by any indication of possible physical removal could be treated in a more relaxed manner, the degree of relaxation depending on the confidence placed in the monitoring system. Similarly, anomalous surveillance indications (e.g. equipment failures, which do not seem to be avoidable) unsupported by any evidence of missing nuclear materials could also be discounted or down-graded.

If the monitoring system is applied to all technically feasible penetrations of a defined containment boundary, the term penetration monitoring is used. While it is not the purpose of this report to give a complete evaluation of penetration monitoring, there are indications that the number of penetrations to be monitored, the lack of suitable monitoring devices, and other problems may limit the usefulness of this type of monitoring system.

An alternative less frequently considered is to monitor selected points within the process to establish that no plutonium-rich solution is being lost. If plutonium is to be diverted from the process MBA, (either in an abrupt or in a protracted manner), there are a limited number of tanks or process vessels which might be used as a source of plutonium. If the most logical sources of plutonium could be monitored to show that no solution is unaccountably missing, the resulting complementary assurance of non-diversion should be of significant value both in adding to the total assurance and in helping to assess and resolve anticipated false positives in the materials accountancy data.

The most logical source for diverting plutonium from a reprocessing plant process MBA would be either the product accountancy tank itself or the evaporator immediately preceding the product accountancy measurement. Specific possibilities include:

a. discharge the evaporator into the product accountancy tank, and then remove a quantity of solution prior to making the accountancy measurement;

b. discharge the evaporator into the product accountancy tank, but stop the transfer before all solution has been discharged, then remove the remaining solution in the evaporator via some unspecified line; or

c. during the later stages of evaporator operation (i.e., when the solution in the evaporator is near its maximum concentration) remove a quantity of solution via some unspecified line, possibly the normal line leading to the product accountancy tank.

All of these possibilities could be monitored with an in-line continuous measurement of plutonium concentration in the evaporator feed. Data from this in-line monitor, coupled with flow monitoring, could be fed to a mini-computer programme designed to maintain a time-integrated plutonium inventory for the evaporator. Such an in-line monitor, based on X-ray fluorescence, is currently being developed at the Lawrence Livermore Laboratory and tested at the U.S. Savannah River reprocessing plant.

The next most logical source from which to make an undeclared physical removal of plutonium from a process MBA would be one of the buffer storage tanks, especially one of the later ones, where purification is more nearly complete. These tanks are equipped with strip chart recorders for total volume, and with either flow indicators or flow recorders for both inlet and outlet flows. A straightforward on-line computer monitor, comparing the directly monitored total volume with the volume derived from inlet and outlet flows, should be capable of detecting any attempted diversion from that buffer tank, regardless of the manner in which the physical removal is attempted, unless the removal is carefully balanced, on a real time basis, by identical additions of water or nitric acid. A more elaborate model might include density monitoring to detect this balancing.

The only remaining "logical" plutonium source would be the aqueous product output from one of the solvent extraction systems, with the removal somehow occurring prior to the flow indicator referred to above. The piping necessary for such a removal may or may not exist, but identification of specific removal paths is not a part of the current work.

An abrupt removal of a significant quantity from this aqueous product flow would be reflected in a drop in the flow and volume associated with the downstream buffer tank. It might also be reflected in a lack of agreement between the aqueous flow into the particular solvent extraction system and the apparent flow out of it, but the objective in the development of process monitoring should be to identify the minimum necessary set of monitors, not all monitors which might possibly contribute to an assurance of non-diversion. Thus the suggestion in this report is that monitoring of the inlet and outlet flows to the buffer tanks, in comparison with tank volumes, should be sufficient to detect both a diversion from the tank itself and an abrupt diversion from the aqueous product output of the corresponding solvent extraction system.

Basically two possibilities remain. One is the possibility of diversion from the aqueous outflow from a buffer tank, after the flow monitor and before the flow disappears into a solvent extraction system. The other is a diversion of plutonium-rich organic from one of the solvent extraction systems. It is not immediately obvious that the limited number of monitors thus far specified would be adequate to cover all these possibilities. However, operations in a reprocessing facility are closely coupled, and it may be that a diversion (or at any rate an "abrupt" diversion) from one of these intermediate points could not be prevented from having a visible effect on one of the monitored measurements.

The possibility of additional monitoring points might also be considered. The basic premise in this section is that only a limited number of points should be monitored, and that the resulting effectiveness should not be required to cover all secondary possibilities. Both "additional monitoring points" and "secondary diversion possibilities", however, are subject to comparative evaluation. If a few additional monitors provide effective coverage for significant diversion possibilities, and the monitoring points do not adversely impact on operations (or result in excessive inspector access to operating data) then it would be logical to add them. If a technically feasible but nevertheless somewhat complex diversion possibility cannot be protected against without recourse to extensive complex monitors, then the assumption is that monitoring would not be attempted, and reliance would be placed in the materials accountancy systems.

The detection sensitivity achievable with such a monitoring system has not been determined. Dunn and his associates at Lawrence Livermore Laboratory [16] have studied the monitoring of tank volumes, and have given particular attention to filtering out random signal fluctuations, concluding that accuracies of a few tenths of a percent should be possible. Similar results were obtained under TASTEX task I, although the emphasis there was on the practicalities of monitoring, not on signal processing.

If 8 kgs Pu are to be diverted over a period of one year during which there are about 250 days of actual process operations, the minimum diversion rate is 32 grams Pu per day. If, as in the PNC-Tokai facility, the process flowsheet requires a maximum solution concentration of 2 g/l, then the minimum diversion is 16 litres per day. For a buffer tank with a capacity of perhaps 1500 litres this is 1% of tank capacity, and probably more nearly 2% of actual tank content since the buffer tanks are seldom truly full. Monitoring to detect volume discrepancies of this magnitude should be possible, especially since the protracted diversion scenario does not require immediate detection, but allows time for patterns to develop. As previously noted, an abrupt diversion of 8 kgs Pu would require removal of more solution than is available at any one point in the process except the product accountancy tank, and should be immediately obvious to the process monitors.

In summary, the suggestion here is that a total of fifteen process points should be monitored, as follows:

1. liquid level in the input accountancy tank;
2. liquid level in the first buffer storage tank;
3. liquid level in the second buffer storage tank;
4. liquid level in the third buffer storage tank;
5. liquid level in the fourth buffer storage tank;
6. liquid level in the product evaporator;
7. flow rate from the input accountancy tank to the first buffer storage tank;
8. flow rate from the first buffer storage tank to the first extraction cycle;
9. input flow rate to the second buffer storage tank;
10. flow rate from the second buffer storage tank to the second extraction cycle;
11. input flow rate to the third buffer storage tank;
12. flow rate from the third buffer storage tank to the third extraction cycle;
13. input flow rate to the fourth buffer storage tank;
14. flow rate from the fourth buffer storage tank to the product evaporator;
15. liquid level in the product accountancy tank.

A complete list of anomaly indications which might result if diversion were attempted, together with the manner in which these anomalies would be detected using process monitoring data, is given in a companion report STR-141 [17]. Some examples can be given here, however. Since solution can only be transferred from the dissolvers to the process MBA through the input accountancy tank, any of the diversion possibilities discussed in section 3.4 would lead to anomalous level indications on monitor 7. Diversion from any of the buffer storage tanks would lead to a discrepancy between the liquid level and the volume derived by integrating the input and output flow rates (for example, for the third buffer tank, monitor 4 compared to monitors 11 and 12).

One of the criticisms often voiced concerning process monitoring is that it results in an unacceptable degree of inspector access to process operating data. It is not immediately obvious to the authors that the limited system described above in fact involves an unacceptable degree of access. However, at least one possibility exists for reducing access while preserving the monitoring system. Volumes and flow rates are in actual practice measured in terms of pneumatic signals which in turn are converted to electrical signals, usually millivolts, for transmission to control equipment. It is only when combined with calibration factors that these millivolt signals acquire physical meaning in terms of litres or litres per minute. Since in any case the process monitoring data will be computer processed, it seems logical to suggest that the inspector need not know these calibration factors. An anomaly of say 2.5 millivolts may seem strange, and difficult to assess in terms of how much plutonium may have been diverted, but it is still an anomaly requiring investigation. If the investigation shows that solution is indeed unaccountably missing, it is for the materials accounting system to say how much plutonium appears to be unaccounted for.

5. PLUTONIUM STORAGE

5.1 Diversion Possibilities

The product from the process MBA, plutonium nitrate solution with a plutonium concentration of about 250 g/l and a nitric acid concentration of at least 2.0 N, is stored in the Pu storage MBA pending offsite shipment. In the reference PNC-Tokai design, storage occurs in one of seven tanks having an annular geometry. The original three of these tanks have differential pressure volume measurement capabilities, but lack the third line necessary for density measurements. The remaining four, having been added later, have both volume and density measurement capabilities. All seven tanks are interconnected by a pipe manifold which permits transfers between tanks, recirculation within a tank, receipt from the product accountancy tank, return to the process MBA via transfer to a rework tank, or offsite shipment via a separate constant volume accountancy tank.

As previously described, plutonium nitrate solution is transferred from the process MBA to one of the tanks at intervals of about once every one or two days. Offsite shipment of plutonium nitrate occurs at irregular intervals. Typically there will be one or more shipments every day or every few days until a required quantity has been shipped, then no transfers at all for some days or weeks until another "batch" is to be shipped.

Plutonium nitrate solution is not dependably stable for long periods of time. (Some would probably say it is dependably unstable). It may undergo auto-oxidation/reduction, leading to a plating out of a solid phase on vessel surfaces, and unless the nitric acid concentration is at least 2.0 N the plutonium may form a soluble but not easily destroyed polymer. In an effort to restrict the significance of these undesirable side effects, it is common practice to mix the solutions at frequent intervals (daily to weekly). During these mixings, or at any other time, the operator may choose to inter-mix the contents of various tanks.

Since the plutonium concentration is high, stored plutonium nitrate solution is commonly perceived as being highly susceptible to diversion. The assumed goal of 8 kgs Pu could be achieved by removal of 30-40 litres, depending on the actual concentration available, with little or no shieldding. There is normally only one transfer line through which plutonium can be removed from the storage MBA, but safeguards experts usually are reluctant to assume that facility design review can be adequate to detect undeclared piping. Appropriate sealing of the known transfer line therefore usually is not considered sufficient to provide a high degree of assurance of non-diversion. There is also the possibility that solution might be transferred back to the accountancy tank between the process and storage MBAs, and diverted from that point.

5.2 Materials Accountancy

Conventional materials accountancy, with re-measurement of the plutonium concentration in all tanks at six month intervals, presents no significant difficulties. The tanks must be sampled for chemical analysis, but the limited number of tanks imposes no unexpected materials accountancy burden.

With the availability of NDA instruments such as the K-edge densitometer, it may be questioned whether a maximum of seven analytical measurements (typically not all tanks are in use) on a weekly basis would really constitute an unacceptable burden. The samples can be taken, analyzed and returned to storage (the K-edge densitometer is in that sense nondestructive) in a matter of two or three hours. Thus the suggestion in this report is that the primary safeguards measure in the product storage area should be near-real-time materials accountancy, based on weekly inventories taken using the K-edge densitometer. This would be coupled with an on-line monitoring system designed to detect possible discrepancies in total volume. This monitoring system derives generally from the TASTEX task I work, and is described in the next section.

5.3 Storage Monitoring and Surveillance

It is usually suggested that the product storage MBA at reprocessing facilities should be safeguarded by conventional materials accountancy combined with seals to prevent undetected solution transfers. Since the valves which are to be sealed are inside glove boxes, and since in any case valves must be opened and closed routinely to provide for solution recirculation, this conventional C-S approach is not appealing. It probably could be made to work, but its effectiveness is likely to be constantly in question. Effectiveness is especially likely to be questioned if the conventional materials accountancy system reveals a sizeable MUF which might or might not have been caused by solution instability problems.

The routine availability of volume measurement indications, however, suggests that an on-line computer programme should be used to monitor total solution volume. Many aspects of such a system were tested and demonstrated under TASTEX task I, although that project made little attempt to correlate data obtained from different locations. The suggestion here is that the on-line computer should go significantly beyond being a modern version of a strip chart recorder. It should take as input data the volume transferred into the system from the product accountancy tank, as output data the volumes transferred off-site via the off-site transfer system, and as inventory data the indicated tank volumes, and maintain a real time accountancy system for solution volume.

Several corrections would be necessary. Evaporation and radiolytic decompositon of water both lead to volume decreases. However, these can be predicted empirically from an approximate knowledge of plutonium isotopic composition. Samples are taken from time to time for reasons of interest only to the plant operator. Recirculation will introduce temporary gross fluctuations, and may lead to a redistribution of volumes among the seven tanks. All these corrections should be straightforward. From published data [16], an on-line computer volume control system should be able to detect unexplainable volume changes of less than 0.5%. Since an abrupt 8 kg diversion would require a 1% removal if all tanks were full, and more likely a 2% removal based on probable average inventory levels, a detection sensitivity of 0.5% should be adequate.

Of greater importance is the question of whether the system could be defeated by careful additions of nitric acid to balance solution removals. Since three of the storage tanks are not instrumented for density measurement, detection of this substitution by density monitoring is not possible.

It is tempting to suggest that the solution to this problem would be to instrument the three tanks in question. Certainly for any future facility density monitoring instrumentation should be given serious consideration. Unless other maintenance work in the same area is required, however, it is doubtful if backfitting an existing facility is worth the cost. Density measurements are not highly precise when performed using on-line differential pressure instrumentation, and it is not at all certain that nitric acid substitution could be detected even if instrumentation were available. For an abrupt removal of 35-40 litres over a period of one or two weeks, the nitric acid addition might sufficiently alter the density to permit detection. For a semi-protracted diversion of three or four litres per week over a period of three months, the nitric acid additions almost certainly would be buried in density measurement noise.

In summary, the safeguards measures suggested here include:

a. valve position monitors on the valves leading from the product accountancy tank to the storage tanks, and from the storage tanks to the offsite measurement tank;

b. an on-line volume monitoring computer programme to provide an assurance that solution is not disappearing in an unexplainable manner;

c. "near-real-time" materials accountancy, using in-process physical inventories based on K-edge densitometer measurements at weekly intervals; and

d. conventional materials accountancy based on accurate chemical analyses at six month intervals.

5.4 Product Withdrawal and Shipment

Offsite shipments of plutonium nitrate solution are made by returning the desired solution to the product accountancy tank, from whence it is transferred to a constant volume measuring tank and drained into bottles for shipment. The plutonium concentration and isotopic data are based on samples taken from the product accountancy tank; the solution volume transferred is based on the number of times the constant volume measuring tank is filled and drained. Transfer from the constant volume tank to shipping bottles is by gravity drain, the assumption is that the tank drains empty without a heel.

Very few safeguards measures are required at this point, and conventional procedures should be adequate. Thus the transfer line from the constant volume measuring pot to shipping bottles should be sealed when not in use, and the inspector should be present and should verify all measurements made when shipments occur. Measures used to safeguard against undeclared transfers from product storage are equally applicable here, and supplementary measures do not appear necessary.

6. SAFEGUARDS FOR URANIUM

6.1 Diversion Possibilities

The ^{235}U content of spent fuel typically is in the range of 1%, depending both on the initial enrichment and on the total burnup level achieved. Occasional high burnup fuels may contain uranium with an "enrichment" of less than 0.711%, such that the safeguards rules applicable to depleted uranium apply, but most spent fuel still at least marginally meets the requirement for enriched uranium.

Most published safeguards approaches for reprocessing facilities assume that safeguards will be applied to this nominally enriched uranium, but give little or no attention to specific safeguards procedures. The unstated assumption is that this uranium is of relatively little safeguards importance, given the availability within the same facility of large quantities of more easily utilized plutonium.

Uranium and plutonium in reprocessing facilities are in fact very closely coupled. The relationships between plutonium concentration in spent fuel and uranium depletion or isotopic composition are well known. Use of uranium MUF data in the evaluation of plutonium MUF data within the reprocessing facility itself is less commonly recognized, but can be very important. If there is an apparent "constant effect" in the plutonium MUF data, and biased input accountancy measurements are being suggested as a possible cause, then there should be a corresponding constant effect in the uranium MUF data. If the effect is not there then one must question the validity of the suggestion that the plutonium MUF data are the result of biased input measurements. If the safeguards applied to uranium are such that the inspector cannot establish whether the uranium and plutonium MUF data are "tracking", then the safeguards applied to uranium are inadequate.

The analysis can (and should) be carried at least one step further. If a would-be divertor wishes to remove plutonium, and to conceal the removal by creating the appearance of a bias in the input accountancy measurement, then he may decide to remove the quantity of uranium necessary in order to create an appearance of tracking. The divertor in this case has no planned use for the uranium, but its diversion becomes a part of the plutonium diversion concealment plan.

This coupling of uranium and plutonium exists only within the process MBA. Prior to dissolution the uranium and plutonium in spent fuel are inseparable, and safeguards applied to plutonium in spent fuel automatically safeguard the uranium. Once separate uranium and plutonium product measurements are made at the output from the process MBA the two materials are decoupled, and further safeguards can consider the two materials separately. Within the process MBA safeguards for uranium must be based not on the diversion potential of the uranium itself, but on the complementary information and assurance which safeguards for uranium can provide with regard to the more important safeguards for plutonium.

The assumed safeguards goal for low enriched uranium is 75 kgs of contained ^{235}U, corresponding approximately to 7500 kgs U. If the assumed goal for plutonium is 8 kgs Pu, however, and if the assumption is that uranium might be diverted as part of a plutonium diversion concealment scheme, then the uranium quantity of interest is about 800 kgs U, dependent not on ^{235}U content but on the burnup level achieved in the spent fuel. These quantities are still large, but they are significantly smaller than is usually assumed.

6.2 Materials Accountancy

It is assumed that conventional materials accountancy measures will be applied, with input measurements being made in the input accountancy tank, and with output measurements being made on containers of UO_3 product removed from the process MBA. Cleanout physical inventories will be taken between campaigns, at approximate six month intervals. All of these measurements are straightforward, and require no discussion here. It is important, however, that these measurements be verified for safeguards purposes. Verification can be by the transmission of chemical samples to the Safeguards Analytical Laboratory for analysis.

Since the nominal in-process uranium inventory is in the same range as the quantity of interest, i.e., 800-1200 kgs U regardless of enrichment, input-output analysis may provide useful information on a near-real-time basis with no increased effort on the part of the facility operator. Data points logically would be determined coincident with the timing of n.r.t. accountancy in-process inventories for plutonium, although consideration should also be given to procedures which maximize the uniformity of the data points. That is, one might arbitrarily alter the weekly data period to coincide with uranium product transfers, such that the in-process book inventory always tended to be at its minimum value. No inventory measurement or verification for uranium on an n.r.t. basis is necessary.

6.3 Monitoring and Surveillance

If input-output analysis as described above is employed, there is little need for monitoring or surveillance measures related to uranium. The transfer of undeclared uranium into the process MBA, independent of any corresponding undeclared transfer of plutonium, might possibly be defined as credible, as a means of concealing the fact that a portion of the dissolver solution has bypassed the input accountancy tank, but most other possibilities make little sense.

Containers of product UO_3 should be sealed, both to prevent their being presented to the inspector a second time, as fresh product, and to preserve the integrity of the verified measurement data for later safeguards use.

7. SUMMARY ESTIMATE OF INSPECTION EFFORT

The preceding chapters have described and discussed the inspection procedures believed to be necessary for effective safeguards in the reference reprocessing facility. No estimates of inspection man-days were made, and indeed certain basic inspection procedures (e.g., auditing of records) were passed over very quickly or even not mentioned. This chapter gives, in tabular form, a summary of all required inspection activities, an estimate of the time required to perform those inspection activities, and from these estimates a further estimate of the number of inspectors required to implement the described advanced safeguards approach.

As has been the assumption throughout this report, the assumption here is of a model reprocessing facility patterned very closely after the PNC Tokai facility in Japan. Two alternative operating assumptions have been considered. The first is that the plant operates at its rated capacity for 300 days per year, in two campaigns of 150 days each. Tables IIIa - IIIc give the inspection activities and estimated time required for this full capacity case.

Very few reprocessing plants have ever successfully operated at rated capacity for extended periods of time, and indeed some studies of future plants have assumed (hopefully conservatively) only 200 days per year of full capacity operation. In order to give a more realistic estimate of inspection effort likely to be required under practical conditions, tables IVa - IVc give the same list of inspection activities with estimated time requirements based on operation in two campaigns of only 100 days each, at a processing rate of 0.5 t/d compared to the rated 0.7 t/d. Both factors are significant, because some inspection activities are time-related and others are throughputrelated.

Tables IIIa - IIIc, full capacity operation, indicate an estimated inspection effort of 3594 man-hours. In converting this to inspection mandays or number of required inspectors, however, it is important to recognize that work can never be 100% efficient in a plutonium environment. It must be assumed first of all that every inspector will spend about one hour per day satisfying health physics requirements (clothing changes, radiation monitoring, etc.). This allows fifteen minutes each for entering in the morning, leaving for lunch, entering in the afternoon, and leaving in the evening. Fifteen minutes may be longer than is needed, but there are also internal monitoring and shoe cover change points which have not been considered, and there will be days when the inspector must enter and leave more than twice.

It must also be assumed that the inspector will lose a significant amount of time through waiting for operations which for one reason or another have been delayed. If the inspector is told that a measurement will occur at 10:00 a.m., he must plan to arrive at least five minutes early, and he must expect that the measurement may not occur until 10:30. In some cases he may be able to leave the area, do something else, and then return; in other cases he may have no choice but simply to wait.

Thus it is suggested here that no more than six hours per day of actual productive inspection work should be expected on any long term basis, and that therefore 3594 man-hours should be considered equivalent to 599 mandays. An inspector who works five days per week for an entire year, taking eight paid holidays and thirty days leave, the IAEA rule, but is never sick, actually works 222 days per year. On this basis 599 man-days is equivalent to 2.7 inspectors. Allowing for shift and weekend coverage, essential office paperwork, occasional minor illnesses, and evaluation work not counted as part of inspections, the safeguards approach described here probably could be implemented by a team of five resident inspectors. Six to eight would allow more flexibility in scheduling, with the expectation that they probably would have some time to assist in the safeguarding of other nearby facilities.

The total for tables IVa - IVc, reduced capacity operation, is 2126 man-hours. Using the same assumption of six hours effective inspection work per day, this is equivalent to 354 man-days, or 1.6 inspectors. If they could schedule themselves in order to cover activities at night or over weekends, three resident inspectors probably would be adequate. As with the previous full capacity operating example, a fourth or fifth inspector would be preferable, again with the expectation that the inspectors probably would have time to assist in the safeguarding of other nearby facilities.

Actual inspector effort statistics are treated as confidential, but the estimates given here are generally comparable to current actual inspection practice at the PNC-Tokai reprocessing plant when that plant is operating on a full-time basis. Comparisons should be made on the basis of the relative effectiveness of current practice versus the advanced safeguards approach described here, not on the basis of the effort required. One comment is in order, however. Many of the verification procedures included in the advanced safeguards approach depend significantly on "continuous inspector knowledge". It is doubtful if this continuous inspector knowledge can be satisfactorily achieved following the current practice of rotating inspection effort among a group of at least 20-30 inspectors, none of whom ever remains at the facility for longer than a week or so at a time.

Table IIIa
Flow Verification Inspection Activities
Full capacity operation

Inspection Activity	Man-Hours / Event	Events / Year	MH / Year
A. Receipt of Spent Fuel			
1. Observe cask receipt, remove seal if one exists, observe removal of cask cover and count assemblies	2	80	160
2. Check i.d. numbers and Cerenkov radiation	2	80	160
3. Observe transfer to storage, and record storage locations	2	80	160
4. Observe placing cask cover in place and removal of empty cask	1	80	80
5. Review video surveillance record and reset unit	1	52	52
B. Input Accountancy Tank			
1. Observe calibration	16	2	32
2. Measure volume of empty tank	0.5	600	300
3. Measure volume of full tank	0.5	600	300
4. Observe sample taking, including laboratory spiking and dilution	3	60	180
5. Observe packaging of samples	4	21	84
6. Verify hulls	2	50	100
C. Plutonium Product Tank			
1. Observe calibration	16	2	32
2. Volume measurement before and after	1	300	300
3. Observe sampling (included in volume time estimates)			
4. Sample packaging and shipment (included with input measurements)			
D. Uranium Product Measurements			
1. Observe scale calibration	0.5	4	2
2. Weigh UO_3 product	0.25	300	75
3. Sample UO_3 product	0.25	42	11
4. Sample packaging and shipment (included with plutonium)			
E. Offsite Plutonium Shipment			
1. Observe scale calibration	0.5	42	21
2. Observe filling and weighing of bottle	0.5	500	250
Total man-hours for flow verification			2299

Table IIIb
Physical Inventory Verification Inspection Activities
Full capacity operation

		Inspection Activity	Man-Hours Event	Events Year	MH Year
A.		Cleanout Physical Inventory Taking			
	1.	Item count spent fuel	2	2	4
	2.	Cerenkov glow verification	8	2	16
	3.	Plutonium nitrate tanks (volume)	0.25	14	4
	4.	Plutonium nitrate tanks (sample)	0.5	14	7
	5.	Sample packaging and shipment	4	2	8
	6.	Process tanks (volume)	0.25	10	3
	7.	Process tanks (sample)	0.5	10	5
	8.	Sample packaging and shipment (included with product tanks)			
	9.	Verify completeness of inventory	16	2	32
B.		In-Process Physical Inventories			
	1.	Check crane monitor record and count spent fuel in storage (baskets)	2	52	104
	2.	Observe volume measurements and sampling of process tanks	2	42	84
	3.	Examine process monitor record on plutonium nitrate tanks	2	52	104
	4.	Sample plutonium nitrate tanks	3	52	156
		Total man-hours for inventory verifcation			527

Table IIIc
Other Inspection Activities
Full capacity operation

	Inspection Activity	Man-Hours Event	Events Year	MH Year
C.	Auditing Activities			
1.	Auditing spent fuel receipts against shippers data			80
2.	Comparison of input measurements with reactor calculations, isotope correlations, etc.			160
3.	General records auditing			100
D.	Evaluation and Anomaly Investigation			
1.	Evaluation of n.r.t. accountancy data			84
2.	Investigation of anomalies			84
3.	Misc. Q.C. data collection and evaluation			160
4.	Meetings			100
	Total Other Inspection Activities			768
	Total Flow Verification			2299
	Total Inventory Verification			527
	Total Effort All Activities			3594

Table IVa
Flow Verification Inspection Activities
Reduced capacity operation

	Inspection Activity	Man-Hours / Event	Events / Year	MH / Year
A.	Receipt of Spent Fuel			
1.	Observe cask receipt, remove seal if one exists, observe removal of cask cover and count assemblies	2	38	76
2.	Check i.d. numbers and Cerenkov radiation	2	38	76
3.	Observe transfer to storage, and record storage locations	2	38	76
4.	Observe placing cask cover in place and removal of empty cask	1	38	38
5.	Review video surveillance record and reset unit	1	52	52
B.	Input Accountancy Tank			
1.	Observe calibration	16	2	32
2.	Measure volume of empty tank	0.5	286	143
3.	Measure volume of full tank	0.5	286	143
4.	Observe sample taking, including laboratory spiking and dilution	3	29	87
5.	Observe packaging of samples	4	14	56
6.	Verify hulls	2	24	48
C.	Plutonium Product Tank			
1.	Observe calibration	16	2	32
2.	Volume measurement before and after	1	75	75
3.	Observe sampling (included in volume time estimates)			
4.	Sample packaging and shipment (included with input measurements)			
D.	Uranium Product Measurements			
1.	Observe scale calibration	0.5	4	2
2.	Weigh UO_3 product	0.25	75	19
3.	Sample UO_3 product	0.25	30	8
4.	Sample packaging and shipment (included with plutonium)			
E.	Offsite Plutonium Shipment			
1.	Observe scale calibration	0.5	30	15
2.	Observe filling and weighing of bottle	0.5	250	125
	Total man-hours for flow verification			1103

Table IVb
Physical Inventory Verification Inspection Activities
Reduced capacity operation

	Inspection Activity	Man-Hours Event	Events Year	MH Year
A.	Cleanout Physical Inventory Taking			
1.	Item count spent fuel	2	2	4
2.	Cerenkov glow verification	8	2	16
3.	Plutonium nitrate tanks (volume)	0.25	14	4
4.	Plutonium nitrate tanks (sample)	0.5	14	7
5.	Sample packaging and shipment	4	2	8
6.	Process tanks (volume)	0.25	10	3
7.	Process tanks (sample)	0.5	10	5
8.	Sample packaging and shipment (included with product tanks)			
9.	Verify completeness of inventory	16	2	32
B.	In-Process Physical Inventories			
1.	Check crane monitor record and count spent fuel in storage	2	52	104
2.	Observe volume measurements and sampling of process tanks	2	30	60
3.	Examine process monitor record on plutonium nitrate tanks	2	52	104
4.	Sample plutonium nitrate tanks	3	52	156
	Total man-hours for inventory verifcation			503

Table IVc
Other Inspection Activities
Reduced capacity operation

	Inspection Activity	Man-Hours / Event	Events / Year	MH / Year
C.	Auditing Activities			
1.	Auditing spent fuel receipts against shippers data			60
2.	Comparison of input measurements with reactor calculations, isotope correlations, etc.			80
3.	General records auditing			80
D.	Evaluation and Anomaly Investigation			
1.	Evaluation of n.r.t. accountancy data			60
2.	Investigation of anomalies			60
3.	Misc. Q.C. data collection and evaluation			120
4.	Meetings			60
	Total Other Inspection Activities			520
	Total Flow Verification			1103
	Total Inventory Verification			503
	Total Effort All Activities			2126

8. EVALUATION OF SAFEGUARDS DATA

8.1 Anomaly Detection vs Anomaly Investigation

The safeguards approach described in the preceding chapters is based on the premise that diversion detection is a two stage process, in which the first stage is concerned with the detection of "anomalies" which might be indicative of diversion, and the second stage is concerned with the investigation of detected anomalies in order to eliminate those anomalies (hopefully all of them) which in fact arose from activities not related to diversion. In actual fact all safeguards approaches are based on this premise of a two stage process, but the two stages are not always explicitly recognized or stated.

The emphasis in the two stages is completely different. Since an attempted diversion which does not result in the generation of any detected anomalies is de facto a successful diversion, the emphasis in the first stage must be placed on detection. An assurance of non-diversion can only be given if the detection probability for diversion-related anomalies is high.

The primary purpose of this chapter is to discuss procedures to be followed in the investigation or evaluation of anomalous indications in safeguards data. The number of subtly different types of anomalies is large, and any attempt at listing them is bound to be incomplete. On the other hand most of the more likely anomalies have occurred in the past, in one context or another, and some general suggestions as to how to recognize common causes, and establish credible evidence that they "explain" the anomalies, can be given. Section 8.3 considers the resolution of anomalous indications given by surveillance instrumentation; Section 8.4 considers the resolution of anomalous MUF data; and Section 8.5 considers the resolution of anomalous monitoring data.

In all cases a heavy reliance is placed on experience and common sense. The data contain a message, and the problem is to decipher what that message is. Computer calculations can be invaluable in anomaly resolution, but any attempt to define routine computer procedures which will "decide" whether an anomaly is or is not indicative of diversion necessarily defeats the purpose of the exercise. Similar remarks apply to general clerical assistance. Anomaly resolution is, or should be, a problem for specialists and experts.

8.2 Assurance of Non-Diversion

If a given safeguards procedure has a high probability of producing an anomaly in the event diversion via that mechanism or route is attempted, and if over some period of time that safeguards procedure produces no anomalies, then there is, _de facto_, a low probability that diversion via that mechanism or route was successfully accomplished. Extrapolating, if a given set of safeguards procedures are believed to have a high probability of producing at least one anomaly in the event diversion via any recognized mechanism or route is attempted, and if over some period of time no anomalies occur, then there is, _de facto_, a low probability that diversion occurred and escaped detection.

"Low probability" is a term which here can only be defined by the reader, but in some qualitative sense the reader's assurance of non-diversion, given that no anomalies were detected, must necessarily be higher than if one or more anomalies had been detected. There are only two possibilities. Either diversion was not attempted, presumably the more likely alternative, or diversion was attempted and by unlikely random chance was not detected.

The preceding paragraphs are totally independent of other factors which might also produce anomalies. If, in an ideal situation, there is no logical mechanism for producing anomalies other than as a result of attempted diversion, then the occurrence of an anomaly can be interpreted as cause for serious concern. If, in the more typical situation, there are logical mechanisms which from time to time will produce anomalies without diversion having been attempted, then the degree of concern resulting from simple occurrence of an anomaly will be less, with concern increasing as investigative efforts fail to resolve the anomaly. In both cases, however, the absence of anomalies should be interpreted as providing a high degree of assurance that diversion has not escaped detection.

8.3 Anomalous Surveillance Indications

8.3.1 Surveillance failure. With surveillance equipment it is necessary to recognize two types of "anomalous indications". One is equipment or system failure, the other is a positive indication of something requiring explanation or investigation.

When a surveillance failure occurs, some part of the overall safeguards system (possibly all of it) loses its ability either to detect diversion or to provide a credible assurance of non-diversion. From the moment the failure occurs (if known) to the moment the failure is corrected (or a substitute safeguards procedure is implemented), the inspector simply cannot state whether diversion might have occurred. If the moment of failure is not known, the time period of concern extends from the last moment surveillance is known to have been intact.

In the context of the advanced safeguards approach described in this report, surveillance failures might occur if:

- the video surveillance unit installed in the spent fuel receiving bay fails,
- the crane monitor installed in the spent fuel receiving bay to indicate whether the heavy duty cask crane was energized fails,
- the spent fuel storage pond crane location monitor fails,
- any of the seals used as tamper-indication on surveillance equipment, or to assure the non-use of identified equipment items, are broken, or
- the inspector fails to perform any of the observations/verifications specified in the safeguards approach, either because he is prevented from doing so by some form of operator intervention or because he chooses to omit them, for whatever reason.

While it is unquestionably of interest to know what caused the surveillance failure (and to take appropriate action to preclude future additional failures), the important question in all cases is whether an undetected diversion might have occurred during the time period of the failure. Several redundant safeguards measures have been included in the safeguards approach to aid in answering this question.

If the video surveillance unit installed in the spent fuel receiving bay fails, the crane monitor installed to indicate whether the heavy duty cask crane has been energized should be checked. If the crane has not been energized during the period in question the surveillance failure can be taken as being of little importance. Since the crane monitor (on the cask crane) is intended only as a redundant measure, failures of the crane monitor can similarly be discounted if the video surveillance unit is operating and shows no anomalous indications.

If the spent fuel storage pond crane location monitor fails, recourse can be had to the video surveillance unit in the spent fuel receiving bay coupled with an item count inventory of the spent fuel pond. In this case, however, since inert dummy fuel assemblies could have been placed in storage without passing through the spent fuel receiving bay, further corroborative evidence should be sought, possibly from a check of dissolution records if the assemblies in question are scheduled for processing in the immediate future.

The first and most important question in the case of broken seals should be whether there is any further evidence of equipment tampering or of equipment mis-use. Positive evidence of tampering may be easy to detect; negative evidence that tampering has not occurred may be more difficult. Nevertheless, the important question is not how did it happen, but whether the failure is indicative of a more serious anomaly related to diversion. If there is positive evidence of tampering, the anomaly investigation should proceed as outlined in section 8.3.2. If there is no positive evidence of tampering, the investigation can at least begin as an investigation of surveillance failure.

Inspector failure to perform specified observations/verifications is included here as a surveillance failure. The inspector's task is to ensure the reliability of data through observation and verification; omission of specified verifications is as much a system failure as failure of a video camera. It is sometimes argued that the mere threat of verification serves as a deterrant even though verifications are only performed at random intervals. The entire principle of random sampling, however, assumes that the operator is committed prior to the point at which he knows whether verification will or will not occur. When the safeguards approach calls for 100% inspector verification, and the inspector chooses not to make the verification, the operator knows that the inspector is not present, and is completely free to implement those diversion scenarios which the verification was supposed to detect.

8.3.2 Positive Surveillance Anomalies. If a surveillance device gives a positive indication of unexplained activity, a much more significant cause for concern exists. Nevertheless, the basic investigative procedures are more or less the same. The first step is to ask the facility operator for an explanation, but the second step must necessarily be to seek independent corroborative evidence in support of the explanation given. Diversion analyses credit potential divertors with the capability to develop and implement relatively complex scenarios, it must be assumed that potential divertors are equally capable of developing "cover stories" to explain any anomalous indications which the inspector might observe.

If the spent fuel receiving bay video monitor shows movement of a large object resembling a spent fuel cask at a time when no cask was declared to be present, an attempt should be made to establish (a) whether the object in question is a cask, or in any event could have been used to transport radioactive spent fuel, (b) why it was in the spent fuel receiving bay without having been declared so the inspector could observe and verify operations, (c) how long it was in the spent fuel receiving bay, and (d) whether in fact the object was used for undeclared fuel transport. The last question obviously is the most important, but it also will probably be the most difficult.

If the spent fuel storage area crane location monitor reveals a reverse flow of spent fuel to the receiving bay, or an undeclared flow from the receiving bay to storage, again the first step should be to ask the operator for an explanation, and the second step should be to seek independent corroborative data to support the explanation. The crane location monitor and the receiving bay video monitor are highly complementary, investigative steps for one would logically closely parallel investigative steps for the other. If both simultaneously give positive surveillance anomalies the evidence for possible diversion is too strong to ignore, and careful investigation is indicated.

An item count inventory of the spent fuel pond should probably be made at an early moment, coupled with Cerenkov verification if feasible. If the object was indeed a fuel cask and has been shipped somewhere, it may be useful to try to arrange a verification of its status on arrival, although removal of diverted fuel in transit probably cannot be ruled out. If the operator makes a statement as to the source of received fuel, verifications at that location may also be appropriate. Note that the redundant crane monitor probably will be of no value, since whatever the object was and whatever its purpose, the heavy duty crane undoubtedly was energized in order to move it. The spent fuel storage pond crane location monitor, however, should be of value, since undeclared movement of spent fuel is very nearly impossible without using the storage area bridge cranes.

Positive evidence of seal tampering, or a broken seal combined with positive evidence of equipment use or instrument tampering should also be taken seriously. The ultimate verification is the taking of a physical inventory of the affected portion of the total facility inventory. This step should be avoided if possible, especially as related to the total inventory. Consideration should first be given to all available corroborative information, and special inventories should be requested only as a last resort. In the absence of serious positive surveillance anomalies, the design of the advanced safeguards approach should be such that special inventories will not be necessary.

8.4 Anomalous MUF Data

There are basically three kinds of anomalous MUF data, as follows:

- a single MUF value which is abnormally large in comparison with known (estimated) measurement uncertainties,
- a sequence of MUF values which appear to define a pattern that cannot be characterized as a random distribution about a zero mean, or
- a sequence of MUF values whose internal variability (scatter) is not consistent with known (estimated) measurement uncertainties.

In actual practice many variations and combinations of these three basic possiblities are likely to arise. A single abnormally large MUF value may be offset by an equally large MUF having the opposite sign (inventory error), or there may be two or more large MUFs either in sequence or separated by a small number of more normal values. A sequence of MUF values may appear to define one pattern, then either gradually or abruptly change to a different pattern. It is not uncommon for the internal variability of MUF data to exceed combined measurement uncertainties without the magnitude of MUF being abnormally large, but it is also common for abnormally large scatter to be accompanied by abnormally large MUFs or by an apparent MUF pattern.

While it is impossible to cover all possibilities, the subsections that follow define some of the more common anomalous MUF indications and suggest the most probable (non-diversion) causes. In all cases the investigation should proceed with the two-sided attitude that the anomaly probably (hopefully) has an innocent explanation, but that nevertheless it cannot be dismissed as innocent until it has been positively demonstrated to be innocent.

As with surveillance anomalies, one of the first actions in investigating any anomalous MUF data should be to seek a logical explanation from the facility operator. It should be recognized, however, that the operator's first reaction most likely will be that he too does not know, and that he will himself investigate. In keeping with the philosophy that divertors will develop cover stories to explain anomalies to inspectors, it is recommended that the investigation of anomalous MUF data proceed jointly. The inspector cannot in any case accept the operator's explanation until it has been independently verified; the most efficient procedure usually is for the operator and the inspector to work together in the investigation.

8.4.1 Single MUF Anomalies. A single abnormally large MUF value, of either positive or negative sign,* which is followed by an MUF having more or less equal magnitude but opposite sign is strongly suggestive of an inventory error, and the first investigative action should be a careful re-examination of the inventory data for the common inventory (i.e., the ending inventory of the first period in question and the beginning inventory of the second period). This examination should consider the measurements themselves, possible clerical errors, failure to inventory an item or container, recording the same inventory quantity twice, etc.

A single abnormally large MUF value, of either positive or negative sign, which is not followed by an offsetting MUF in the next period, is much more suggestive of flow measurement error, and the first investigative action should be a careful re-examination of all flow measurement data for the period in question. Again, the examination should consider not only the measurements themselves but also clerical transcriptions, failure to record a receipt or shipment, recording the same quantity twice, etc.

In a variation of the above possibilities, one or more normal MUF values may separate the offsetting positive and negative MUFs. This usually suggests that the inventory quantity on which the error occurred remained on inventory at the same erroneous value for some period of time. It could also have been caused by a flow measurement error (receipt), with the received quantity remaining on inventory at the erroneous value for at least one material balance period before being processed.

If the suspected measurement error is quickly found and corrected the anomalous MUF data of course disappears and requires no further investigation. If an error is not easily found, recourse should be had to monitoring and surveillance data. If the MUF anomaly is positive the surveillance and

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* Following long-standing convention, a positive MUF indicates an apparent loss of nuclear material and a negative MUF indicates an apparent gain.

monitoring data may assist in determining whether there is evidence of an attempt to remove nuclear material, or whether there is a corresponding unexplained loss of solution volume. If there is, the possibility of diversion should be given more serious consideration. If there is no evidence of missing solution, the anomaly is at least equivocal, and investigative efforts can proceed more normally. Even if the MUF anomaly is negative the monitoring data may assist in localizing the probable measurement problem, for example by showing a tank volume/concentration which is not consistent with a later inventory or flow measurement.

In near-real-time materials accountancy the exact timing of inventory and flow data must be controlled very carefully. One obvious example relates to the first buffer storage tank, which receives solution from the input accountancy tank. If an in-process physical inventory is scheduled for, say, midnight, an input transfer at 12:30 a.m. would be recorded as having occurred after the inventory. However, if the operator instructed to sample the first buffer tank was delayed and actually took the sample at 1:00 a.m., the sample would represent the solution after the input transfer, and might be grossly in error.

Erratic patterns of abnormally high MUFs of varying magnitude, perhaps interspersed among other MUF values which are more nearly normal, are more difficult to judge. However, one common cause of such data is a measurement procedure which is producing incorrect results, and which is used varying numbers of times during the various material balance periods. Such a cause would be strongly suspected, for example, if the MUF data appear more uniform when translated into MUF/batch data. If the exact length of the material balance period varies (e.g., if "weekly" inventories are in fact taken at 5-15 day intervals) it may also be useful to see what happens when the MUF data are adjusted for the variable length of the material balance periods. Possible explanations would include a leaking tank (presumably leaking into the cell itself), or a leaking valve allowing solution transfer without measurement.

8.4.2 Anomalous MUF Sequences. Under ideal conditions a sequence of MUF values should tend toward a zero mean, and should have a derived standard deviation which is consistent with estimated measurement uncertainties. This subsection considers sequences of MUF values which do not tend toward a zero mean. The actual statistical test used may or may not test the observed mean value; some proposed tests examine the cumulative MUF or the slope of a cumulative MUF line, both of which should also tend toward zero over time. Some tests also examine residuals obtained by subtracting some estimate based on past data. In all cases, however, the fundamental result is the same, the MUF data are or are not exhibiting random fluctuations about an expected value of zero MUF. (Some tests are designed to detect only positive mean values. If the mean value is zero or negative the test "resets" and begins again to look for a positive mean. Although these tests have some statistical advantages, it is assumed here that the inspector can detect both positive and negative non-zero means.)

The definition of a sequence is somewhat flexible. Some sequences exhibit non-zero behaviour after only two or three data points, others may not be demonstrably non-zero until ten or twenty points have accumulated. Some sequences may be interrupted, either by a single anomalous MUF which requires investigation under section 8.4.1 or by a short sub-sequence of data points which appear to have a zero mean. These usually suggest that two or more causative factors are at work, and they may seriously complicate data analysis and investigation. They should not be used as an excuse for terminating an investigation, however. Two partially cancelling causative factors cannot be equated with no causative factor at all.

The first thing to be recognized in sequence evaluation and investigation is that causative factors almost always relate to flow measurement data. Something is occurring repetitively and more or less regularly, and it is unrealistic to suspect that the causative factor might be a series of clerical errors in inventory data. The usual first response to any MUF investigation is "take a cleanout physical inventory to find out how much material is truly missing". This is rarely a good idea in any case; it is completely inconsistent with non-zero trends.

The most probable cause of any non-zero trend (excluding diversion) is measurement bias. If the trend is negative this is very nearly the only logical cause. Positive trends of course also open the possibility of protracted diversion, and require more careful examination.

An attempt should be made to identify all possible measurement effects which would be consistent with the observed data. For example, a negative trend (gain) in the process MBA could be caused by:

-erroneous calibration of the input accountancy tank volume, in the direction of understating true volumes,

- erroneous calibration of the product accountancy tank volume, in the direction of overstating true volumes,

- biased analytical measurements at either input or product measurement points, understating at the input measurement or overstating at the product measurement,

- unrecognized solution bypass at the input accountancy tank,

- unrecognized solution return from the product MBA to the product measurement tank, such that solution is transferred twice.

These are broad categories, but they are indeed all the possibilities for the example case.

Once a complete list has been prepared, one can begin to seek corroborative data which may help eliminate some of the possibilities. All of the possibilities related to the product measurement, for example, should also affect the material balance in the product storage area, but in the opposite direction. If the MUF data for the product storage area shows no positive trend, then the observed trend is more likely to relate to measurement problems at the input end.

At the input end, plutonium is mixed with uranium, so the logical question is whether there is also evidence for a trend in the uranium MUF data. This question may be difficult to answer in the absence of n.r.t. accountancy data for uranium, but it is still a question worth examining. Input data is also subject to comparison with fabricator's initial data or reactor calculation data. Despite the high uncertainties usually ascribed to the latter, the comparison can help to suggest where measurement biases may or may not exist.

A curious phenomenon which has been observed many times is that of a measurement bias which spontaneously disappears during the course of its investigation. A plant observes a measurement bias, narrows the possibilities down to perhaps two or three prime candidates, and defines special projects to collect the data necessary to identify and correct the exact bias. The agreed special data is collected, revealing little in the way of measurement bias, but nevertheless the bias in the MUF values disappears, or changes in some significant manner.

Usually this results from the correction of small procedural errors during the special project phase, sometimes with almost no one being aware of the correction. An operator, for example, might not understand the proper way to read the meniscus on a manometer. The foreman, in the course of explaining a project to collect replicate measurements, explains the meniscus reading procedure without having first noted any error by his operators, and the operator, having now learned the correct procedure, begins taking correct measurements. The meniscus bias is corrected, but only the operator is aware of the procedural error. The operator, moreover, probably gave the procedural change little thought, and is in any case unlikely to report his previous misunderstanding.

Consistent differences between analytical laboratories (e.g., operator - inspector differences) are extremely difficult to resolve. One of the first things which should be tried (but unfortunately usually is not tried until much later, if at all), is for each laboratory to perform a series of measurements using the others' analytical procedures in exact detail. Even if a laboratory does not agree with some detail, it should try the procedure to see what measurement data results. If laboratory A confirms B's measurements when using B's analytical procedure, then the two laboratories can look for differences in the two procedures which might be causing a difference in results. If laboratory A still confirms its own measurements when using B's procedures, then the standardization rather than the procedures should be suspect, and the next logical step obviously is an exchange of standards. It is often difficult to establish which laboratory or standard is correct, but this two stage exchange process usually can establish the precise point of difference.

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