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DESIGN FEATURES TO FACILITATE IAEA SAFEGUARDS AT MIXED-OXIDE FUEL FABRICATION PLANTS

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ABSTRACT

A study was conducted for the Nuclear Regulatory Commission (NRC) to identify and analyze nuclear facility design features that could facilitate International Atomic Energy Agency (IAEA) safeguards. This report presents results and conclusions for mixed-oxide fuel fabrication plants. A baseline safeguards system is defined and evaluated. Difficulties in applying safeguards in the baseline system are identified. Design features are identified and described that could help to alleviate the difficulties. The design features are assessed from the viewpoint of cost-effectiveness, impact on the facility operator, and IAEA safeguards practice. On the basis of the analyses, conclusions and recommendations are formulated.

EXECUTIVE SUMMARY

An NRC-commissioned study was conducted to identify and analyze nuclear facility design features that could, if implemented, facilitate IAEA safeguards. This report presents results and conclusions for mixed oxide fuel fabrication facilities. Previous reports have covered light water power reactors and reprocessing facilities; a future report dealing with low-enriched uranium fuel fabrication plants is planned.

The need for and potential benefits of incorporating safeguards considerations into the design of nuclear facilities have received widespread attention in the international safeguards arena in recent years. The objective of the study reported here is to further the development of safeguards-oriented designs for nuclear facilities by:

- Developing a systematic approach for taking IAEA safeguards into account in designing a nuclear facility.
- Demonstrating the approach by applying it to analyze particular types of facilities (i.e., case studies).
- Identifying and evaluating an illustrative set of design and operational features for each case study.
- Formulating conclusions and design guidelines based on the analyses performed.

The technical approach followed in this study consists of seven main steps:

- define a baseline safeguards system and model facility
- evaluate the baseline safeguards system
- identify problem areas
- identify design features that could help to alleviate the problems
- screen the design features and select a subset for detailed analysis
- evaluate the design features
- formulate conclusions and recommendations.

The conclusions can be summarized by types of improvements and the type of impacts resulting from the design changes. Areas of improvement include:

- increased probability of detection
- increased verifiability
- economy of resources
- decreased uncertainty.

Impacts are noted in the following areas:

- cost to facility operator
- cost to IAEA.

RESULTS AND CONCLUSIONS

A baseline mixed-oxide fuel fabrication plant and IAEA safeguards syste were defined and the effectiveness of safeguards in achieving quantitative goals for the timely detection of diversion was evaluated under a range of conditions and assumptions. The effectiveness of the baseline safeguards sy- tem can be summarized as follows. In general, for diversion strategies that are concentrated in a short period of time ("abrupt diversion") or are other wise highly localized, the detection goals can be achieved if the plant is small- or medium-sized (i.e., having a throughput up to about 1500 kg of pl tonium per year). For diversion strategies that are spread out in time ("pr tracted diversion"), the detection goals were not attained in the medium-siz (1500 kg Pu per year) plant; however, with the incorporation of design featu to be described below, this conclusion changes and the detection goals can b attained. For very large facilities (e.g., 8,000 to 10,000 kgs of plutoniu per year) which may be built in the future, some additional capability will needed if the detection goals are to be achieved. For all of the cases considered as part of the baseline analysis, the inspection resources required to implement effective safeguards are substantial. Therefore, design featu aimed at enhancing the efficiency, as well as the effectiveness, of IAEA sa guards inspections are also of interest.

To enhance the efficiency and effectiveness of IAEA safeguards at mixed-oxide fuel fabrication facilities, a total of twenty-six design and operational features were identified. After screening, some fifteen were analyzed in detai Some of the key results and conclusions are as follows.

For improved detection of protracted diversion, seventeen changes in physical design, process design and operational practices were considered. The emphasis was on procedural changes--those that in some way relate to the measurements performed by the facility operator and/or by the inspector. A detailed evaluation showed that incorporation of several of the design and procedural improvements would permit the attainment of the quantitative criteria for detection of protracted diversion. Among the features contributing to the improved probability of detection were:

- Measure both the plant input (PuO_2 powder) and the plant output (sintered pellets) for percent plutonium by the same method. Using the same analytical method for input and output permits partial cancellation of systematic errors due to analysis, which contribute strongly to the uncertainty in MU
- Perform selected replicate measurements. This involves the judicious use of additional scales, replicate samples, and replicate analyses by different analytical techniques.
- Features for the verification of in-process material (DF-1) and containerization of transfers (DF-2) improve the accuracy of bi-weekly material balances thereby permitting a high probability of detection to be achieved in a reasonably efficient manner.
- Features DF-3 through DF-7 (quarantined receiving area; walk-through vault; transportable inspection station; multi-tray sealable containers for pellets; and quarantined rod storage area) are aimed at facilitating the performance of inspection and verification tasks and at reducing the amount of time it might take to examine large numbers of stored items during each inspection. DF-4, DF-5 and DF-6 provide means for quick access and easy item handling. DF-3 and DF-7 provide temporary storage

so that the need for continuous inspector presence in the storage rece ing area and fuel rod manufacturing area is reduced or eliminated. Th features are estimated to save between 100 and 200 mandays of effort p year.

- DF-8 and DF-9 (assembly area designed for containment and surveillance and tamper-detecting sealable assembly container) provide concepts for establishing localized containment and surveillance of fuel assemblies i.e., items whose content cannot be re-verified periodically. These features are aimed at reducing vulnerability to diversion through subs tution of internal rods in completed fuel assemblies.

The cost to the operator of the design features identified in the stud not negligible. It amounts to several percent of the total cost of the fac In some cases, it may be difficult to clearly distinguish the <u>incremental</u> c attributable to the design features from costs that would be incurred in an event.

For very large facilities, five to ten times larger than the reference case, the implementation of some form of extended containment and surveilla will be needed to supplement the accountancy measures. An approach which c bines the concept of path surveillance and direct observation by the inspec appears to be feasible for such large facilities if appropriate safeguards- oriented design features are incorporated into the design. This reasoning based on the following observations: 1) fuel fabrication facilities requi only a small number of penetrations for outside services, and these can be instrumentally monitored for detecting indications of diversion; 2) a cont ment with substantial separation of personnel and material is desirable in large facilities to protect against radiological and inhalation hazards. safeguards purposes a unified containment completely enclosing all nuclear rial and including scrap and waste processing and storage could be devised number of penetrations to the outside of the containment should be minimal These would be monitored or, if used infrequently, sealed. The presence o inspector will be required when the penetrations are unsealed for his dire viewing of the activities when penetrations are opened. The study identified only the requirement for, and the feasibility of, implementing extended surveillance concepts for MOX fuel fabrication facilities.

As applied to sensitive fuel cycle facilities, extended surveillance combines instrumental surveillance of potential diversion paths with direct human observation of activities and actions. The study also indicated the necessity to include safeguards-oriented design features in facility design to make the implementation of C/S concepts possible. The next step should be a more detailed and extensive design study using the concepts described herein as a starting point.

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1.0 INTRODUCTION

An NRC-commissioned study was conducted to identify and analyze nuclear facility design features that could facilitate IAEA safeguards. This report presents results and conclusions for mixed-oxide (MOX) fuel fabrication plants Previous reports have treated light water power reactors and spent fuel reprocessing plants; a future report dealing with low-enriched uranium fuel fabrication plants is planned.

The main body of this report is organized into eight sections:

- Introduction, which defines the background and purpose of the study and presents an overview of the methodology used in identifying and analyzing design features.
- Baseline Assumptions, including technical objectives for IAEA safeguards, a description of a reference mixed oxide fuel fabrication plant, and a baseline safeguards approach.
- Baseline Evaluation, expressed in terms of the effectiveness, efficiency, and other impacts of the baseline safeguards system.
- Identification of Problem Areas associated with the baseline safeguards system.
- Identification of Design Features that could help to alleviate the problems.
- Screening of Design Features to select a limited but representative subset for detailed analysis.
- Evaluation of Design Features to determine their effect if incorporated into the safeguards system.
- Conclusions and Recommendations.

1.1 OBJECTIVES

The objective of the study reported here is to further the development of safeguards-oriented designs for nuclear facilities, specifically mixed-oxid fuel fabrication facilities. As the Background discussion below indicates, the need for and potential benefits of incorporating such safeguards considerations into the design of future nuclear facilities are widely recognized.

Specifically, this study is aimed at:

- Developing a systematic approach for taking IAEA safeguards into account in designing a nuclear facility.
- Demonstrating the approach by applying it to analyze particular types of facilities (i.e., case studies).
- Identifying and evaluating an illustrative set of design and operational features for each case study.
- Formulating conclusions and design guidelines based on the analyses performed.

Designing a nuclear facility is a complex, iterative process leading from a very general statement of desired objectives through conceptual definition and analysis, system and subsystem definition and analysis, design synthesis, and culminating in detailed specifications for construction and operation. This study has concentrated on the initial stages of the design process, where some of the key tradeoffs are made and where the principal characteristics and features of the facility are determined.

The goal has been to lay the foundation for subsequent, more detailed design studies by developing and demonstrating a methodology for systematic selection and analysis of design features. The demonstration includes identifying and evaluating a limited but representative set of MOX fuel fabrication plant design features.

1.2 BACKGROUND

Potential benefits of incorporating safeguards considerations at an early stage in the design of facilities have been recognized since the first safeguards studies shortly after World War II. The Statute of the IAEA, approved in 1956, clearly identifies an interest in design features that influence the effective application of safeguards by the IAEA.[(a)]** The IAEA's attention to facility design information has been formalized in its safeguards agreements.[(b)]

In recent years, in the international arena, there has been a renewed emphasis on the importance of facility design for safeguards. The International Nuclear Fuel Cycle Evaluation (INFCE) attached considerable significance to facility design considerations, particularly in the context of improved safeguards for future large plants.[(c)] On 22 September 1980 at the IAEA General Conference, Ambassador G. C. Smith (U.S.) called attention to the above INFCE results in saying that facilities should be designed to make safeguards more effective and to simplify safeguards implementation.[(d)]

The IAEA has on many occasions underscored the need for consideration of safeguards in the design of nuclear facilities, and has undertaken a number of actions aimed at furthering this objective. Director General Eklund has stated that the problem of expensive backfitting for safeguards could be alleviated by incorporating features for containment/surveillance and accountancy into the facility design. Further, the IAEA's Safeguards Implementation Report for 1980 stressed the need for further efforts to ensure the safeguards-oriented design and construction of future plants, and the IAEA 1979 Annual Report identified some progress on guidelines for the design of nuclear facilities.[(e)]

As a result of international interest in design, the IAEA has initiated several technical groups. The International Working Group on Reprocessing Plant Safeguards has a Subgroup especially for facility design considerations, which first met in September 1979.[(f)] In addition, the IAEA is organizing an Advisory Group on Design of Facilities to Permit Easy and Effective Implementation of Safeguards.

In the United States, the U.S. Government's Interagency Action Plan for Strengthened International Safeguards includes an action in the area of facility design considerations. The Nuclear Regulatory Commission is responsible for pursuing this action for a number of different types of facilities. In support of this action, NRC has commissioned a study entitled "Design Features for Facilitating IAEA Safeguards." This report is a case study for MOX for that NRC-sponsored study.

** Reference notes are listed at the end of the report.

1.3 METHODOLOGY

A key concern in this study has been to develop and demonstrate a systemati methodology for factoring safeguards considerations into the design of nuclear facilities. This section presents an overview of the methodology.

The approach consists of seven main steps:

- define a baseline safeguards system for the reference facility
- evaluate the baseline system
- identify problem areas
- identify design features that could help to alleviate the problems
- screen the design features and select a subset for detailed analysis
- evaluate the design features
- formulate conclusions and recommendations.

A brief discussion of these steps follows.

The approach can be divided into two phases--a baseline system definition and evaluation, and an analysis of design features aimed at improving the baseline system.

1.3.1 Baseline Safeguards System Definition

The baseline definition includes the following elements:

- A statement of safeguards technical objectives. This includes quantities of safeguards significance for various kinds of nuclear material; criteria for timeliness of detection, probability of detection, and false alarm probability; assumptions about the diversion strategies that the safeguards system must be designed to detect; and other basic technical groundrules and guidelines that are needed to interpret and apply the technical objectives in practice.

- A survey of the mixed-oxide fuel fabrication facilities at which IAEA safeguards are applied. The survey is drawn from the open literature and provides information that is useful in establishing a representative reference facility.

- A detailed description of a reference facility. In some cases, it is necessary to consider several reference facilities, or to vary certain key parameters like throughput, measurement accuracies, and so forth. For this study, several published documents were used to develop a reference plant model similar to, but somewhat larger than, current MOX fabrication plants. Parametric studies were also performed.
- Assumptions about safeguards agreements, State Systems of Accounting and Control, and safeguards technology and capabilities available to the IAEA.
- A baseline safeguards approach. This is based on the assumptions about current technology and capabilities, and characteristics of the reference facility and is aimed at satisfying the specified IAEA technical objectives.

1.3.2 Baseline Safeguards System Evaluation

The baseline safeguards system evaluation includes two parts. The first is an evaluation of the effectiveness of the baseline safeguards system relative to the technical objectives. The second is an assessment of the costs and other impacts associated with the baseline safeguards system.

1.3.2.1 Safeguards Effectiveness Evaluation

In measuring the effectiveness of safeguards, a key phrase used to characterize effectiveness is the "probability of detection." Although the concept of detection probability is relatively simple to comprehend, the precise meaning and interpretation of detection probability are often situation-dependent.

There are a number of statistical procedures that may be used as a basis for deciding whether diversion has occurred. Those used in this study include the facility MUF; the difference statistic, $\hat{D}$; the so-called inspector's estimate of the MUF, MUF-$\hat{D}$; and attributes inspection. In what follows, these statistics are discussed individually, and then consideration is given to the overall assessment of accountancy safeguards effectiveness using appropriate combinations of these individual statistics. Effectiveness is discussed generically at first, and then some specific comments are presented on effectiveness evaluation for short detection time safeguards and on the use of diversion path analysis to assess vulnerability to concealment.

Facility MUF. The facility MUF is based solely on facility-generated data, and represents the difference between the book inventory and the physical inventory. A MUF can only be calculated for the period between two measurements of a physical inventory.

From the point of view of international safeguards, the facility MUF by itself is of limited usefulness because, due to the possibility of falsified data, it may not represent the true material balance. However, if the facility material balance data are verified by the inspector on an inspection sampling basis, (as described in the next section), then the facility MUF can be used as a basis for detecting losses, including diversions. Further, in evaluating the impact of specified design features, one may interpret the detection probability for MUF in a comparative way in the sense that improvements in the material accountancy often translate directly into improvements in detection probability with the parallel statistic, MUF-$\hat{D}$, as discussed below.

The effectiveness of MUF in detecting losses is inversely related to its standard deviation, denoted by σ_{MUF}. In the context of the theory of hypothesis testing, a large MUF signals a statistically significant loss if it exceeds some critical value, M_o, where M_o is chosen such that the probability is α of its being exceeded when in fact the expected value of MUF is zero (no loss). The quantity α is interchangeably called the probability of a type I error, the significance level, or false alarm rate, and is fixed in advance. Under the generally accepted assumption that the observed MUF is normally distributed then M_o is chosen such that

$$\text{Prob}\,(\text{MUF} > M_o \mid E(\text{MUF}) = 0) = \alpha \tag{1}$$

The critical value M_o is easily found to be a function of α and σ_{MUF}.

$$M_o = t_\alpha\, \sigma_{MUF} \tag{2}$$

where t_α is defined such that the area under the standardized normal curve from t_α to ∞ is α.

Suppose now that $E(MUF)\neq 0$, i.e., there is a true loss of an amount equal to a_4M units. Then the probability of detecting this loss is

$$\text{Prob}\ (MUF>t_\alpha\ \sigma_{MUF}\ |\ E(MUF) = a_4M) = \text{Prob}\ (Z>t_\alpha - a_4M/\sigma_{MUF}) \tag{3}$$

where Z is normally distributed with zero mean and unit standard deviation.

As a note of explanation, the non-zero E(MUF) under the alternative hypothesis of diversion is labeled a_4M to be consistent with the notation of Part F of the IAEA Safeguards Technical Manual$^{(13)}$ which provides the basis for, and a more complete description of, the entire underlying methodology.

Thus, in summary, given a prescribed value for α, a calculated σ_{MUF} value, and an amount diverted into MUF, a_4M, the detection probability is given by equation (3).

Inspection $\hat{D}$ Statistic. The $\hat{D}$ statistic is defined in equation (4) below. Within each material stratum, measured values are independently determined by the inspector for a sample of items, and his results are compared on an item by item basis with those of the facility. The difference, facility value minus inspector value, is calculated for each item; and the differences are averaged over each stratum. Letting $\bar{d}_k$ be the average difference in stratum k, then the extrapolated total difference is $N_k\bar{d}_k$, N_k being the total number of items in the stratum. The $\hat{D}$ statistic is then

$$\hat{D} = \sum_k A_k N_k \bar{d}_k \tag{4}$$

where A_k = +1 for input and beginning inventory strata, and -1 for output and ending inventory strata.

The statistic, $\hat{D}$, is designed to detect small data falsifications, or small biases. With $\hat{D}$ defined as above, a positive value of $\hat{D}$ means that the reported MUF is biased on the high side while a negative value means that it is biased low.

A test for significance of an observed $\hat{D}$ differs somewhat from that for MUF. This is because under the alternative hypothesis of diversion through falsification the variance of $\hat{D}$ may be inflated due to statistical sampling errors related to which items happen to be selected by the inspector in his random sampling of items.

For the $\hat{D}$ significance test, detection probability is the probability of detecting a given amount by which the material balance data are falsified to hide diversion. Calling this amount a_3M, to be consistent with Part F of the IAEA Safeguards Technical Manual,$^{(13)}$ and following a development parallel to that used for MUF in the preceding section, the detection probability for $\hat{D}$ is

$$\text{Prob}\left(Z > \frac{t_\alpha\sqrt{1+\theta} - a_3m}{\sqrt{1+C_1{}^2\theta}}\right) \qquad (5$$

where t_α is defined as in equation (2), but for the $\hat{D}$ test, when m is M divide by σ_s, the systematic error standard deviation of $\hat{D}$, θ is the ratio of the random error variance of $\hat{D}$ under the hypothesis of no diversion to σ_s^2, and C_1^2 is the amount by which the random error variance is inflated under the alternative of a_3M units diverted. The random variable Z is usually assumed to be normally distributed with zero mean and unit standard deviation.

The (MUF-$\hat{D}$) Statistic. There are two fundamentally different approaches to analyzing a combination of MUF and $\hat{D}$ values. On the one hand, a test could first be made using $\hat{D}$ to see if the facility material balance data are free of small falsifications or biases. If the test on $\hat{D}$ does not lead to rejection of the hypothesis of no bias (i.e., the hypothesis that D=0), then the facilit MUF data are accepted as verified and the facility MUF is tested for significance as described earlier.

As another approach, $\hat{D}$ may be used for estimation rather than hypothesis testing. That is, a test of significance is not made using $\hat{D}$, but rather, the facility MUF is adjusted for the bias by subtracting $\hat{D}$ so that the test statistic is (MUF-$\hat{D}$), and only a single test is made. This statistic is responsive to a combination of diversion through data falsification and diversion into MUF. This second approach is used in this study, for reasons detailed in Part F of the Safeguards Technical Manual.$^{(13)}$ Thus, in determining the effectiveness of safeguards approaches, the key accountancy statistic is (MUF-$\hat{D}$).

Once the variances of MUF and of $\hat{D}$ are calculated, the variance of (MUF-$\hat{D}$) can also be calculated. Following the same reasoning as in the two previous sections and the notation of Part F, the detection probability for (MUF-$\hat{D}$) is

$$\text{Prob}\left(Z > \frac{t_\alpha\sqrt{a+\theta} - (a_3+a_4)m}{\sqrt{a+C_1{}^2\theta}}\right) \tag{6}$$

where Z, t_α, a_3, a_4, m, C_1, and θ are defined as before except that α is now the significance level for the (MUF-$\hat{D}$) test. In equation (6), the quantity a is $1-k_2$ where

$$k_2 = \frac{\sigma^2_{MUF} - 2V_0}{\sigma^2_s} \tag{7}$$

The quantities σ^2_{MUF} and σ^2_s have been defined previously. V_o is that part of σ^2_{MUF} due to systematic errors that are common to both the facility and the inspector. For example, if both parties should use the same tank calibration curve, then the same systematic error due to the calibration is committed by both parties.

Attributes Inspection. In a generic facility, the variables inspection leading to the value for $\hat{D}$ is preceded by attributes inspection to detect larger defects. Attributes inspection normally is performed with relatively crude measurement devices, but the relative crudeness of the devices is not the feature that distinguishes variables inspection from attributes inspection. Rather, this distinction is made on the basis of the end use to which the data are put. For attributes inspection, a judgment is made for each item measured as to whether the item is acceptable or a defect. The random variable is the number of defects in the sample.

As explained in detail in Part F,(13) there are a number of kinds of attributes inspection that may be performed. A principal distinction is made between inspection for gross defects as opposed to inspection for medium-sized defects. Also, individual tests are made for each of the material strata. The key unifying feature of all these tests is that they are all zero-acceptance type plans, i.e., detection is said to occur if even a single defect is found in any of the individual tests that may be performed.

With this in mind, the detection probability for attributes inspection is very simple to evaluate. In this event, the adversary strategy is to falsify material balance data through medium or gross data falsifications, and detection refers to detecting the occurrence of such falsifications.

The probability of detection is simply

$$1 - \beta^{a_2}$$

where β determines the inspection sample size in each stratum, and for each type of attributes inspection, and is defined to be the probability of failing to detect (i.e., no defects in the sample) an amount of data falsification corresponding to M units for that particular attributes test. The quantity a_2 is defined by the total amount, a_2M, falsified through medium and gross falsifications. It is noted that if β is not the same for all tests, then the largest value of β must be used in calculating the probability of detection.

Overall Effectiveness of Accountancy. There are three basic types of diversion strategies, any combination of which may be used to accumulate M units over the material balance period:

(1) medium or large data falsifications
(2) small data falsifications
(3) diversion into MUF (no falsification).

Diversion type (1) is combatted by attributes inspection; type (2) by $\hat{D}$; and type (3) by the MUF test. As pointed out earlier, types (1) and (2) are responded to in combination by the (MUF-$\hat{D}$) statistic.

In this study, the attributes inspection tests and the (MUF-$\hat{D}$) test are used to detect diversion; i.e., the $\hat{D}$ and MUF tests are not separately applied.

Then, if

a_2M = amount diverted by strategy type (1)
a_3M = amount diverted by strategy type (2)
a_4M = amount diverted by strategy type (3)

the overall probability of detecting the total amount diverted:

$(a_2+a_3+a_4)$ M, or M units (since $a_2+a_3+a_4=1$)

is

$$1 - Q = 1 - \beta^{a2} Q_5 \tag{8}$$

where Q_5 is the probability of failing to detect the amount $(a_3+a_4)M$, i.e., is the complement of the probability given by equation (6).

It is apparent that the detection probability is a function of the diversion strategy, i.e., the specific values of a_2, a_3, and a_4. The quantity Q_{max} is introduced, this being the probability of <u>non</u>-detection corresponding to the adversary's best strategy. Clearly, the probability of detection is a minimum at Q_{max}. The quantity Q_{max} may be found by a trial and error approach.

<u>Effectiveness of Short Detection Time Safeguards</u>. In considering the effectiveness of short detection time safeguards, the probability of detection is again the measure of effectiveness. The interpretation of detection probability, however, is not as simple nor precise as it was for conventional material balance accountancy. In the case of accountancy, the probability of detection is computed over a given material balance period as a function of amount diverted, where the numerous strategies open to the diverter are reduced essentially to a single decision on his part, namely, what fraction of the goal amount should be diverted through a combination of medium and gross falsifications, with the remainder diverted into a combination of small falsifications and MUF. Detection probability for a given goal amount is a function of that selected fraction; all other decisions as to how to allocate the falsifications among the strata do not affect the detection probability for the totality of safeguards measures used in accountancy.

For short detection time safeguards, each inspection activity is treated individually as far as its effectiveness is concerned. For a given activity, the probability of detecting a given amount diverted is calculated for each of a number of well-defined alternatives, ranging from an abrupt diversion (easiest to detect) to a uniformly spread-out diversion (most difficult to detect). Following the same philosophy as in accountancy where Q_{max}, corresponding to the best adversary strategy, defines effectiveness, then the measure of effectiveness for short detection time safeguards should logically be that detection probability for the uniformly spread-out diversion. On the other hand, short detection time inspection activities are specifically intended to counteract abrupt diversions, so there is some interest in evaluating the effectiveness of such activities against abrupt diversion, even though abrupt diversion may not be the optimal strategy for a diverter who seeks to avoid detection. This also avoids the problem of combining detection probabilities for the several short detection time safeguards approaches that may be in place. No attempt is made to make statements of effectiveness for the whole battery of such approaches, nor is any attempt made to combine the evaluation of containment and surveillance and accountancy safeguards approaches. The details of the calculations of detection probability are case-dependent.

Methodology for Assessing Vulnerability to Concealment

The vulnerability of the baseline safeguards system to concealment is determined via diversion path analysis.(2,6) This technique, now being modified for use in international safeguards systems, requires a thorough examination of many diversion paths that include (for each material form or stratum in the plant and location) - falsification of records, substitution, stealth or deceit to conceal removal from surveillance, and stealth or deceit to conceal removal from the containment and associated containment inspections. Substitution includes substitution to duplicate a measured property of the nuclear material such as weight or gamma-ray emission, substitution of a sample given to the inspector, or substitution of false signals to duplicate signals from instruments.

1.3.2.2 Assessment of Costs and Other Impacts

The next step in the baseline analysis is an assessment of the impacts of the safeguards approach. Although the full range of impacts associated with IAEA safeguards are of interest, the analysis concentrates most closely on those impacts that are sensitive to changes in facility design features. In practice, the emphasis is on IAEA resource requirements (including inspection manpower and equipment costs), facility construction costs, facility operational costs, and facility costs associated with IAEA inspections. Some consideration is also given to other costs incurred by the IAEA, facilities, and states, health and safety aspects (primarily occupational radiation exposure of inspectors and facility personnel in connection with inspections), and political, legal, and institutional impacts (primarily involving the provisions of existing safeguards agreements).

It is noted that the key concern in this study is to determine the <u>incremental</u> costs and impacts associated with specified design features. The problem of making comparative cost evaluations is discussed further in a subsequent section where the effects of selected design features are evaluated.

1.3.3 Identification of Problem Areas Associated with the Baseline System

The method for identifying high priority safeguards problems in a way that approaches completeness is as follows. The method is based on the premise that the overall safeguards problem could be defined in terms of three sets of input variables: 1) technical objectives (<u>what</u> safeguards are to do); 2) the facilit descriptors (<u>where</u> safeguards are to do it); and 3) the safeguards descriptors (<u>how</u> safeguards are to do it). The results of the baseline assessment (including sensitivity studies) are reviewed in order to determine the major problems to be corrected, i.e., low effectiveness (e.g., low detection probability, lack of timeliness, or vulnerability to concealment), low efficiency (e.g., excessiv manpower), and other high costs (e.g., "intrusiveness"). Then, by using the results of the sensitivity study or by performing additional sensitivity studie the causes of the problems are identified. The question of establishing the completeness of the problems identified in this way is difficult. It revolves around the completeness of the input variables, i.e., the technical criteria and the facility and safeguards descriptors. Completeness in regard to the technical criteria for safeguards is difficult to assure. In this study the current criteria are used. If, in the future, the criteria evolve, then other design features might become important.

By taking a top-down approach to safeguards we can address most of the safeguards descriptor completeness issue. First, we consider two general safeguards approaches, one based on physical inventory verification and the other based on containment of the nuclear material and surveillance of all possible removal paths. The safeguards descriptors can include elements of both approaches. Furthermore, one approach may be used in one part of the facility and the other elsewhere, or a hybrid approach can be used. Completeness becomes less clear when the specific safeguards techniques for inventory verification or surveillance are considered because this is often a question of technical credibility. Thus, a design feature to facilitate the ability to move spent fuel assemblies for measurement is based on the credibility of NDA for spent fuel. Likewise, a number of design features might be studied that would be unnecessary if a universal seal for assemblies were considered credible. We believe that there can be no guarantee that design features will be identified for all safeguards techniques, only for those that are currently under consideration.

The facility descriptors will be complete if the evaluation methods are complete, i.e., evaluate all important measures, because the descriptors are required as input to the methods. One measure often overlooked is the vulnerability of the safeguards to concealment tactics, which tends to be high when the IAEA inspection approach lacks independence from the facility and state activities. If a diversion path analysis method is not used to evaluate concealment vulnerability, then important design features could be overlooked.

1.3.4 Design Feature Identification: Functional Requirements and Conceptual Designs

Once a safeguards problem is identified, e.g., the criteria cannot be met or the required inspection effort exceeds the MRIE,** then there are three

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** Maximum Routine Inspection Effort, as defined in INFCIRC/153.

ways to reduce or eliminate the problem. First, the technical criteria or the MRIE can be changed. Second, the safeguards can be improved; this solution is actively being pursued in research programs throughout the world. Third, the operating procedures, process, and facilities can be changed. Change in the facility design is the alternative pursued in this study, although in some instances these changes are difficult to distinguish from process and procedural changes.

Once a problem has been identified that is potentially solvable through design changes, a functional requirement is formulated. As an example, assume the problem is low detection probability due to a large systematic calibration error on the volume of liquid input to the process. The sensitivity study shows this problem is influenced by the size and number of input accountability tanks. Thus a functional requirement is to have n accountability tanks of size m, where n and m are determined to reduce the error to an acceptable level.

Given the functional requirement, a conceptual design can be developed to meet it. In the example, the number, size, interconnection, operation, and utilization of input accountability tanks would be developed.

1.3.5 Design Feature Screening and Evaluation

The screening part of this step is a qualitative evaluation to estimate the important measures and determine if the feature warrants a detailed evaluation. For example, features that obviously give a very small improvement in effectiveness but are very costly to the facility would not be evaluated using the quantitative methodology. The reason for this preliminary screening is to avoid spending time and resources conducting detailed evaluations of design features that, for one reason or another, are clearly of marginal interest.

Evaluation of Selected Design Features

The "inspection efficiency" of IAEA safeguards operations is defined as a measure of the productivity of IAEA safeguards, i.e., how well the available resources (manpower, equipment, money) are used to produce the IAEA's part in the implementation of safeguards.(7) All the inspection activities required to implement the safeguards approach, including those that are for calibration and other support, are listed. An estimate of the effort (in man-hours) to perform each activity is made based on expert judgment. These estimates are multiplied by the number of times each activity is performed per year and the products are added to give the annual effort. The equipment needed on-site as well as the off-site support is also considered.

Costs and Other Impacts

The state and facility costs are incremental costs to include the feature in the plant, to operate the plant, and to support the inspector while at the plant.

The cost to include the design features in a new nuclear plant can be determined in two ways:

1. Comparison to Similar Projects - If the cost of a project of similar complexity is known then it can be used or scaled up or down to give an estimate;
2. Component Estimates - Estimates of the costs for land, materials, major equipment, construction labor, and engineering can be made and added up to give a rough cost estimate.

The first method for cost estimating is used when possible because the second method requires considerably more effort and to be done properly requires at least a conceptual design. However, nuclear facility cost estimating is an uncertain business even when a detailed design is available. The important point here is to derive costs consistently so that comparisons can be made. There are many cases where the cost may not increase significantly because the design feature is not additional but replaces a feature of comparable complexity.

The incremental cost to operate the plant with the design feature can be estimated by decomposing operating costs into components and estimating the change in the cost of the component impacted. Another approach is to estimate additional manpower required for operation and to compare this to the work force at the plant. A third technique is to estimate a decrease in throughput due to delays in operation.

The costs incurred by the state in connection with IAEA inspections may be reduced if the inspection effort and time at the facility are reduced. This cost is estimated in terms of labor-hours per year and can be converted using an appropriate factor into annual cost.

There are also other impacts such as intrusiveness and safety. Quantitative judgments are made about whether there is a significantly large positive or negative impact on either aspect. No precise estimates are attempted. Finally, if there are unique impacts that a particular design feature makes, these are identified for the evaluation.

1.3.6 Formulate Conclusions and Recommendations

The final step in the process is the recommendation of guidelines for design features. This is done by comparing one feature relative to the others to determine those that facilitate safeguards without significant adverse impact. The extent to which safeguards are facilitated is determined by the degree to which the design feature in question improves the effectiveness of safeguards, enhances the efficiency of IAEA inspection, or reduces costs and other (adverse) impacts. Significance of costs can be assessed relative to current costs, the costs of domestic safeguards, and possible cost savings from reduced inspection effort.

2.0 BASELINE ASSUMPTIONS

2.1 INTRODUCTION

The baseline definitions are summarized in terms of certain assumptions for the following elements:

- safeguards technical objectives, and
- the detailed description of a reference facility.

2.2 STATEMENT OF SAFEGUARDS TECHNICAL OBJECTIVES

In this section, certain quantitative technical criteria postulated for the purpose of this study are summarized. The specific numerical values used here are related to, but not identical with, the quantitative detection goals that have been described by the IAEA.(1) The IAEA detection goals are not regarded as fixed requirements but rather as guidelines for the development of safeguards approaches. The precise quantitative values used by the IAEA in any particular instance may depend on the circumstances. The values used in this study are consistent with the ranges of values that have been cited in various IAEA documents. For the purposes of this study, the precise values that are selected from those ranges are not a major concern since the kinds of design features that would facilitate IAEA safeguards would not differ greatly if other values from those ranges were used. Some of the detailed calculations would be affected, but the basic results and conclusions would not change.

In mixed-oxide fuel fabrication plants, several categories of nuclear material are typically present: plutonium, uranium of low fissile content (i.e., low-enriched, natural, or depleted), and, in some cases, highly enriched uranium. Both the uranium and the plutonium must be safeguarded, but the plutonium is the dominant concern and this report will focus on it. The quantity of safeguards significance for plutonium is 8 kg, irrespective of isotopic composition. For uranium of low fissile content (i.e., with an enrichment less than 20%), the quantity of safeguards significance is 75 kg ^{235}U contained. For highly enriched uranium, the quantity of safeguards significance is 25 kg ^{235}U contained.

The maximum time period over which diversion is considered is one year. Thus the minimum rates of diversion considered are 8 kg per year for plutonium, 75 kg ^{235}U per year for uranium of low fission content, and 25 kg ^{235}U per year for highly enriched uranium.

For diversion of plutonium, detection should occur within two weeks of the time at which the cumulative amount diverted exceeds 8 kg. For diversion of uranium the corresponding times are 1 year for uranium of low fissile content and two weeks for highly enriched uranium.

The probability of detection should be 95%. The false alarm probability should be very low; as a base case, a value of 5% per facility per year is used in this study.

To facilitate the analysis, it was decided for purposes of this study to carry out the evaluation of safeguards effectiveness in two parts. One part of the evaluation concentrated on protracted diversion and the inspection activities associated with its detection. The other part concentrated on abrupt diversion and the associated "short detection time" inspection activities. It was recognized that evaluating these two subsystems separately in this manner produced only approximate results. To obtain exact results would necessitate a comprehensive evaluation methodology to integrate the contributions of the various inspection activities and to include the entire spectrum of diversion possibilities. Such methodology is not available.

2.3 FACILITY DESCRIPTION

The facility description consists of two parts: a general process overview and a detailed material accountancy model.

2.3.1 Process Overview

As shown in Table 2.1, there are at present, three sizable mixed oxide fuel fabrication facilities in non-nuclear-weapons states, and a small, pilot-scale facility that is classified as a research and development location. All of the states in question are parties to the Non-Proliferation Treaty, so safeguards of the INFCIRC/153-type would apply. A rough estimate of the throughput of each of the three main facilities is about 500 kg Pu per year, although the design capacities of the plants are probably somewhat larger.

TABLE 2.1. Mixed-Oxide Fuel Fabrication Plants in Non-Nuclear-Weapon States

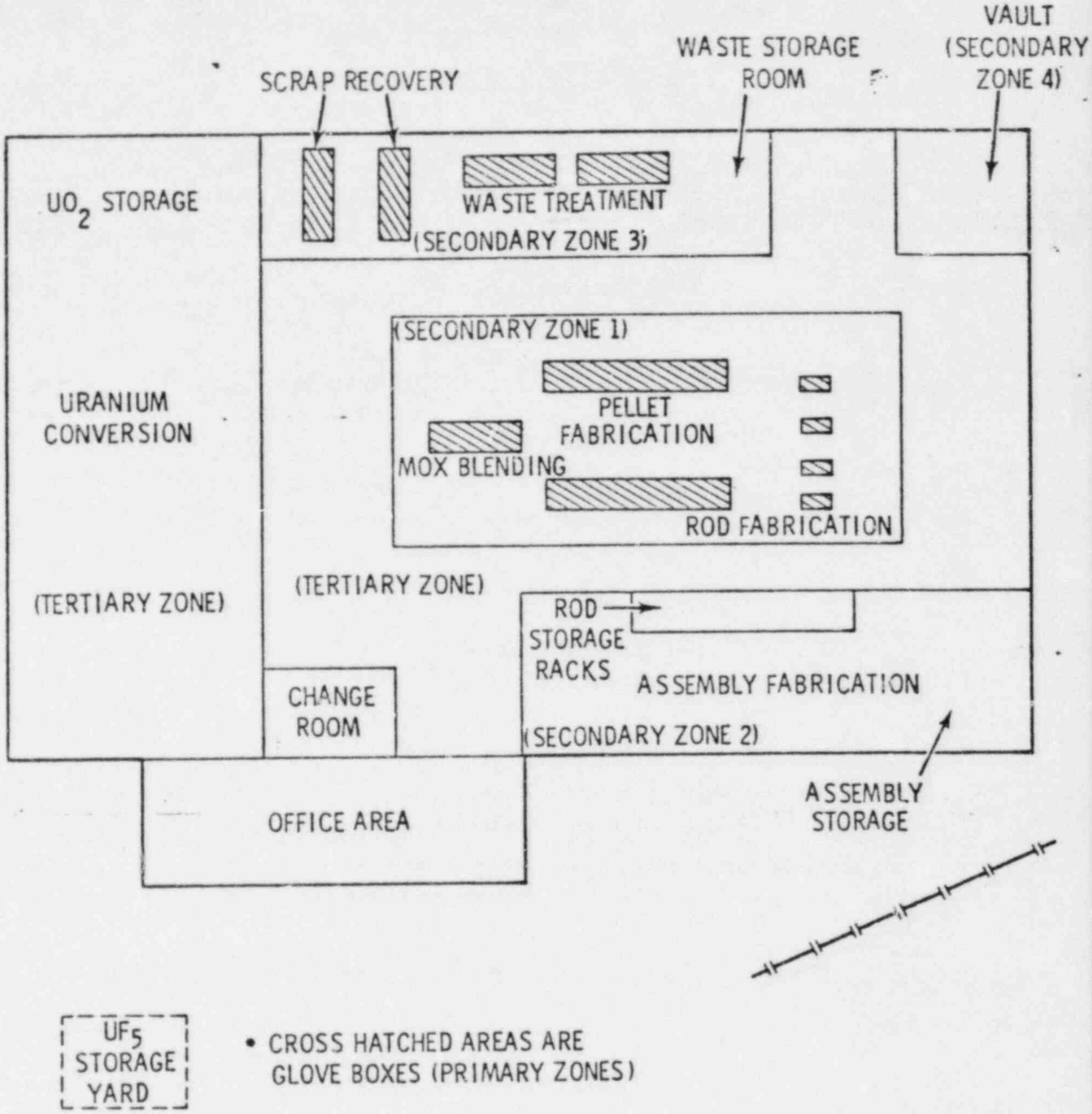
Country	Facility	Location	Facility Attachment In Force	Remarks
Belgium	Belgonucléaire	Dessel	Yes	
Federal Republic of Germany	ALKEM	Hanau/ Karlstein	Under Negotiation	
Japan	PPFF	Tokai-Mura	Yes	
Italy	CNEN LAB. PU	Casaccia	Yes	Pilot scale R&D location

The reference case assumed for this study is a mixed oxide fuel fabrication facility with an average throughput of approximately 1500 kg Pu/year. The general layout of the facility is shown in Figure 2.1, which also indicates the containment zones and the expected flow of personnel and material across the barriers. Figure 2.2 shows the process and storage areas in the facility, the weekly flows of material from one area to the other, and the buffer and in-process inventories.

The different material forms present in the facility are assumed to be stored in containers (except for the fraction of material being processed). Table 2.2 contains the inventory data for the model facility.

2.3.2 Material Accountancy Model

The reference plant is a mixed oxide fuel fabrication facility with an annual throughput of 1536 kg plutonium. The plant plutonium balance is of key interest, i.e., although a uranium balance would also be computed, attention is focussed in this report on the plutonium balance. The length of the material balance period considered in this report is one year, since this corresponds to the limiting case of protracted diversion at the rate of 8 kg plutonium per year. Plant operation is assumed to have reached equilibrium, i.e., the inventory composition is assumed to remain fixed, but to turn over completely within the material balance period.



		Containment		
	Zone	Barrier	Personnel Flow	Material Flow
PU	Primary	Steel & Plexiglass Gloveboxes	None	High (Daily)
PU	Secondary	Concrete	High	High
PU	Tertiary	Concrete	High	Medium (Weekly)
U	Tertiary	Concrete	High	Low (Monthly)

FIGURE 2.1. MOX Fabrication Facility Layout

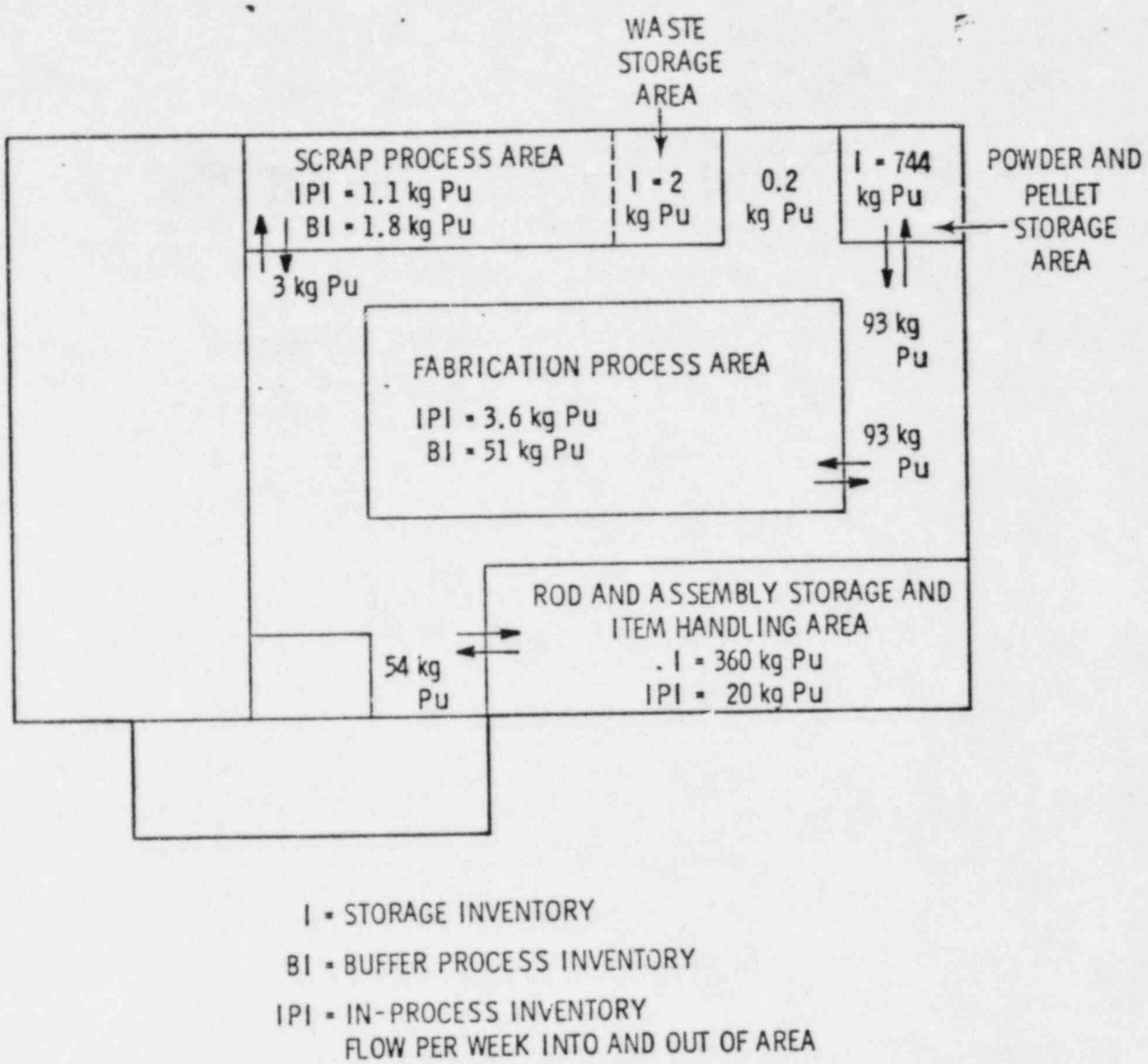


FIGURE 2.2. MOX Fabrication Facility Layout Showing Inventories and Flows for Containment Areas

TABLE 2.2. Inventory Data for the Model Fabrication Facility

Area	Forms	Normal Operation Inventory	Clean-Out Inventory
Storage Areas			
1. UF_6 Storage Yard	UF_6	15 MTU 2 cylinders	No Change
2. UO_2 Storage Room	UO_2	3 MTU 30 buckets	No Change
3. Vault	PuO_2	500 kg Pu 250 cans	No Change
	MOX	3 MT MOX 15 blends	No Change
	Pellets	3 MT MOX 3,000 trays	No Change
	Scrap	100 kg MOX	No Change
4. Rod Storage Racks	Rods	3 MT MOX 1500 rods	No Change
5. Assembly Storage Area	Assemblies	6 MT MOX 12 PWR 12 BWR	No Change
6. Waste Storage Area	Waste	50 kg MOX 330 buckets 160 drums	No Change
	Total	1.1 MT Pu 32.5 MTU	
Process Areas			
1. Uranium Conversion	UF_6	7.5 MTU 1 cylinder	Zero
	UO_2	1.5 MTU (1 batch) 15 buckets	Zero
	In-process	0.5 MTU	Zero

TABLE 2.2. (Contd)

Area	Forms	Normal Operation Inventory	Clean-Out Inventory
MOX Blending	PuO_2	8 kg Pu 4 cans	Zero
	UO_2	192 kg U 2 buckets	Zero
	MOX	200 kg MOX 20 cans	Zero
	In-process	50 kg MOX	Zero
3. Pellet Fabrication	MOX	70 kg MOX 7 buckets	Zero
	Green Pellet Buffer	200 kg MOX (2 days flow) 200 boats	Zero
	Sintered Pellets	200 kg MOX 200 trays	Zero
	In-process	25 kg MOX	Zero
4. Rod Fabrication	Pellets	200 kg MOX (1 batch) 200 trays	Zero
	Rods	200 kg MOX 100 rods	Zero
	In-process	16 kg MOX (4 lines at 2 rods)	Zero
5. Assembly Fabrication	Rods	250 kg MOX (1 assembly) 125 rods	Zero
	Assemblies	250 kg MOX (1 assembly)	Zero
6. Scrap Recovery	Scrap	25 kg MOX 1 bucket	Zero

TABLE 2.2. (Contd)

Area	Forms	Normal Operation Inventory	Clean-Out Inventory
	MOX	20 kg M 2 cans	Zero
	In-process	25 kg M	Zero
7. Waste Treatment	In-process	0.5 kg M 4 buckets and drums	Zero
Total	Buffer	72 kg Pu 11 MTU	
	In-process	4.7 kg Pu 612 kg U	

There are ten material strata defined for the reference plant: one input stratum, three output strata, and three beginning and ending inventory strata. In the strata description to follow, only "active" items are considered. This deletes any item appearing identically in a plus and minus component of MUF. For example, if a sealed item is in beginning and ending inventory, and if the seal is intact, then the contents of that item do not affect the MUF or its variance. However, if the facility operator were to remeasure the item and book the verified value, then it would be included in the MUF variance calculations. It is assumed that such facility verification measurements are not booked.

The composition of each stratum is defined. The word "batch" as used here is consistent with its usage in Part F of the IAEA Safeguards Technical Manual, i.e., it consists of all items having a uniquely determined element factor (percent plutonium in this instance).

The strata are described.

Stratum 1. An input stratum consisting of PuO_2 receipts. The PuO_2 is packaged in cans, each containing a nominal 2 kg Pu. Each group of 32 cans forms a batch. The batch plutonium factor is based on sampling each of 4 randomly selected cans, performing duplicate analyses for percent plutonium on each sample, and using the average result to characterize all cans in the batch. PuO_2 is inputted to the process at the rate of two batches (or 128 kg Pu) per month.

Stratum 2. This is the product stream. For error propagation purposes, the product stream consists of trays of sintered pellets; surveillance procedures are needed to fulfill the IAEA safeguards function beyond that point. Each tray contains a nominal 37.5 g Pu. Each group of 200 trays forms a batch. The batch plutonium factor is based on sampling single pellets from each of 5 trays, performing a single analysis for percent plutonium on each sample, and using the average result to characterize all trays in the batch. The trays are created at the rate of 16-2/3 batches (or 125 kg Pu) per month.

Stratum 3. This is an output flow stream consisting of cans of MOX powder scrap shipped offsite for reprocessing. Each can is sampled and a single analysis is performed to determine the percent plutonium to be applied to that can. Thus, there is only one item per batch in this stratum. Each can contains a nominal 900 g Pu. Cans of such scrap are shipped offsite at the rate of 5 cans (or 4.5 kg Pu) per month.

Stratum 4. This is an output waste stream consisting of drums of solid wastes. The plutonium content of each drum is measured by nondestructive assay so that there is one item per batch in this stratum. The average item contains 4 g Pu. Items are created at the rate of 12.5 drums (or 0.050 kg Pu) per month.

Stratum 5. This is a beginning inventory stratum consisting of cans of MOX powder. Each can contains a nominal 375 g Pu. There are 20 cans per batch, and each batch percent plutonium value is based on sampling from three randomly selected cans and making a single analysis per sample. There are 18 batches (or 125 kg Pu) in the beginning inventory.

Stratum 6. This is a beginning inventory stratum consisting of cans of MOX powder scrap (see stratum 3). There are 5 cans (or 4.5 kg Pu) in the beginning inventory.

Stratum 7. This is a beginning inventory stratum consisting of cans of grinder swarf. Each can is sampled with a single analysis performed to determine the percent plutonium to be applied to that can. Each can contains a nominal 750 g Pu. There are 3 cans (or 2.25 kg Pu) in the beginning invento

Stratum 8. Same as stratum 5, but an ending inventory stratum.

Stratum 9. Same as stratum 6, but an ending inventory stratum.

Stratum 10. Same as stratum 7, but an ending inventory stratum.

The information in the above narrative description is summarized in Table 2.3, along with additional information on measurement methods.

Input information on measurement error standard deviations is given in Table 2.4. The tabular entries are in relative percents. For example, an entry of 0.025 means that the standard deviation for that particular measurement is 0.025 percent of the characteristic value for the item in question. Some comments are in order for purposes of clarification:

1) The error standard deviations shown are based on experience for an actual operating plant, and represent values that should be quite easily attainable in practice. In some areas, it is felt that improvements can be made. This subject is pursued in some detail later in this report.

TABLE 2.3. Information on Reference Plant (One Year)

	Stratum						
	1 Input PuO2	2 Output Pellets	3 Output Scrap	4 Output Waste	5,8 Inventory MOX Powder	6,9 Inventory Scrap	7,10 Inventor Swarf
Items/batch	32	200	1	1	20	1	1
Batches	24	200	40	100	18	5	3
Samples/batch	4	5	1	1	3	1	1
Analyses/sample	2	1	1	1	1	1	1
Scale ident.	1	2	3	4	5	3	3
Material type	1	2	3	4	5	3	6
Analytical ident.	1	2	3	4	3	3	2
Kg Pu/item	2	.0375	.9	.004	.375	.9	.75
Kg Pu/stratum	1536	1500	36	.4	135	4.5	2.25

TABLE 2.4. Relative Percent Errors

	Stratum						
	1	2	3	4	5,8	6,9	7,10
	PuO$_2$	Pellets	Scrap	Waste	Powder	Scrap	Swarf
Random							
Scale	.025	.05	.04	--	.04	.04	.04
Material	.01	.80	3.5	--	.40	3.5	2
Analytical	.40	.50	.60	20	.60	.60	.50
Long Term Systematic							
Scale	.02	.035	.025	--	.025	.025	.025
Material	0	.10	1.5	--	.24	1.5	.8
Analytical	.07	.12	.15	8	.15	.15	.12
Short Term Systematic							
Analytical	.13	.16	.20	6	.20	.20	.16

2) There are rather large material sampling errors. This is somewhat characteristic of mixed oxide materials and can lead to systematic errors in sampling if care is not taken to select representative samples. It should be relatively easy to eliminate or at least greatly reduce the size of systematic errors in sampling, and later in this report, such errors are reduced in size.

3) In the case of analytical measurements, three kinds of errors are identified: random, long-term systematic, and short-term systematic. This last kind of error is introduced in order to model the shift in analytical bias that may occur periodically due to instrument recalibration and/or other perhaps unidentified causes. The assumptions on how frequently such analytical biases shift are displayed in Table 2.5. Similar assumptions could perhaps be made about shifting biases in the scales. However, this error source is not as important, and it is reasonable to make the more conservative assumption that scale biases are enduring ones.

TABLE 2.5. Assumptions on Short Term Systematic Error for Analytical

Stratum	Description	Number of Errors in 12 Months
1	Shifts every month (every 2 batches)	12
2	Shifts every month (every 17 batches)	12
3	Ship every 3 months; measure at time of shipment	3
4	Shifts every 6 weeks (every 12 barrels)	8
5-7	All created under condition 1	1
8-10	All created under final condition	1

Tables 2.3, 2.4, and 2.5 complete the body of information about the plant accountability system.

3.0 BASELINE EVALUATION

3.1 SAFEGUARDS APPROACH

3.1.1 Introduction

The basic approach to international safeguards based on verified materia accountancy complemented by containment and surveillance has been denoted by the term "conventional" safeguards. In recent years, as a result of problems associated with the application of safeguards at facilities containing large amounts of material from which nuclear explosive devices could readily be mac various studies and working groups have emphasized extensions and enhancement of this basic approach. Consideration of these extensions and enhancements h been prompted by two major concerns: the need for more timely detection of diversion of direct-use material, and the need for improved sensitivity of detection in large bulk processing facilities.

Two basic kinds of extensions or enhancements have been proposed: 1) extended containment and surveillance, and 2) more timely material accountancy. Extended containment and surveillance has been investigated in depth in connection with reprocessing plants; its potential application at fuel fabrication plants has received less attention. The studies of extended C/S approaches at reprocessing plants have indicated the following limitations:

- Cost. The cost and complexity of a safeguards system relying primarily on containment and surveillance is likely to be very high because of th need for substantial containment and extensive instrumentation to monit boundaries and penetrations.
- Technology. The technology for such systems has not yet been fully developed and demonstrated.
- Evaluation. Methods for evaluating the effectiveness of containment an surveillance systems are not yet fully developed.

Similar limitations can be expected to apply to extended C/S approaches at fuel fabrication facilities.** As a result, possible safeguards approaches relying primarily on containment and surveillance have not been considered in detail in this study. Instead, attention has been focused mainly on more timely material accountancy; where necessary or appropriate, the practical elements of containment/surveillance have been used to complement and supplement the basic material accountancy approach.

Modified forms of material accountancy involving frequent material balanc based on estimates of in-process inventory and buffer storage can detect, with the required probability and timeliness, the relatively high rates of diversio characteristic of abrupt diversion scenarios. In some cases these modificatio may also increase the sensitivity and timeliness of detection at rates intermediate between the limiting cases of abrupt and protracted diversion. The approach described in this report is primarily material accountancy with biweekly process inventories. Cleanout physical inventories are assumed to be performed annually. This basic approach is integrated with the containment and surveillance techniques necessary to establish the completeness and validi of the material balances.

As noted earlier, the safeguards approach is somewhat artificially divide into two parts: a short detection time inspection approach and a material accountancy inspection approach. In practice, there is considerable overlap between the two.

3.1.2 Short Detection Time Inspection Approach

The technical objectives state that diversion of plutonium from mixed-oxide fuel fabrication facilities should be detected within two weeks. In order to achieve this, the safeguards system must include inspection activitie that will permit conclusions concerning diversion to be reached in time frames much shorter than the period between physical inventory takings. The approach proposed in this study is essentially an extension of conventional material accountancy. The scheme is based on the availability of one or more inspector

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**However, these limitations may be less severe than is the case for reprocessing facilities. See Chapter 7.

who, in addition to more or less continuous flow verification, perform a partia inventory in the process and storage areas once every two weeks.

In order to set up such an inspection scheme, one has to postulate a certain level of safeguards technology. In what follows, it is assumed that the following safeguards technology is available:

- Seals - Field readable, reliable seals exist which can be applied to a variety of containers, such as cans, buckets, trays or groups of trays, boats, and storage racks.
- Portable Scale - The inspector can reliably measure the weight of items ranging from 0.1 to 10 kg.
- Nondestructive Assay - A battery of radiation detectors is available for attributes and variable measurements. These instruments include:
  - Neutron coincidence counters for PuO_2 and MOX powders
  - Gamma-ray assay (Ge) for scrap cans and pellet boats or trays, in a fixed and reproducible geometry
  - Gamma-ray survey (NaI) for qualitative checking
  - Gamma-ray rod scanner (Ge)
- Laboratory Support - Chemical and isotopic analysis on a limited number of samples can be performed at an outside Agency laboratory.
- Mini-computer - For data storage, inventory listing, sample plan generation, data analysis, etc.

If the scheme is to be workable, two additional assumptions are necessary:

- Measurement techniques to satisfy the criteria must be available, so that over a two-week period the uncertainty on measured material will not be so high that the diversion of a significant amount could be masked by measurement errors. To satisfy the criteria, one should use more refined measurement techniques which implies more effort.
- Once every two weeks, the facility will agree to shut down transfers between MBAs for about eight hours. The processing of material may continue, however.

From a macroscopic point of view, the facility can be considered as consisting of the following:

- A receiving point, where the containers of nuclear material arriving at the facility are measured and sealed.
- A storage area, consisting of several vaults. All the containers in the storage area are sealed by the Agency. Sealing takes place at the time of arrival, if the containers come from the receiving point, or at the most convenient time, if they come from process.
- A process area in which the material, including that in buffer storage, is not sealed.
- A shipping point, where the material is verified by the Agency (to the extent possible) and further sealed for shipment.

In addition to the measurements performed at the receiving and shipping points, the inspection approach includes the following activities:

- Seal the containers at the receiving and shipping point.
- Count the containers in the storage area and check the seals on a sampling plan basis.
- Seal the containers after they come from the process area into storage, and after some of them have been verified using a sampling plan.
- Inspect the process area periodically and perform a rough material balance by estimating the inventory in the buffer storage areas.

In what follows, the procedures used for the inspection of different strata are described. The inspection activities are carried out with sampling plans designed to attain a 95% detection probability. Table 3.1 gives some details on the specific inventories and sampling plans at different storage areas.

Vault

The vault contains an average of 250 cans of PuO_2. To ensure that there has not been a gross removal, one has to check 118 cans. Also, 30 cans are transferred into storage every two weeks. After verifying 16 cans, all 30 cans are sealed. Verification of these cans is by weighing and a qualitative gamma-ray measurement. Other forms transferred into the vault are MOX powder,

TABLE 3.1. MOX Fabrication Item Storage Area Inspection Activities (1500 kg Pu/yr)

Storage Areas	Forms	Normal Operation Inventory	No. of Items To Obtain A Goal Amount	No. of Sealed Items To Be Checked To Obtain 95% Detection Probability	No. of Items Transferred In 2 Weeks	No. of Items Transferred Which Must Be Verified To Obtain 95% Detection Probability	Verificat Metho
Vault	PuO_2 powder	250 cans	4	118	30	16	Weight/N
	MOX powder	300 cans	20	41	160	12	Weight/N
	Pellets	3000 trays	200	44	1563	22	Weight/γ-
	Scrap	8 buckets	15	2	6	2	Weight/γ-
Rod Storage Racks	Rods	1500 rods	100	44	700	22	γ-ray sca
Assembly Storage Area	Assemblies	24 assemblies	1	22	6	6	γ-ray sur
Waste Storage Area	Waste	500 buckets or drums	2000	1	80	1	γ-ray sur

pellets and scrap. The number of pellet trays in large. This would require a large number of seals if each tray had to be sealed independently. It may be possible to seal groups of trays, so that the total number of sealing oper tions would be reduced.

Rod Storage Racks

There are 1500 rods in storage. Of these, 44 would have to be scanned using a passive gamma-ray rod scanner or a passive rod assay by calorimetry o neutron coincidence counting. Seven hundred rods enter the storage area ever two weeks and 22 would have to be rod-scanned at the time of inspection.

Assembly Storage Area

Essentially all the assemblies need to be checked and verified. There are an average of 24 assemblies in storage, with about three being produced weekly. Verification would be by visual inspection of the assemblies and a random check of rod serial numbers using an assembly load map. A qualitative gamma-ray measurement would also be made.

Waste Storage Area

There is no way of carrying out a gross diversion based solely on waste. Therefore, no seals are applied. If the inventory of waste becomes larger than 8 kg Pu, then a minimal sampling plan could be used and some barrels checked by weight and qualitative gamma-ray counting.

All the sampling plans are based on the assumption of random sampling. In all cases, it appears reasonable that the inspector would have an inventory list or transfer records to use for the sampling.

Process Area

The inspection activities in the process area consist of estimating the amount of material in buffer storage and in-process and performing a rough material balance. The book inventory is known from the information provided by the facility on material transferred to storage. This information has been checked on a sampling plan basis.

A brief description of the inspection activities in the different process areas follows (the numbers given are average numbers).

MOX Blending - Estimate the amount of material contained in four cans of PuO_2 and 20 cans of MOX powder. Count all cans and weigh a fraction of the cans and do a gamma-ray check. The fraction has not been determined.

Pellet Fabrication - Estimate the amount of Pu in 7 buckets of MOX powder and in 200 boats and 200 trays containing pellets. Boats and trays may be partially empty. Again, all would be counted and a fraction would be weighed and gamma-ray counted.

Rod Fabrication - Estimate the amount of Pu in 200 trays of pellets and 100 rods. Trays would be counted and a fraction would be weighed. Rods would be counted and some would be gamma-ray counted.

Assembly Fabrication - Estimate the amount of Pu in 125 rods and one assembly being fabricated. Rods would be counted and a fraction gamma-ray counted. The assembly would be checked by visual inspection.

Scrap Recovery - Estimate the amount of Pu in one bucket containing clean scrap and two cans containing recycled MOX powder. Buckets and cans would be weighed and a factor used.

The total uncertainty of the amount of Pu contained in the process area is evaluated from estimated uncertainties on different material forms as shown in Table 3.2 and discussed below. The amount of Pu in a single form in a process area is obtained by counting the number of similar containers present,

TABLE 3.2. Process Area Buffer Inventory Uncertainties (Primary Activiti

Process Area	Material Form	Number of Batches	Content of Batch	Pu Content (kg) of Batch	Percent Systematic Error	Contributio Variance (kg
MOX Blending	PuO_2	4 cans	2 kg Pu	2.0	25	4.0
	MOX	20 cans	10 kg MOX	.4	25	4.0
Pellet Fabrication	MOX	7 buckets	10 kg MOX	.4	25	.5
	Green pellet buffer	200 boats	1 kg MOX	.04	10	.64
	Sintered pellets	200 trays	1 kg MOX	.04	10	.64
Rod Fabrication	Pellets	200 trays	1 kg MOX	.04	10	.64
	Rods	100 rods	2 kg MOX	.08	10	.64
Assembly Fabrication	Rods	125 rods	2 kg MOX	.08	10	1.0
	Assemblies	1 assembly	250 kg MOX	10.00	25	6.25
Scrap Recovery	Scrap	1 bucket	25 kg MOX	1.0	50	.25
	MOX	2 cans	10 kg MOX	.4	20	.01

Total uncertainty = 4.3 kg Pu.

by weighing some fraction and using a factor for the Pu content, and by che ing a fraction by qualitative gamma-ray measurement to assure there has bee no substitution. This inventory verification approach introduces an error, due primarily to the sampling error and the error in the Pu factor, that is probably larger for bulk forms than for finished forms, such as pellets and rods. The uncertainties on the different forms are added quadratically if there is no correlation among the estimates. Under the assumptions for the uncertainties in Table 3.2, the uncertainty in the material in buffer stora in the process will be 4.3 kg.

To achieve 95% detection probability for 8 kg Pu, with a false alarm r of 5%, the total uncertainty must be less than approximately 2.5 kg Pu. Th requires a more accurate verification of the buffer inventory. This can be achieved by weighing a larger fraction of the containers (even up to 100% i required) and by using quantitative NDA (HLNCC and passive gamma-ray counti to confirm the Pu factors and assure no substitutions. If this is done, th uncertainty of buffer inventory verification can be reduced to approximatel 2.1 kg Pu for the base case.

This inspection scheme is also believed to be effective if a significant amount were taken from two or more strata in the storage area. (The sampling plans would have lower probabilities of detection in each stratum, but there would be more chances for detection, and the total detection probability would be greater.)

3.1.3 Material Accountancy Inspection Approach

The material accountancy inspection approach consists of a full and independent IAEA verification of the plant operator's material balance accounting. In this section, the uncertainty in the operator's material balance is determined and an inspection plan is then formulated. The inspection plan defines the number and kind of verification measurements to be made in all strata.

Variance of MUF for the Reference Plant

The variance of MUF is calculated by the methods of Part F of the IAEA Safeguards Technical Manual with the results displayed in Table 3.3 (random error variance) and Table 3.4 (systematic error variance). The results are identified by measurement method (see Table 2.3). Table 3.5 is a summary table. It is noted that for the base case the standard deviation of the facility MUF is 0.193% of the throughput.

The uncertainty in the facility MUF, in itself, does not provide a measure of the capability of the inspection system to detect missing amounts of material since the element of inspection is not included. That is, the MUF must first be verified by the IAEA. In the next section, consideration is given to the planning of an inspection designed to verify the facility MUF.

Inspection Planning for Reference Plant

Inspection planning proceeds along the lines of Chapter 8, Volume 2, of Part F of the IAEA Safeguards Technical Manual. First, the selection of sample sizes for use in attributes inspection is addressed.

Attributes Inspection Sample Sizes

The sample size for attributes inspection in stratum k is based on an acceptance number of zero, i.e., the stratum does not pass inspection if even one "defect" is found in the sample. This type of plan results in the minimum

TABLE 3.3. Random Error Variance of MUR by Measurement Method (Kg^2 Pu)

Source of Error	Contribution to Variance
Scales 1	0.0002
2	0.0000
3	0.0000
4	0.0000
5	0.0000
Total	0.0002
Sampling 1	0.0002
2	0.1440
3	0.0496
4	0.0000
5	0.0108
6	0.0014
Total	0.2060
Analytical 1	0.1966
2	0.0563
3	0.0258
4	0.0001
Total	0.2788
Total Random Error Variance	0.4850

TABLE 3.4. Systematic Error Variance of MUF by Measurement Method (Kg^2 Pu)

	Contribution to Variance
Scales	
1	.0944
2	.2756
3	.0001
Total	.3701
Sampling	
2	2.2500
3	.2916
Total	2.5416
Analytical	
1	1.1561
2	3.2400
3	.0029
4	.0010
Total	4.4000
Short Term Analytical	
1	.3323
2	.4800
3	.1670
4	.0001
Total	.9794

TABLE 3.5. Variance of MUF: Summary

Random	.4350
Systematic	7.3117
Short Term Systematic	.9794
Total	
V_t (MUF) =	8.7761
σ (MUF)	2.962
Throughput	1536.
Percent σ (MUF)	0.193%

inspection sample size for a given combination of β and M, where β is the probability of failing to detect the goal amount M (kg Pu) missing in the particular stratum but hidden through data falsification. It is assumed that the largest amount by which an item can be falsified is the maximum amount of Pu contained in any item in the stratum.

The attributes inspection sample size in stratum k is given by (1):

$$n_{ak} = N_k \left(1-\beta^{1/r_k}\right) \tag{1}$$

where

n_{ak} = attributes inspection sample size in stratum k
N_K = number of items in stratum k
r_k = number of items falsified
β = M/x_k

where

x_k = maximum amount of Pu contained in any item in stratum k.

According to the technical objectives, β for inspection should be 0.05. This applies to the entire inspection and not just to attributes inspection in a single stratum. However, in order to achieve this overall range of values for β, it is necessary that β be no larger than 0.05 for this phase of inspection. Inspection sample sizes using equation (1) with β = 0.05 and M = 8 kg Pu for the 12 months material balance period are given in Table 3.6. Note that over 1000 total items require attributes inspection under this plan. (Later the effect on sample size of increasing the value of β is considered.)

Variables Inspection Sample Sizes; Variable Inspection in Attributes Mode

Variables inspection provides a plutonium value for each item inspected, that value to be compared with the value assigned by the plant. The intent is to use the paired data resulting from this part of the inspection in the so-called $\hat{D}$ statistic (see next section) to measure the bias in the reported plant MUF that occurs as a result of the accumulation of small biases, or data falsifications.

The same variables inspection data are also used to detect item "defects", where a defect is a discrepancy between the facility and inspection values that is larger than can be explained by stated errors of measurement. Thus, there are two quite distinct applications of the same data: to detect the presence of small biases or data falsifications, and to detect so-called medium-size defects, those just small enough to escape detection with the attributes tester. The sample size to use for variables inspection in stratum k is the

TABLE 3.6. Attributes Inspection Sample Sizes

Stratum	Sample Size	
	N_k	n_{ak}
1	768	405
2	40,000	558
3	40	12
4	100	1
5	360	48
6	5	2
7	3	1
8	360	48
9	5	2
10	3	1
Total		1078

larger of two values; one value determined assuming the data are to be used in an attributes mode; and the other value assuming the data are to be used in a variables mode. This section addresses the first consideration, and the next section addresses the second.

The formula for determining the variables sample size for its use in an attributes mode is identical to (1) except that r'_k replaces r_k, where

$$r'_k = M/\gamma_k x_k.$$

The parameter γ_k is a constant that describes the ability of the attributes tester to detect a defect in stratum k. For example, if $\gamma_k = 0.10$ for a given stratum, then this means that a defect equal in size to 10 percent of the item value would not be detected by attributes inspection (although a larger defect would be).

For the reference plant, it is assumed that $\gamma_k = 0.04$ for all strata except the solid waste stream stratum. For that stratum, $\gamma_4 = 0.50$.

Inspection sample sizes for the variables tester in the attributes mode are given in Table 3.7 for $\beta = 0.05$ and $M = 8$ kg Pu for the 12 months material balance period.

Variables Inspection Sample Sizes; Variables Inspection in Variables Mode

A second purpose of the variables measurements data is to evaluate the bias in the facility's reported MUF due to small biases or data falsifications. This evaluation is based on the so-called difference statistic, or $\hat{D}$ statistic.

The primary data point in developing the $\hat{D}$ statistic is the paired difference between the plant value and the inspector value for item i in stratum k. This is denoted by d_{ki}, and the average paired difference in stratum k is denoted by $\bar{d}_k$. $\hat{D}_k$ is then defined as $N_k\bar{d}_k$, and finally, $\hat{D}$ by

$$\hat{D} = \sum_k A_k \hat{D}_k \tag{2}$$

where $A_k = +1$ for input and beginning inventory strata, and $A_k = -1$ for output and ending inventory strata.

TABLE 3.7. Variable Inspection Sample Sizes (Attributes Mode)

	Sample Size	
Stratum	N_k	n_{vlk}
1	768	23
2	40,000	23
3	40	1
4	100	1
5	360	2
6	5	1
7	3	1
8	360	2
9	5	1
10	3	1
Total		56

There are alternate ways to judge material balance performance using the $\hat{D}$ statistic and the facility MUF. One approach is to test whether or not the facility's reported MUF is biased, using the $\hat{D}$ statistic and testing the hypothesis: $D = 0$. If this hypothesis is not rejected, then the facility MUF is regarded as being a valid measure of the true MUF, and it is tested for significance. The other approach is to utilize the so-called (MUF-$\hat{D}$) statistic, which has the physical interpretation of being the "inspector's MUF" in the sense that it is the facility MUF adjusted for bias as estimated from the inspection measurements.

This latter approach, utilizing the (MUF-$\hat{D}$) statistic, is the preferred approach. It has important advantages over the approach that first conducts a test on $\hat{D}$ and then on MUF. As one advantage, the (MUF-$\hat{D}$) statistic is independent of the facility's systematic errors (unless the inspector should commi the same errors, as will be illustrated). This means that the facility cannot obscure losses by overstating the size of such errors. Further, systematic error variances are very difficult to check for validity. The second advantag is also an important one: (MUF-$\hat{D}$) provides better protection against the best strategy that might be employed by an adversary to mask diversion. This advantage will be illustrated for the reference facility.

Inspection planning in this study utilizes the $(\mathrm{MUF}-\hat{D})$ statistic. The total variables sample size, n_{v2}, is selected such that a loss of M units (the goal quantity) will be detected by the $(\mathrm{MUF}-\hat{D})$ statistic with probability $(1-\beta)$. In mathematical terms, if the expected value of $(\mathrm{MUF}-\hat{D})$ is M, then the probability is set at $(1-\beta)$ that the observed value of $(\mathrm{MUF}-\hat{D})$ will exceed its critical value. The critical value is selected to provide a fixed significance level, α. Having found n_{v2}, the total variables sample size, this is then allocated among the strata to minimize the variance of the $(\mathrm{MUF}-\hat{D})$ statistic. In determining n_{v2}, it will have been assumed that this optimum allocation of samples will occur.

The two equations to solve to find n_{v2} are:

$$\mathrm{Prob}\ [(\mathrm{MUF}-\hat{D}) > M_0 \mid M=0] = \alpha \tag{3}$$

$$\mathrm{Prob}\ [(\mathrm{MUF}-\hat{D}) > M_0 \mid M=M] = 1-\beta \tag{4}$$

To solve these equations, certain information is required. Clearly, one must specify values for α and β. The value for M is given. The variance of $(\mathrm{MUF}-\hat{D})$ must be found.

It can be shown that

$$\mathrm{var}\ (\mathrm{MUF}-\hat{D}) = \mathrm{var}\ \hat{D} - \mathrm{var\ MUF} + 2\ V_0 \tag{5}$$

where V_0 is that part of the variance of MUF that is due to systematic errors in measurement that are common to both the facility and the inspector. Most notably, if the inspector uses the same sampling procedures as the facility, then both would commit the same systematic errors in material sampling, and V_0 would be the systematic error variance in sampling.

Consider the variance of $(\mathrm{MUF}-\hat{D})$ under the hypothesis that $M = 0$. The variance of MUF has already been computed. For the $\hat{D}$ statistic, let σ_s^2 denote the systematic error variance of $\hat{D}$. (This includes the variance components that are random in origin but which become systematic in nature once even a single sample is taken. For example, in the case of a batch percent plutonium factor, once even one item in that batch is sampled by the inspector, then additional samples will not further reduce the error associated with the facility's determination of the batch factor in question.) Then, define the parameter k_1 as the ratio of the random error variance of $\hat{D}$ to σ_s^2. A solution is found for k_1, and then the sample size n_{v2} is readily calculated. The sample size is inversely proportional to k_1.

Having defined σ_s^2 and k_1, then the variance of $\hat{D}$ under the hypothesis that $M = 0$ is

$$\text{var}\ (\hat{D}|H_o) = \sigma_s^2 + k_1\sigma_s^2 = \sigma_s^2\ (1 + k_1) \tag{6}$$

The variance of (MUF-$\hat{D}$) can then be calculated from (5) and (6) as a function of k_1. A similar development holds for the variance of $\hat{D}$ under the alternative that $M = M$. Here, it is assumed that the random error variance of $\hat{D}$ may be inflated because of statistical sampling errors, i.e., not all items would be biased by the same amount.

A variance inflation factor, c_o^2, is introduced. A reasonable, but conservative, value used in this study is $c_o^2 = 4$. Thus, under the alternative H_1,

$$\text{var}\ (\hat{D}|H_1) = \sigma_s^2\ (1 + c_o^2 k_1) \tag{7}$$

Again, the variance of (MUF-$\hat{D}$) under H_1 is found using (5) and (7). If one introduces the notation

$$K_2 = \frac{\text{var MUF-}2V_O}{\sigma_s^2} \tag{8}$$

then

$$\text{var}\ (\text{MUF-}\hat{D})|H_o = \sigma_s^2\ (1 + k_1 - k_2) \tag{9}$$

and

$$\text{var}\ (\text{MUF}-\hat{D})\ \Big|\ H_1 = \sigma_s^2\ (1 + c_o^2 k_1 - k_2) \tag{10}$$

Equations (3) and (4) are then solved for k_1. The equation to solve reduces to

$$m = t_o\ \sqrt{1+k_1-k_2} + t_1\ \sqrt{1+c_o^2\ k_1-k_2} \tag{11}$$

where t_o and t_1 are defined by

$$\frac{1}{\sqrt{2\pi}} \int_{t_o}^{\infty} \exp\ (-x^2/_2)dx = \alpha \tag{12}$$

$$\frac{1}{\sqrt{2\pi}} \int_{t_o}^{\infty} \exp\ (-x^2/_2)dx = \beta \tag{13}$$

Keep in mind that the variance of $(\text{MUF}-\hat{D})$ is limited by the systematic error variance, σ_s^2. It may not be possible to achieve the desired value for β, no matter how large the sample size. Thus, the "solution" of interest may well be a range of solutions derived from the relationship between β and k_1 (and hence n_{v2}), from which a tolerable sample size may be selected to result in an achievable β value.

Before calculating the sample size for the reference facility inspection, one additional result is needed. Once k_1 is determined, the sample size n_{v2} must be found. This is given by

$$n_{v2} = (\sum s_k)^2/k_1\sigma_s^2 \tag{14}$$

where s_k is the random error standard deviation of $\hat{D}$ per item measured by the inspection in stratum k.

Values for σ_s^2 and for s_k are now calculated. These quantities are affected by measurement errors for both the facility and the inspector. Facility measurement errors were given in Table 2.4. Inspector measurement errors are in Table 3.8. Systematic errors in sampling are not included in Table 3.8. It is assumed that the inspector uses the same material sampling procedures as the facility, and hence, commits the same systematic errors in sampling. It is also assumed that the analytical short term systematic errors for the inspector shift with the same frequency as those of the facility.

The systematic error variance of $\hat{D}$, σ_s^2, is given in Table 3.9. In Table 3.10, s_k is given for each stratum.

For M = 8 kg Pu for the twelve months material balance period, it is impossible to attain a value of 0.05 for β as specified by the technical objectives. Rather, for reasonable total sample sizes, the actual β for the (MUF-$\hat{D}$) test is generally in the 0.40 to 0.60 range, considerably short of the specification. In Table 3.11, β is given as a function of n_{v2}, the total sample size for variables inspection. Suppose that n_{v2} is set at 200. Then for a twelve month material balance, β = 0.395.

TABLE 3.8. Inspector Measurements (Relative Percent Errors)

	Stratum						
	1 PuO_2	2 Pellets	3 Scrap	4 Waste	5,8 Powder	6,9 Scrap	7,10 Swarf
Random							
Scale	.050	.075	.075	--	.050 .070	.050 .075	.050 .075
Material	.01	.80	3.5	--	.40	3.5	2
Analytical	.50	.70	1	40	1	1	.70
Systematic							
Scale	.03	.05	.05	--	.03 .05	.03 .05	.03 .05
Analytical	.12	.15	.20	15	.20	.20	.15
Short Term Systematic							
Analytical	.16	.20	.25	12	.25	.25	.20

TABLE 3.9. Systematic Error Variance of $\hat{D}$ (Kg^2 Pu)

Source	Contribution to Variance
Operator	5.7495
Inspector	
Scales	.9870
Analytical	8.4688
Short term Analytical	1.5146
**	.4442
Total σ_s^2	17.1341
σ_s	4.1393

**Contribution to systematic error from random components that do not decrease in size with additional inspection.

TABLE 3.10. Random Error Standard Deviation of $\hat{D}$ Per Inspected Item (s_k)

Stratum	s_k
1	5.5002
2	14.1758
3	1.8132
4	0.1789
5,8	1.1027
6,9	0.1607
7,10	0.0464
Total = s_k	24.2877

For n_{v2} = 200, the sample size allocation among the strata is given in Table 3.12. In comparing these values with those in Table 3.7, it is seen that the variables sample sizes are uniformly larger than the corresponding sample sizes when the variables tester is used in the attributes mode. Thus, using these larger values, the actual β for variables inspection in the attributes mode will be somewhat smaller than the design value of 0.05.

TABLE 3.11. β Versus Sample Size for (MUF-$\hat{D}$) Statistic

β	Sample Size
0.35	436
0.40	186
0.45	100
0.50	58
0.55	34
0.60	19
0.65	10

TABLE 3.12. Variables Inspection Sample Sizes by Stratum

β = 0.395 for a 12 Month Material Balance

Stratum	Sample Size
1	45
2	117
3	14
4	2
5	9
6	1
7	1
8	9
9	1
10	1
Total	200

Overall Detection Probability

Having found the inspection sample sizes needed to implement the inspection plan, the next step is to evaluate the overall capability of the material accountancy inspection approach to detect diversion of the goal amount, M. Various diversion routes are identified. Diversion of the goal quantity, M, may be accomplished by one or a combination of the following strategies:

1) diversion through large data falsifications (combatted by attributes inspection)

2) diversion through medium data falsifications (combatted by variables inspection in the attributes mode)

3) diversion through small data falsifications (combatted by the $\hat{D}$ statistic; variables inspection in the variables mode)

4) diversion into MUF (combatted by the MUF statistic).

The optimum strategy from the diverter's viewpoint is that mix of diversion routes that results in a minimum probability of detection or, alternatively stated, a maximum probability of non-detection.

To compute the detection probability, it is necessary to define detection. In this context detection is assumed to occur if one or more of the following happens:

1) At least one defect is found in one or more strata in attributes inspection with either the attributes or the variables tester.

2) The (MUF-$\hat{D}$) statistic exceeds its critical value.

It is simpler to compute the probability of nondetection. Let this be denoted by Q. Its maximum value is denoted by Q_{max} which is the probability of nondetection corresponding to the diverter's best strategy.

As previously indicated, an alternative approach to step 2) above is to first test the $\hat{D}$ statistic for significance and then test the MUF statistic for significance once it has been verified by the $\hat{D}$ statistic. Denote the probability of nondetection in this case by Q', with its maximum value denoted by Q'_{max}.

In Table 3.13, values of Q and Q' are given for a number of strategies. Also shown are Q_{max} and Q'_{max}. In these calculations, the value for β in the attributes inspection was somewhat arbitrarily set at 0.20 rather than 0.05. This is reasonable because with the variables β so much larger than 0.05, the effect on Q_{max} or Q'_{max} of performing the large numbers of attributes inspections needed to achieve an attributes β of 0.05 is negligible. For $\beta = 0.20$,

TABLE 3.13. Probability of Nondetection

a_2 = fraction diverted into large and medium falsifications
a_3 = fraction diverted into small falsifications
a_4 = fraction diverted into MUF

a_2	a_3	a_4	Q	Q'
1	0	0	0.190	0.190
0	1	0	0.385	0.536*
0	0	1	0.368	0.211
.5	.5	0	0.325	0.364
.5	0	.5	0.332	0.314
.3	0	.7	0.371	0.310
.3	.7	0	0.365	0.441
.7	0	.3	0.277	0.275
.7	.3	0	0.273	0.288
	Q_{max}		0.385	
	Q'_{max}			0.536

the number of attributes inspection measurements is reduced from over 1000 to around 650. Actually, β for attributes inspection could be made even larger without affecting Q_{max} or Q'_{max} in this instance. This will be illustrated later.

Effect of Improved Measurements

The measurement errors depicted in Tables 2.4 and 3.8 result in values of Q_{max} and Q'_{max} that are much larger than the goal probability of non-detection which is 0.05. The effect of reducing certain error standard deviations was considered. It is felt that the reductions discussed here are attainable in practice. Measurement error parameter values were changed as follows:

1) In Table 2.4, systematic error standard deviations for material sampling of pellets and scrap were changed from 0.10% and 1.5% to zero. With careful steps taken to insure representativeness of samples, by random selection processes and/or careful mixing of container contents, there should be essentially zero systematic error in sampling.

2) Also in Table 2.4, systematic errors in analytical for strata 1 and 2 were changed respectively from 0.07% and 0.12% to 0.035% and 0.06%. The systematic errors are largely limited by the adequacy of the reference standards. It is felt that improved reference standards will result in these smaller systematic errors in analytical.

3) Similarly, in Table 3.8, the systematic error standard deviations for analytical were halved, again assuming that improved reference standards can be developed.

The net effects of these changes in measurement errors are shown in Table 3.14. The variables sample size is still 200. Of particular interest is the last column of data, incorporating changes 1), 2), and 3) described above. Even for this case, however, Q_{max} is still much larger than the technical objectives specify. The cases in Table 3.14 are:

Case 1: base case

Case 2: case 1 + eliminate systematic errors in sampling

Case 3: case 2 + reduce facility systematic errors in analytical by 50% for primary flow streams

Case 4: case 3 + reduce inspector's systematic errors in analytical by 50%.

TABLE 3.14. Measures of Detection Capability with Improved Measurement Performance

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Sigma MUF (kg Pu)	2.962	2.497	1.714	(Same As Case 3)	(Same As Case 3)	(Same As Case 3)
Sigma MUF (% of throughput)	0.193%	0.163%	0.112%	(Same As Case 3)	(Same As Case 3)	(Same As Case 3)
σ_s (kg Pu)	4.139	(Same As Case 1)	3.720	2.736	(Same As Case 4)	(Same As Case 4)
σ_s (% of throughput)	0.269%	(Same As Case 1)	0.242%	0.178%	(Same As Case 4)	(Same As Case 4)
Sigma, $(\widehat{MUF-D}) \mid H_0$	4.048	3.721	(Same As Case 2)	2.738	(Same As Case 4)	(Same As Case 4)
β for $(\widehat{MUF-D})$	0.395	0.347	(Same As Case 2)	0.194	(Same As Case 4)	(Same As Case 4)
Q_{max}	0.385	0.344	(Same As Case 2)	0.260	0.192	0.374
Q'_{max}	0.536	0.537	0.481	0.341	0.332	0.416

(For 200 variables measurements)

For Cases 1-4, β for the attributes inspection is set at 0.20. Cases 5 and 6 are the same as Case 4 except that β for attributes inspection is 0.05 and 0.35 respectively.

Note that Cases 2 and 3 give the same results for Q_{max}. This is because the $(MUF-\hat{D})$ statistic is independent of systematic errors for the facility, given that such errors are not also committed by the inspector.

3.2 IMPACTS AND IMPLICATIONS

The previous section showed that under a range of groundrules and assumptions, the specified quantitative detection goals are not attained with a combination of conventional material accountancy and extended material accountancy (short detection time) techniques. Assuming good quality measurements and estimates at the time of the biweekly inventory check, an abrupt diversion of 8 kg plutonium can be detected with high probability within about two weeks. But diversions occurring over longer periods, and in particular a diversion of 8 kg Pu over a year's time, cannot be detected with the required high probability by material accountancy alone. The reason for the inadequate probability is the presence of limiting systematic measurement errors in the flow strata.

It should be mentioned on the other hand that in plants smaller than the reference case considered here the detection goals might be attainable. The mixed-oxide facilities at which IAEA safeguards are currently being applied are believed to have throughputs perhaps 1/2 to 1/3 as large as the reference case.(14)

Since the quantitative detection goals are not attained for some diversion strategies in the base case, the IAEA has suggested that (depending on the circumstances), "Additional containment and surveillance measures may be necessary to enable the inspectorate to detect the diversion of a significant quantity by application of a combination of measures." (Gruemm 1980). In Chapter 7, the potential role of extended containment and surveillance in mixed-oxide fual fabrication plants is discussed and some pertinent design considerations are addressed.

The rest of this section considers some of the other impacts and implications associated with the implementation of technically effective safeguards at mixed-oxide fuel fabrication plants.

3.2.1 Inspection Manpower

For the reference case considered in this study, routine inspections are estimated to require 700-900 man-days of inspection effort per year. (The terms "routine inspection" and "man-days of inspection" are formally defined in INFCIRC/153.) This total is broken down roughly as follows. In the base case, it is assumed that (at least) once a year a complete shutdown, cleanout physical inventory is conducted by the plant operator and verified by the IAEA. At a minimum, each such inventory would involve about 25 man-days of inspection effort, i.e., a team of five IAEA inspectors over a period of five days; a better estimate, allowing ample time for thorough application of necessary inspection procedures and follow-up actions would be somewhat higher: perhaps 35-40 man-days per physical inventory verification. In the base case we considered one physical inventory per year; in some instances, a physical inventory frequency of two or four per year might apply. Physical inventory frequencies are specified in the Facility Attachments negotiated between the IAEA and the State in which the facility is located.

Routine flow verification requires a very large inspection effort in the base case because of the need to maintain continuity of knowledge of flows, especially of product; essentially continuous presence is needed while the plant is operating. The precise number of man-days required would depend on plant operating schedules. For the base case, 250-300 man-days per year are estimated.

For the short detection time inspection activities an estimated 400-500 additional man-days would be needed. In the next section, some details concerning this estimate are provided.

For purposes of comparison, it is noted that the maximum routine inspection effort (MRIE) as defined in INFCIRC/153 would be about 1175 man-days for the reference facility.

3.2.2 Calculation of Short Detection Time Inspection Effort

This section describes a methodology for calculating the effort necessary for implementing the previously described short detection time inspection plan and gives the results for the base case. A sensitivity analysis is also presented.

The total short detection time inspection effort (man-days/year) is subdivided into effort for primary activities, E_1, and effort for secondary activities, E_2. The total effort E is calculated as follows:

$$E = n_1E_1 + \varepsilon_1E_2$$

where n is the number of primary short detection time inspections per year and ε_1 is the expected number of false alarms per year resulting from primary inspections.

The effort for a short detection time inspection, either primary or secondary, is required to perform the following activities:

- accessing the area containing a material form
- securing the areas containing similar material form until the total amount of that form has been verified (this is done to prevent possible shuffling of material)
- verifying seals on containers that were already in the storage area
- NDA measurements on containers that have been transferred between storage and process
- applying seals to containers that have been transferred to the storage area
- estimating the amount of the various material forms in the process area.

Accordingly, the following general equation has been applied for the calculation of the effort required for an individual surveillance inspection:

$$E_s = \sum_{i=1}^{N_f} E_{Acc}\, N_a^i + \sum_{i=1}^{N_f} E_{Sec}(N_a^i - 1) + \sum_{i=1}^{N_f} \Big(N^i_{\substack{Seal\\Ver}}\, E_{\substack{Seal\\Ver}} +$$

$$N^i_{Meas}\, E_{Meas} + N^i_{Tr}\, E_{\substack{Seal\\Appl}}\Big) + \sum_{i=1}^{N_f} E^i_{Proc}$$

where the symbols have the following meanings:

N_f = Number of material forms

N_a^i = Number of areas containing form i

E_{Acc} = Effort for accessing area

$N^i_{\substack{Seal\\Ver}}$ = Number of containers in storage areas for which seals must be verified (Form i)

N^i_{meas} = Number of measurements on containers transferred (Form i)

N^i_{Tr} = Number of containers transferred between process and storage during period (Form i)

$E^i_{\substack{Seal\\Ver}}$, E_{Meas}, $E_{\substack{Seal\\Appl}}$ = Effort for verification of seals; measurement; and application of seals

E^i_{Proc} = Effort for estimating amount of Form i in process area.

Seals are verified and measurements on the transferred containers are made according to a sampling plan. For example, the number of seals verified is calculated with the equation:

$$N^i_{\substack{Seal\\Ver}} = N^i_{Sto}\left(1 - \beta^{\frac{1}{N^i_r}}\right)$$

where N^i_{Sto} is the number of containers of Form i in storage, N_r is the number of containers that must be removed to obtain a significant amount and B is the non-detection probability desired.

The input data are uncertain, and estimates, based on informed judgment have been used for the individual components of the effort and for the relative uncertainties. The results of the calculations for the base case indicate manpower requirements for the short-detection time approach in the range of 400 to 500 man-days.

Besides the bi-weekly material balance check, the short detection time approach requires frequent inspector presence to maintain records related to internal flows, apply seals to containers transferred to storage, make NDA measurements on selected containers transferred from process to storage, etc.

In order to investigate the sensitivity of short detection time manpower requirements to modifications of the parameters and assumptions of the base case, some sensitivity analyses were performed. In this section, effects of changes in the following parameters are presented:

- inventory
- process inventory
- goal detection probability
- NDA measurement uncertainty
- container size.

Variation of Inventory

Figure 3.1 shows the sensitivity of the short detection time inspection effort to the size of the inventory (that is, items in storage). Increasing the inventory results in increased effort, due to the need for larger sampling plans.

Variation of Process Inventory

Figure 3.2 shows the variation of the inspection effort when the in-process inventory is halved or doubled. It can be seen that there is a significant variation in effort.

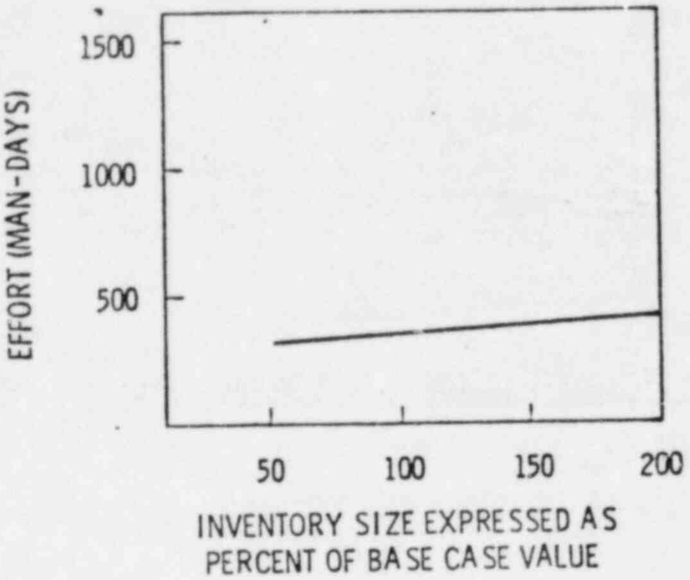

FIGURE 3.1. Sensitivity of Short Detection Time Inspection Effort to Inventory Size

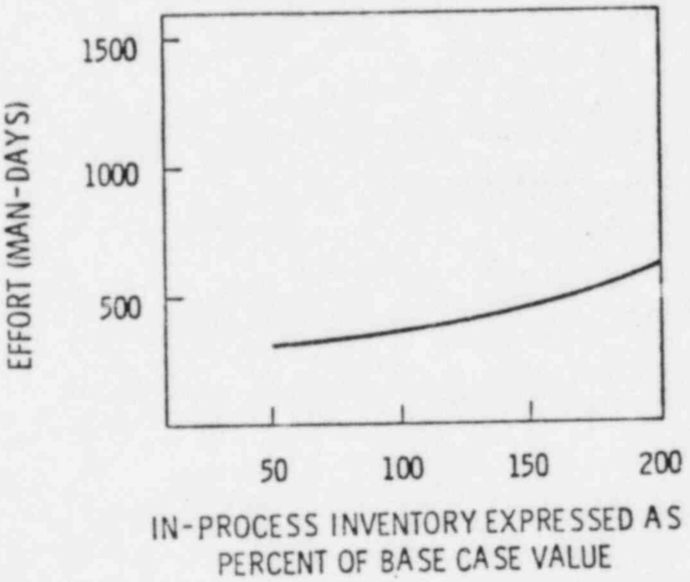

FIGURE 3.2. Sensitivity of Short Detection Time Inspection Effort to In-Process Inventory

Variation of NDA Measurement Uncertainty

Figure 3.3 shows the variation in short detection time activities effort when the NDA uncertainty is reduced or increased by a factor of 2. The effort for primary activities does not change; however, the total effort increases because the number of false alarms increases.

Variation of Container Size

Figure 3.4 shows the variation in total short detection time activities effort when the container size is reduced or increased by a factor of 2. The effort varies in this case because the size of the sampling plans varies with the container size.

Sensitivity of Manpower to Throughput

The throughput of the MOX plant has been varied between 500 and 3000 kg of Pu per year. The effect of this variation on the short detection time effort is illustrated in Figure 3.5. The curve indicates a non-linear increase of manpower requirements as a function of throughput. This is mainly caused by the increase in the number of false alarms and added effort for secondary verifications.

3.2.3 Equipment Requirements

The equipment required to implement the safeguards approach assumed in this study is available today, although it is not necessarily in routine use by the IAEA. Costs of several key instruments are estimated as follows:** A high level neutron coincidence counter (HLNCC) costs about $50,000 per unit. A SILENA multichannel analyzer with germanium detector is $17,000. The SAM-II or BSAM for qualitative gamma ray surveys is about $10,000. Inspectors also would want to make use of the facilities' rod scanner, and for this purpose a set of independent fuel rod standards would be needed (estimated cost: $20,000-$30,000). The inspection approach assumes the availability of an on-site minicomputer for the inspector. Such computers are relatively inexpensive (a few tens of thousands of dollars, depending on the specifications); but the

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** Cost data obtained from Higinbotham, 1981.

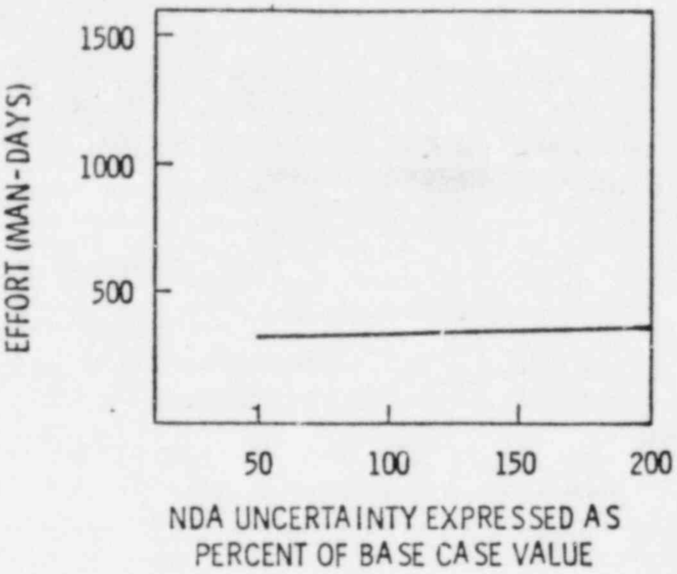

FIGURE 3.3. Sensitivity of Short Detection Time Inspection Effort to NDA Uncertainty

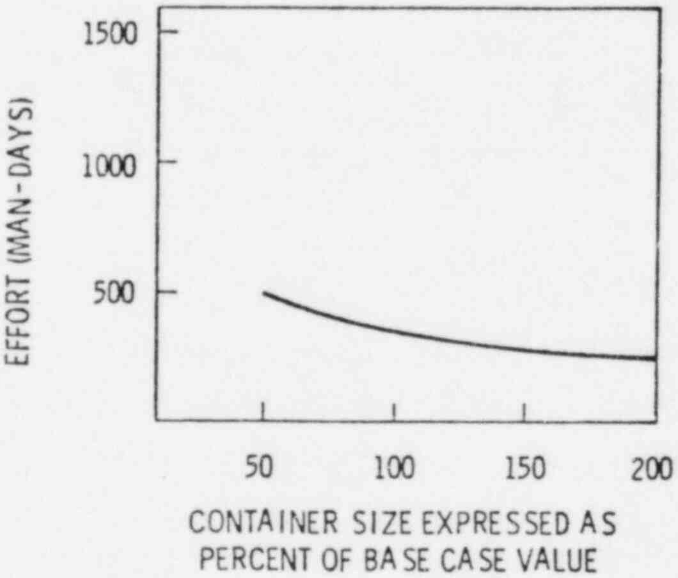

FIGURE 3.4. Sensitivity of Inspection Effort to Container Size

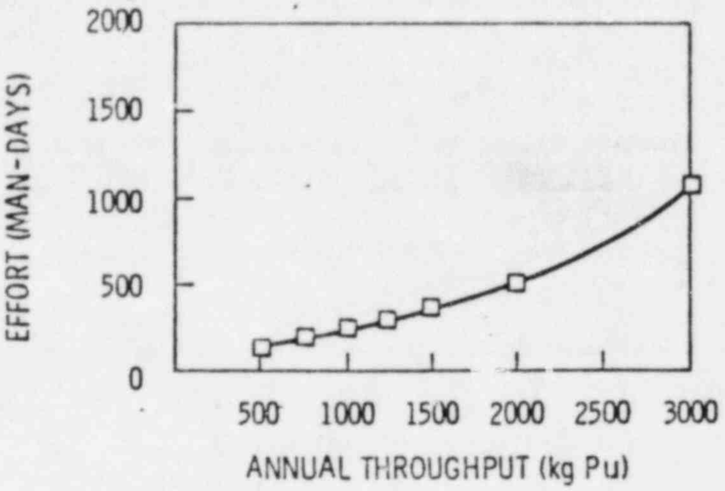

FIGURE 3.5. Sensitivity of Inspection Effort to Annual Throughput

development (software) costs associated with such systems are higher than the hardware costs. The IAEA is just beginning to acquire such computers and several years of developmental work will probably be needed before minicomputers can be used routinely. Another point that must be mentioned in this regard is that additional training of inspectors will be needed to ensure that the computers can be used effectively. At present, only a limited number of inspectors have experience with computers.

4.0 IDENTIFICATION OF PROBLEM AREAS

From the baseline analysis, the following conclusions are noted:

- For small facilities with throughputs on the order of 500 kg Pu per year (i.e., comparable in size to some facilities at which IAEA safeguards are currently applied), the quantitative detection goals postulated for this study can be attained. However, the inspection resources needed to attain the goals are considerable.
- For medium-sized facilities of about 1500 kg Pu per year throughput both the conventional accountancy for the detection of protracted diversion and the short-detection time accountancy for the abrupt diversion can meet the goals under the assumptions described in this report. As in the previous case, considerable inspection resources are necessary.
- In large future plants with throughputs of 8,000 to 10,000 kg Pu per year, it becomes increasingly difficult to satisfy the quantitative detection goals and some type of supplemental surveillance will probably be required if the desired levels of technical effectiveness are to be achieved. The costs and other impacts associated with effective safeguards are likely to be substantial.

These problems, and the role that design features may play in alleviating them, are discussed in the next three sections. Section 4.4 discusses a diversion path analysis (DPA) carried out for a mixed-oxide fuel fabrication plant and the implications of the DPA for the current study of design features are noted.

4.1 SMALL MOX FABRICATION FACILITIES OF UNDER 500 KG OF PU PER YEAR THROUGHPUT

A safeguards approach based on the combination of conventional accountancy and short detection time strategy can satisfy quantitative detection goals. The required inspection effort is large but is probably acceptable. These results are in part due to the following: 1) such facilities contain small inventories including small in-process inventories; and 2) the problem of measuring and counting the material is relatively easy since most operations are performed in glove boxes and materials are largely stored in discrete containers.

Some improvements in the safeguards of these plants could be achieved by implementing suggestions for the near-term design features listed in Appendix A.

4.2 MID-SIZE MOX FUEL FABRICATION FACILITIES (1500 KG OF PU PER YEAR THROUGHPUT)

In the medium size plants, the short-detection time safeguards concept for detecting abrupt diversion approaches the limits of practicality: to achieve 95% detection probability with 5% per year alarm rate, it is necessary to measure a large number of items with a high degree of precision. The in-process inventory also must be measured because unlike the situation in smaller facilities, it cannot be included as a part of measurement uncertainty. These conditions result in the need for both extensive quantitative NDA and a large inspection effort.

The reference facility was assumed to be constructed and operated in a manner similar to the existing smaller facilities. Contact operations are carried in glove boxes and most of the nuclear material is in the storage vault. Only a small amount of nuclear material is assumed present in the process area.

Two design features of future plants could make the application of short-detection time safeguards more difficult: 1) implementation of canyon-type construction, with the remote handling of materials; and 2) use of pneumatic systems for transfer of powders between process steps.

In facilities designed for remote canyon-type operation, for reasons of safety, radiological protection of workers, or environmental requirements, access to materials will be more difficult and will require additional time expenditure by the inspector. These problems are discussed in Chapter 6.

In facilities employing a pneumatic transfer system, additional bulk storage equipment such as silos or hoppers may be required for intermediate storage. This additional equipment need creates greater demands on the measurement strategies of bulk materials. The feasibility of short-detection time safeguards for such a system has not been investigated in this study.

4.3 LARGE-SIZE MOX FUEL FABRICATION FACILITIES (8000 KG TO 10,000 KG OF PU PER YEAR THROUGHPUT)

In large facilities which might be considered in the future, neither conventional accountancy nor short-time detection inspection activities appear to be practical means for meeting quantitative detection goals for protracted and abrupt diversion.

Larger facilities probably will be constructed for remote in-canyon processing, with large amounts of materials in intermediate storage between process steps. Extended surveillance may be required to supplement accountancy and is discussed in Chapter 7.

4.4 PROBLEMS IDENTIFIED VIA DIVERSION PATH ANALYSIS

A detailed diversion path analysis (DPA) of a 500 kg Pu per year throughput MOX fuel fabrication facility was performed recently as a part of safeguards evaluation methodology development tasks. The details are described in the report entitled "Case Study: Application to Mixed Oxide Fuel Fabrication Facility"(1). Because of the similarities to the reference plant of this study, the results of that diversion path analysis were reviewed to obtain an insight to potential vulnerabilities of the baseline safeguards system.

Figure 4.1 shows a tree representing the fabrication facility, with three branches indicating each of the three major locations or MBAs, and limbs from each branch representing the target material at each location and the removal paths. Solid lines indicate the target/path sets that were analyzed and dotted lines indicate those not analyzed. The logic used in excluding path sets was primarily that another path set was protected by the same safeguards and therefore the DPA of the remaining sets would still identify all vulnerabilities.

The diversion path vulnerabilities for abrupt diversion are summarized below for each of the MBAs and according to the expected level of technical complexity for its implementation. A technical complexity of A is assumed to be the easiest for the facility to perpetrate while a technical level of C is considered to be the most difficult.

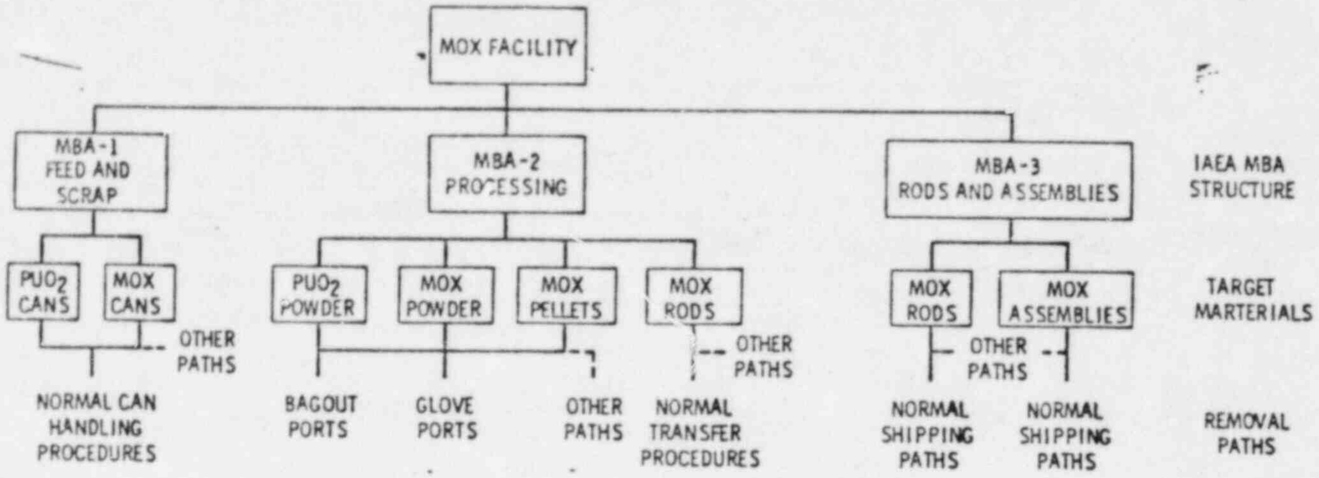

FIGURE 4.1. Tree Showing Diversion Paths for MOX Fabrication Facility

4.4.1 Feed and Scrap Storage (MBA-1)

1-A With less than 100% flow verification between MBAs 1 and 2 material can be diverted and documents issued to show transfer into MBA 2. Diversion detection is dependent on detection of MUF in bulk handling area. (Difficulty level A)

1-B Tampering or counterfeiting IAEA seals or bypassing the seal by drilling containers, etc., leads to paths that may not be readily detected. (Difficulty level B)

4.4.2 Processing (MBA-2)

2-A With high throughput, substitution of inert materials (dilution of Pu with natural uranium) would be difficult to detect. (Difficulty level A)

4.4.3 Rods and Assemblies (MBA-3)

3-A Removal of inner rods from assemblies during fabrication would be difficult to detect. (Difficulty level A)

3-B Tampering with or counterfeiting IAEA seals on completed assemblies and either substituting dummy assemblies or removing material from assemblies may not be readily detected. (Difficulty level B)

5.0 IDENTIFICATION OF DESIGN FEATURES

A two-stage precedure is used to identify design features. In the first stage, the analysis concentrates on identifying design features associated with material accountancy. The aim is to find possible ways of improving the low detection probabilities for protacted diversion, as described in Chapter 3.

The second stage in the process of identifying design features involves a broader look at a wide range of design features associated with short detection time safeguards and containment and surveillance in addition to the design features associated with material accountancy.

5.1 DESIGN FEATURES ASSOCIATED WITH MATERIAL ACCOUNTANCY

As used in this study, "design features" is a rather broad term intended to encompass not only changes in physical design but also process and procedural changes. Furthermore, it includes such changes for the inspector's part of the safeguards system as well as the facility operator's part. In this section the emphasis is on procedural changes - those that in some way relate to the measurements performed by the facility operator and/or by the inspector.

A listing of candidate design features is given below. Screening and evaluation of the design features are described in Chapters 6 and 7. There is no particular significance to the ordering of the list. The features are numbered for later reference.

5.1.1 Facility Design Features

F-1: Minimize scrap holdings by having scrap reprocessing capability on site.

F-2: Provide alternate packaging schemes for solid wastes to permit more accurate measurement of plutonium content in such wastes.

F-3: Perform selected replicate measurements. This could involve the use of additional scales, replicate samples, replicate analyses with possibly different analytical techniques, etc.

F-4: Perform frequent calibrations to reduce the effect of short-term systematic errors.

F-5: Install parallel process lines.

F-6: Alter the process to minimize the amount of scrap and waste generated.

F-7: Make use of the calorimeter in assaying for plutonium.

F-8: Supplement the product measurement by using a rod scanner to measure the fissile content of the fuel rods.

F-9: Design the facility to minimize the amount of holdup, especially after a cleanout inventory.

Use the same analytical method for measuring the input and output product streams for percent plutonium.

5.1.2 Inspection Design Features

I-1: Same as F-3.

I-2: Same as F-4.

I-3: Same as F-7.

I-4: Use the rod scanner to verify the fissile content in fuel rods.

I-5: Make a large number of inspection measurements by NDA; reduce the systematic error by calibrating against comparison samples whose plutonium contents are more accurately determined by destructive analysis.

I-6: Same as F-10.

I-7: Perform duplicate analyses of important inspection samples, spreading out the measurements in different time frames in order to reduce the effects of short-term systematic errors.

5.2 IDENTIFICATION OF ADDITIONAL DESIGN FEATURES

The design features described in this section provide concepts for plants up to the size of the reference plant (i.e., about 1500 kg Pu per year). Design features that might be required for implementation of extended surveillance in future large plants (8,000 to 10,000 kg Pu per year) are discussed briefly in Chapter 7.

The design features described in this section are aimed at satisfying the following functional requirements:

1. Features that enable accurate NDA measurements during bi-weekly inspections in the process area and thus increase the effectiveness.
2. Features that minimize requirements for inspection effort, especially those associated with short detection time approach.
3. Features that eliminate vulnerability to the concealment of diversion from finished fuel assemblies.

The features described in this section are applicable in general to facilities designed for contact and glove box operations. The inspector is assumed to have access to, and is able to perform measurements on, materials stored in vaults, buffer storage and in the in-process equipment which has sufficiently small volume for him to witness run-out. As discussed subsequently in Section 7, these features are also applicable to remote in-canyon type process operations. Canyon-type construction is most likely to be used in facilities much larger than the reference plant although the possibility of applications in medium-size facilities should not be entirely excluded.

Table 5.1 below summarizes the design features described in this section.

TABLE 5.1. List of Candidate Design Features

Identifier	Design Feature	Purpose
DF-1	Features minimizing amount of material in the process equipment	Improve effectiveness Reduce inspection effort
DF-2	Containerized transfer between process steps	Improve effectiveness Reduce inspection effort
DF-3	Quarantined receiving area	Reduce inspection effort
DF-4	Walk-through vault	Reduce inspection effort
DF-5	Transportable inspection stations	Reduce inspection effort
DF-6	Multi-tray sealable containers for pellet trays	Reduce inspection effort
DF-7	Quarantined rod storage area	Reduce inspection effort
DF-8	Assembly area designed for containment and surveillance	Reduce inspection effort Eliminate vulnerability to substitution concealment
DF-9	Tamper-indicating sealable assembly container	Eliminate vulnerability to substitution concealment

5.2.1 Features Minimizing the Amount of Material in Process Equipment (DF-1)

The objective of these features is to enable the inspector to accurately verify the amount and composition of material in the process equipment and to be able to accomplish this in the time available.

The equipment may include blenders, mills, press feeders, etc. It should be designed with minimum volumes; containing not more than several kilograms of Pu at any one time.

To safeguard the material in process equipment one of the following approaches may be considered:

1. Measuring the amount and the composition of material in the process equipment.
2. Waiting for the equipment involved in a particular process step to be run-out and then performing the measurement.
3. Providing containment and surveillance for the process area.

It appears that alternative 2 is the most direct approach. With the equipment designed for small capacity the duration of any process step should not exceed more than several shifts, i.e., a period much less than even a periodic presence of the inspector in the facility.

Alternatives 1 and 3 appear to be more difficult to implement and have not been considered in this study.

To maintain high production levels with small volume process equipment it is expected that high utilization rates might be required. To assure adequate reliability of these operations redundant equipment might be introduced. Redundant equipment not in use would be sealed empty by the inspector.

5.2.2 Containerization of Transfers Between Process Steps (DF-2)

For the efficient performance of short detection time tasks most of the material present in the facility should be in discrete containers which can be measured or seal-checked. Therefore the facility equipment and operations should be designed in such a way that the transfers between the process steps are in containers. The output from one process step (e.g., Pu blending) is processed into containers that are passed into storage. The input for the next step (e.g., Pu-U mixing) is obtained from the storage. In this way an unambiguous record of all transactions can be available to the inspector. This is especially significant in verification of materials, such as clean scrap, that were recirculated for rework. This arrangement is shown schematically in Figure 5.1.

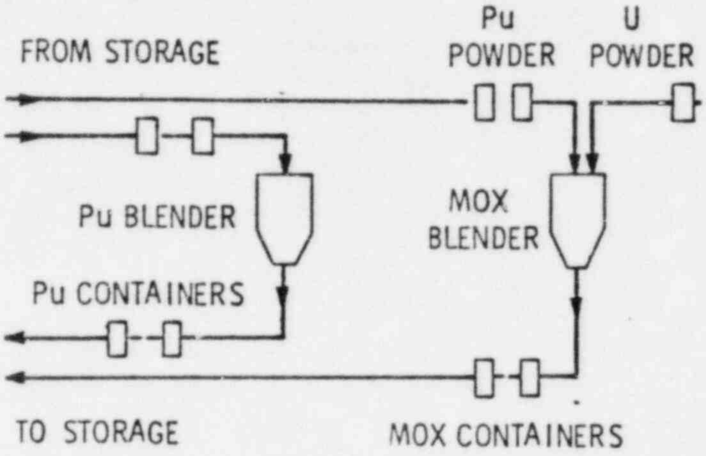

FIGURE 5.1. Containerized Transfers Between Process Steps

The size of the containers should be designed to achieve a compromise between several conflicting requirements: 1) large size is preferable to minimize amounts of inspection effort in performing the counting and measuring tasks (see Figure 3.4 and discussion in Chapter 3); 2) the size of the containers must not exceed the capacity of NDA equipment; 3) criticality requirements and facility operational requirements must be considered.

5.2.3 Quarantined Receiving Area (DF-3)

To avoid the need for a resident inspector in the receiving area for the verification of receipts, a concept of a quarantine for the temporary retention of these receipts is proposed. The incoming containers will be retained until the arrival of the inspector for periodic facility inspections. The transfer to the permanent storage will be performed after verification of the contents and sealing of the containers.

Both the quarantined material and the material in permanent storage could be kept in the same vault, but separate areas should be designated to make the process of transfer to permanent storage more efficient.

If the shipped containers are sealed, e.g., when the shipping facility is under safeguards, the verification activity prior to transfer from the quarantine consists of checking the integrity of the seal and the container and item identification.

If the facility receives containers which are not sealed, their contents must be verified by measurements.

Figure 5.2 shows the functional relationship of the activities involved in the quarantined receipts concept.

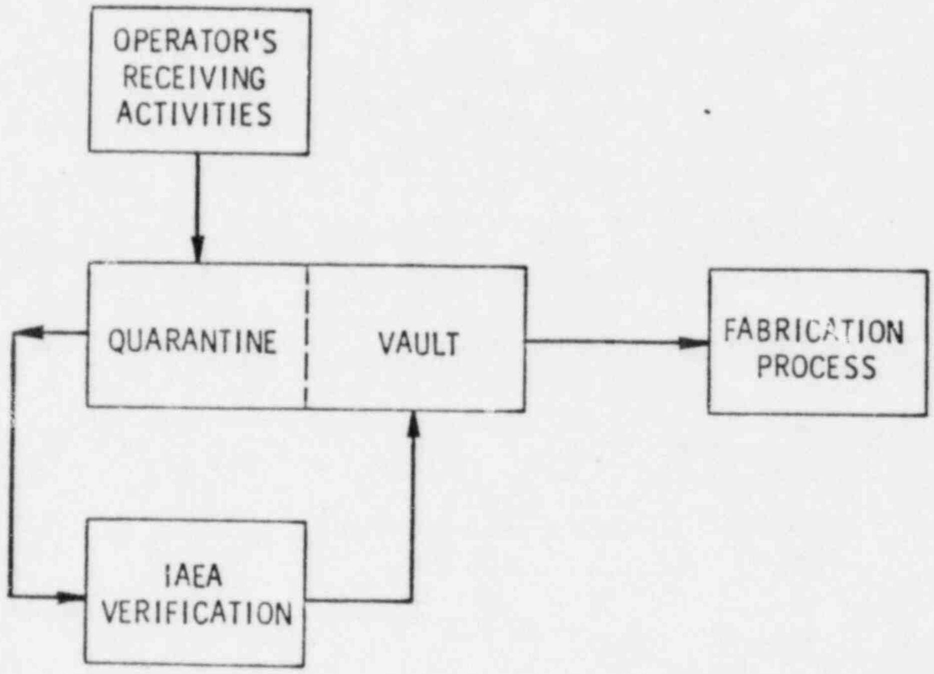

FIGURE 5.2. Schematic of Quarantined Receipts

5.2.4 A Walk-Through Vault for Rapid Seal Verification (DF-4)

In order to minimize inspection effort for the items stored in the vault, the inspector must be able to quickly verify the integrity of seals and stored containers and to retrieve other containers for NDA. There might be several hundred items requiring verification at any one time, such as cans, trays, buckets, etc. It would be desirable to achieve a rate of 1 to 2 minutes per seal and 10 to 20 minutes per verification. For this purpose these items must be stored in such a way that there is hands-on access to the material without requiring the use of remote handling equipment. This implies that the inspector must be able to carry out a walk-through inspection of the vault.

The feasibility of such a design has not been analyzed in this study, but there are no apparent obstacles why adequate compartmentalization and shielding cannot be provided to achieve this objective.

5.2.5 Transportable Inspection Station (DF-5)

In order to implement required NDA testing of containers in storage in sufficiently short time, a relatively rapid rate of 10 to 20 minutes/container may be required. This could be achieved if the inspector could perform his task in a transportable inspection station available to him at the point where inspections are performed. The station would contain all the necessary NDA, utilizing both neutron and gamma ray techniques (e.g., HLNCC, rod scanner), as well as weighing scales. The sensing devices will be permanently installed within the station. The station will also contain remote manipulators or glove ports to provide suitable means for item handling. It will be located on a movable carriage and coupled with a quick disconnect to containment penetrations. The interfacing penetrations will be located at suitable strategic locations for easy access to stored materials.

An important feature of the inspection station is that the measuring and computational processes can be automated. Suitable computer hardware and software should be developed for this purpose.

5.2.6 Multi-tray Sealable Containers (DF-6)

The large number of pellet boats and trays (up to 3000 in storage and possibly up to 1000 in buffer storage), each containing several hundred pellets, produces excessive requirements on the verification effort, since each would have to be visually inspected and counted. A fraction would be weighed and gamma counted.

A potential approach that would reduce effort requirements is to devise a container in which a number of individual trays would be stacked vertically and sealed until required for use in the succeeding process step.

There are two possible approaches that should be considered:

1. The inspector verifies a sample of pellets from individual trays. If no anomalies are found, the entire set of trays is accepted and placed in the container. The container is then sealed.
2. The pellet trays are stacked in the container and the container is sealed during the manufacturing process. The container geometry is designed in such a way that its contents can be verified by NDA.

The second approach is preferable from the point of view of expediting inspection processes. The feasibility depends on the ability to integrate the design of trays, the multi-tray containers, handling equipment and NDA equipment, to produce a unified system for expediting the verification process.

The concept may require inclusion of innovative ideas such as circular boats and trays for the pellets (instead of conventional rectangular shapes) so that the multi-tray stack can be placed easily in the well of HNLCC for verification. This is shown in Figure 5.3.

5.2.7 Quarantined Rod Storage Area (DF-7) and Assembly Area Design for Application of C/S (DF-8)

The purpose of these features is: 1) to eliminate the need for the continuous presence of the inspector in the rod manufacturing area by establishing rod quarantine, 2) to eliminate the vulnerability to undetectable substitution of inner rods in the assemblies by establishing containment and surveillance of the assembly manufacturing area. This is shown in Figure 5.4.

5.2.8 Quarantined Rod Storage Area (DF-7)

The quarantined area is located between the rod manufacturing and the assembly manufacturing area and contains racks for rod storage. The inspector's functions in the rod manufacturing and quarantine areas include the following:

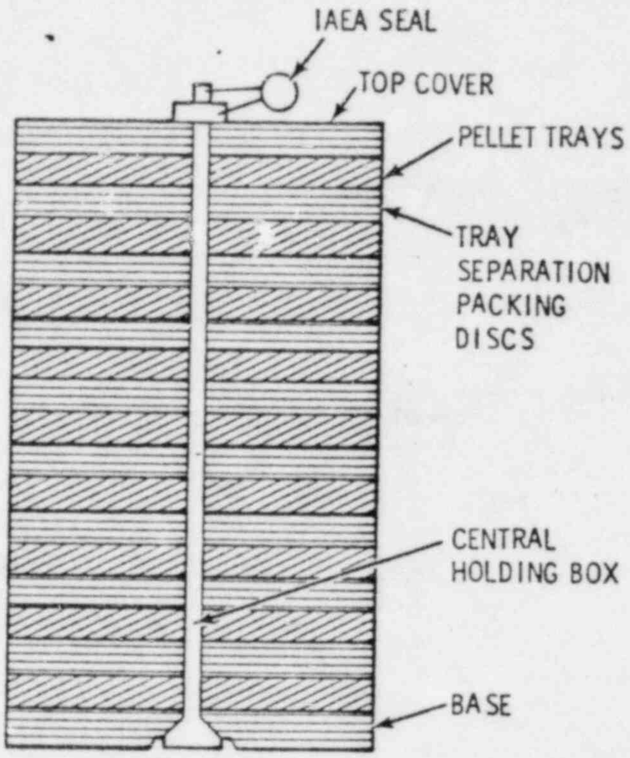

FIGURE 5.3. Multi-tray Pellet Container

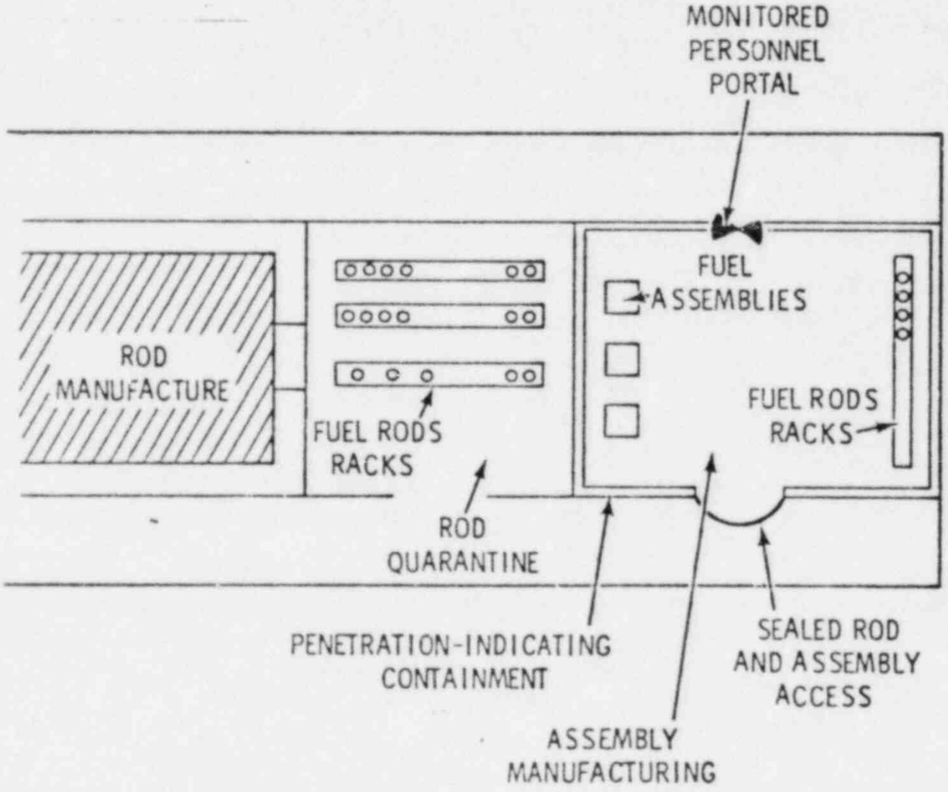

FIGURE 5.4. Rod and Assembly Manufacturing Area for Containment Surveillance

1) He performs attribute tests on a sample of pellets and verifies total content of Pu by tray counting (partially filled rods are not inspected and are considered an unmeasurable portion of the inventory); 2) He performs a NDA verification of a sample of rods and counts the rods in the quarantine. He seals the verified batch for subsequent transfer to the assembly containment area.

5.2.9 Assembly Area Design for Application of C/S (DF-8)

The assembly manuracturing area includes the following features: 1) The area is enclosed by a penetration-indicating containment, e.g., constructed of interlocked glass panels, 2) A single access in provided for the transfer of rods and assemblies: this is under IAEA seal and can only be used during the inspector's presence; 3) Access for the working personnel is provided through a monitored portal. The portal may include additional geometrical constraints which would prevent removal of full length rods or assemblies; 4) Surveillance cameras for area surveillance may be installed to provide additional assurance that rod disassemblies have not been carried out.

The inspector's activities in this area include the following: 1) Visual inspection of finished assemblies and counting all of the rods both finished and [illegible] the assemblies which are not in containers; 2) Verficiation of seals on the assemblies in containers; 3) Witnessing of placement of new assemblies in containers and sealing them; 4) Removing the seal from the materials access port and observing the transfer of finished assemblies out and transfer of verified rod batches into the containment; 5) resealing the materials access port; 6) Reviewing of surveillance data and verifying containment integrity.

5.2.10 Verifiable Assembly Containers (DF-9)

The concept of applying containment and surveillance to the assembly manufacturing area, as described above, provides assurance that no diversion was made from the fuel placed in the shipping containers and sealed by the inspector.

However, after the removal of the containers from the assembly area, they are outside of the surveillance system. Since no practical methods are currently in routine use for verifying the content of a finished MOX fuel assembly, there is a need for an assembly container with integrity which could be easily ascertained. A possible solution to this problem involves designing a seamless container which has a coating that retains permanent markings of tools such as saws, drills, flame cutting, etc. There are a number of such coatings commercially available, e.g., anodizing, enameling, etc. The surface should be able to resist being marked in handling. Adequate protection could be provided during handling activities including transportation to minimize damage to the container surface.

6.0 SCREENING OF DESIGN FEATURES

In the preceding section, a number of design features were identified that might conceivably facilitate IAEA safeguards by enhancing their effectiveness, their efficiency, or both. Before proceeding to a quantitative evaluation of the design features, it is useful to take a brief qualitative look at some of them to decide whether they warrant a detailed evaluation. It may be possible in this way to eliminate from consideration some candidate features that are clearly unattractive for one reason or another. The quantitative evaluation can then concentrate on the more interesting design features.

The design features described in Chapter 5 were subjected to such an initial screening. All of the design features in Section 5.2 were retained for quantitative evaluation. However, some of the design features in Section 5.1 (those associated with material accountancy) were eliminated from further consideration as a result of the qualitative screening process. The following comments discuss this screening process.

6.1 QUALITATIVE DISCUSSION OF CANDIDATE DESIGN FEATURES ASSOCIATED WITH MATERIAL ACCOUNTANCY

F-1: The effect of this design feature is to delete the output stream of scrap shipped offsite, stratum 3 in the base case. To make a reasonable material balance, the plutonium in that stratum is made a part of the product stream. This feature is included in the further evaluation.

F-2: The measurement of the solid waste contributes very little to the variance of MUF, so this design feature is not needed. It is excluded from further evaluation.

F-3: This design feature is included in the further evaluation. Specific instances where replicate measurements are made will be identified.

F-4: Calibrations are already performed monthly in the base case. Although one could theoretically reduce the variance of MUF by more frequent calibrations, it is judged that monthly calibrations already are at the limit of acceptable practice. This feature is excluded from further consideration as being not practicable to implement.

F-5: The installation of parallel process lines proved to be a significant feature in an earlier study of design features for reprocessing plants. This was because the variance of MUF was influenced to a great extent by systematic errors in bulk measurement of the major flow streams. This is not true for the reference MOX fuel fabrication facility, and parallel process lines would accomplish very little in increasing the probabiliy of detecting <u>protracted</u> diversion. This feature is excluded from further consideration.

F-6: Although not explicitly called out, an inherent feature of the facility in the base case was that the process generated minimal amounts of scrap and wastes. In particular, as seen from Table 2.3, only 400 grams of plutonium waste are assumed to be generated, a characteristic of very clean operation. Actually, the amount of waste could <u>increase</u> by a fair amount without impacting to any degree on the variance of MUF, so further reduction of waste is not only unreasonable, it is not necessary. This design feature is excluded from further evaluation.

As a related comment, the process assumed for the reference plant is the standard pelletizing process. Studies have been and are being made of alternate processes that could have safeguards advantages (among other advantages). Examples include the Sphere Pac [8] and Cogepel [9] processes. The time available for this study of design features did not permit a detailed evaluation of such alternative processes. They were excluded from this study on the basis of the time constraint, and not because it can be assumed a priori that their impact on detection probability would not be appreciable.

F-7: Calorimetric assay is an NDA method. Its principal benefit, if any, would be derived from its use as an inspection measurement. In that connection, it is a part of design feature I-5. Its use by the operator is not considered further.

F-8: The final precise and accurate measure of the facility product comes from weighing the pellets into the rod and using factors based on destructive measurements to determine the plutonium content. The rod scanner from the facility standpoint provides a quality control measurement, and not an accountability measurement. As a facility design feature, it is excluded from further consideration.

F-9: It is inherently assumed in the base case that the facility has already been designed to minimize holdup. The residual holdup at the inventory time is assumed to be very small and is part of the MUF since it is not measured in any sense. This feature is excluded in the further evaluation.

F-10: This design feature can have potentially significant impact because it permits at least partial cancellation of systematic errors in analytical for the input and product streams. It is included as a design feature for further evaluation.

The following comments apply to the proposed inspection design features.

I-1: This design feature, which calls for replicate measurements, is included in the final evaluation. Specific instances where replicate measurements are made will be identified.

I-2: The discussion under F-4 is generally applicable here also. The more frequent calibrations are excluded from further study.

I-3: As discussed under F-7, calorimetric assay is an NDA measurement that may be used by the inspector. Its potential use is discussed under I-5 which deals with NDA measurements in general.

I-4: The rod scanner as used by the inspector provides a valuable verification measurement. Its real use, however, is limited to attributes measurements, and the data generated by the rod scanner are not included in the $\hat{D}$ statistic. It is assumed that the rod scanner is utilized by the inspector in attributes testing for the base case as well as for other cases that will be studied. Further quantitative evaluation of this design feature is not included.

I-5: This design feature, which utilizes a relatively large number of NDA measurements and calibrates them against a smaller number of results based on destructive analyses to reduce the effect of systematic errors that normally limit the effectiveness of NDA measurements, sounds very attractive on the surface. However, a closer look at this design feature points out a fallacy in this reasoning. (This discussion relates to NDA measurements as being a part of the $\hat{D}$ statistic, and not to their use in attributes testing. It is assumed in the base case that NDA measurements will be used by the inspector in this latter capacity.)

The fallacy in the use of NDA data as variables data is that it would be calibrated against the smaller amounts of destructive analyses data, where the destructive analysis plays the role of a "known" standard to be used in bias-correcting the NDA results. When correcting for bias, the uncertainty in the standard becomes a part of the systematic error in the bias-corrected results. This uncertainty in the standard is affected by the errors in the destructive analyses--random, short-term systematic, and long-term systematic. Thus, although the use of the destructive analyses to bias-correct the NDA results would normally reduce the systematic error in the NDA results, it would not reduce it below that associated with the destructive analyses results. The net effect is that one does just as well (in fact, slightly better) with a relatively small number of bias-corrected NDA results. Thus, although NDA is retained as an attributes measurement tool in detecting protracted diversion, the data generated thereby will not be incorporated in the $\hat{D}$ statistic. This "promising" design feature is excluded from further consideration.

I-6: The comments under F-10 apply here also. This design feature, which utilizes the same analytical technique for verification measurements of facility input and product, is retained for further evaluation.

I-7: This design feature would be a reasonable and relatively simple one to incorporate if effective. It calls for providing replicate analyses of inspection samples of the principal flow streams, and performing these analyses in different time frames (i.e., under different calibrations) to reduce the efforts of short-term systematic errors in analytical. Such a feature would not be reasonable for the facility where results must be booked as soon as available, but the inspection samples of the flow streams, while taken over the entire year, are not utilized in the $\hat{D}$ statistic until the material balance is closed. Thus, sample retention for later analyses is feasible. The design feature is retained for further study.

In summary, the following design features are retained for further evaluation.

Facility	Inspection
F-1	I-1*
F-3*	I-6
F-10	I-7

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*The replicate measurement general design feature will have specific features that will be identified.

7.0 EVALUATION OF DESIGN FEATURES

The evaluation of design features proceeds in two stages. First, in an attempt to assess possibilities of improving the effectiveness of material accountancy with respect to protracted diversion, the design features associated with material accountancy (described in sections 5.1 and 6.1) are evaluated in terms of their impact on material balance uncertainty and detection probability. In the second stage, the additional design features associated with the short detection time inspection approach and containment/surveillance are assessed.

7.1 EVALUATION OF DESIGN FEATURES ASSOCIATED WITH MATERIAL ACCOUNTANCY

In Chapter 3, the baseline evaluation of the effectiveness of material accountancy covered six cases. To provide a point of reference against which the effect of design changes can be assessed, Case 5 from Chapter 3 is selected as the benchmark. It is felt that the measurement error standard deviations for this case are readily attainable with a good measurement control program. Further, for direct comparison with design feature cases, $\beta = 0.05$ for attributes inspection is a reasonable design criterion. Throughout the remainder of this section Case 5 from Chapter 3 will be referred to as the base case or Case 1.

For ready reference, the relative percent measurement errors for the base case (Case 5 from Chapter 3) are given in Table 7.1 for the operator and the inspector, with the top entry in each cell being the operator value. For the short term systematic error in analytical, it is assumed that for strata 1 and 2, the error shifts monthly; for stratum 3, the scrap shipment is made quarterly at which time the scrap is measured with a different error in effect; for stratum 4, a new error applies to each group of 12 waste barrels; for strata 5-7, all measurements are made under condition 1; and for strata 8-10, all are made under the final condition. (These assumptions are those given in Table 2.5).

Finally, some summarizing results for the base case are given in Table 7.2 and 7.3. Table 7.2 gives the contribution to the variance of MUF in kg^2 Pu for each error source, and is helpful in identifying where design features are

TABLE 7.1. Relative Percent Errors for Base Case

	Stratum						
	1 PUO$_2$	2 Pellets	3 Scrap	4 Waste	5,8 Powder	6,9 Scrap	7,10 Swarf
Random							
Scale	.025 .05	.05 .075	.04 .075	-- --	.04 .05(.075)**	.04 .05(.075)**	.04 .05(.075)**
Material	.01 .01	.80 .80	3.5 3.5	-- --	.40 .40	3.5 3.5	2 2
Analytical	.40 .50	.50 .70	.60 1	20 40	.60 1	.60 1	.50 .70
LT Systematic							
Scale	.02 .03	.035 .05	.025 .05	-- --	.025 .03(.05)**	.025 .03(.05)**	.025 .03(.05)**
Material	0 0	0 0	0 0	-- --	.24 .24	0 0	.80 .80
Analytical	.035 .06	.06 .075	.15 .10	8 15	.15 .20	.15 .20	.12 .15
ST Systematic							
Analytical	.13 .16	.16 .20	.20 .25	6 12	.20 .25	.20 .25	.16 .20

** The value in brackets applies to the ending inventory measurements.

TABLE 7.2. MUF Variance Components (kg^2 Pu x 10^{-4}) for Base Case

	Scales			Sampling			Analytical		
	Random	L.T.Syst.		Random	L.T.Syst.		Random	L.T.Syst.	S.T.Syst.
1	2	944	1	2	0	1	1966	2890	3323
2	0	2756	2	1440	0	2	563	8100	4800
3	0	1	3	496	0	3	258	29	1670
4	0	0	4	0	0	4	1	10	1
5	0	0	5	108	0				
			6	14	0				
Totals	2	3701		2060	0		2788	11029	9794

Variance MUF = 2.9374 kg^2 Pu; σ_{MUF} = 1.714 kg Pu.

TABLE 7.3. Relevant Detection Probability Results for Base Case

σ_{MUF} = 1.714 kg Pu
= 0.112% of throughput

σ_s = systematic error in $\hat{D}$
= 2.736 kg Pu
= 0.178% of throughput

$\sigma(\text{MUF}-\hat{D})/H_0$ = 2.738 kg Pu

β for (MUF-$\hat{D}$) test = non-detection probability for 8 kg Pu
= 0.194

Q_{max} = maximum non-detection probability for attributes, (MUF-$\hat{D}$)
= 0.192

needed to reduce the variance of MUF. Table 7.3 gives results that relate to the detection probability based on verified accountancy. The Table 7.3 data are extracted from Table 3.14.

7.1.1 Effect on Variance of MUF of Incorporating Facility Design Features

Two alternatives to the base case are considered. With the base case being re-designated as Case 1, Cases 2 and 3 are specifically defined as follows:

Case 2: Incorporate design feature F-10. Specifically, measure both the plant input, PuO_2 powder, and the plant output, sintered pellets, for percent plutonium by the titration method. The titration method is chosen over the potential coulometric method because measurements of PuO_2 and of the pellets should be more closely correlated with titration than with the potential coulometric method, whereas the two methods would have comparable measurement accuracies and precisions. To better cancel systematic errors, the more closely correlated results would be preferred. In this evaluation, a correlation coefficient of 0.8 is assumed to exist between a systematic error for a measurement of percent Pu in PuO_2 and a corresponding error in the measurement of percent Pu in sintered pellets. In Case 3 to follow, a correlation coefficient of 0.5 is assumed for the potential coulometric method.

Case 3: Incorporates the Case 2 feature plus design features F-1 and F-3. The specifics of F-1 and F-3 are as follows:

F-1: Eliminate stratum 3, the scrap shipped offsite for reprocessing.

F-3:
- (a) Weigh all PuO_2 receipts on a second scale, obtaining independent gross and tare weights.
- (b) Use a second scale for output pellets, weighing half of the pellets on each scale. This will have no effect on the random error, of course, but reduces the systematic error variance component by a factor of two.
- (c) For characterizing sintered pellets, sample 10 pellets per pellet factor rather than 5.
- (d) For measurement of PuO_2 input and sintered pellets output, perform each analysis by titration and by potential coulometric; i.e., perform duplicate analyses using two analytical techniques.

Table 7.2 gave the MUF variance components for the base case. The variance components for Cases 2 and 3, along with those for the base case (Case 1), are given in Table 7.4, but only for those components affected by the design features of Cases 2 and/or 3. It can be seen that the design features yield substantial improvements in the standard deviation of MUF.

7.1.2 Effect on Detection Capability of Incorporating Facility and Inspection DF's

Before considering the design features for the inspector, the question of attributes inspection is addressed.

Attributes Inspection for Gross Defects

For β = 0.05, Table 3.6 called for a sample size of 1078 items. The design features for the operator would not affect this sample size, except that stratum 3, with only 12 items sampled, would be deleted.

TABLE 7.4. Effect of Design Features on MUF Variance Components (kg^2 Pu x 10^{-4})

Error Type	Source	Case 1	Case 2	Case 3
Random	Scale 1	2	2	1
	Samp. 2	1440	1440	755
	Samp. 3	496	496	99
	Anal. 1	1966	1966	983
	Anal. 2	563	563	293
	Anal. 3	258	258	246
	All 15	4850	4850	2502
ST Systematic	Anal. 1 and 2	8123	1733	1510
	Anal. 3	1670	1670	1557
	All 4	9794	3404	3068
LT Systematic	Scale 1	944	944	472
	Scale 2	2756	2756	1434
	Anal. 1 and 2	10990	3249	2451
	Anal. 3	29	29	0
	All 15	14730	6989	4368
All	V_t (MUF)	29374	15243	9938
All	σ_{MUF} (kg Pu)	1.714	1.235	0.997
All	σ_{MUF} (%)	0.112%	0.080%	0.065%

Attributes Inspection for Medium Defects

In Table 3.7, sample sizes to detect medium defects using variables measurements in the attributes mode were given. The total sample size was 56. This was based on a γ value of 0.04, i.e., assuming the attributes inspection to detect gross defects would not detect an item with a discrepancy of 4% relative. Although this γ value of 0.04 is perhaps optimistically low, calculations show that increasing its value to 0.10 - 0.15, which probably errs on the conservative side, still results in sample sizes that are not larger than would be needed to detect small defects. Thus, attention should be focussed on designing the inspection plan to detect the small defects through the $\hat{D}$ statistic.

Variables Inspection for Small Defects ($\hat{D}$ Statistic)

The design features for the inspector are now incorporated into the measurement structure. In Section 6.1, those to be studied were identified as I-1, I-6, and I-7.

Not all combinations of possible operator and inspector design features will be individually evaluated. Rather, the following combinations are studied.

Case A: The base case (i.e., Case 5 from Chapter 3).

Case B: Operator Case 2 from Section 7.1.1 plus inspector design feature I-6. This Case is the base case modified such that both the operator and the inspector measure the materials in strata 1 and 2 for percent plutonium by titration in order to permit partial cancellation of systematic errors.

Case C: Operator Case 3 from Section 7.1.1 plus inspector design features I-1 and I-7. Specifics of I-1 and I-7 are as follows.

(a) Perform duplicate analyses for %Pu of PuO_2 (stratum 1) and of sintered pellets (stratum 2), using the same analytical technique for both analyses (I-1).

(b) Perform one of the duplicate analyses in one time frame, and the other in a second time frame (I-7).

Relevant summarizing statistics that relate to detection capabilities are given in Table 7.5 for Cases A, B, and C. In this table, a variable inspection sample size of 200 items is assumed. The goal quantity is 8 kg Pu.

In Table 7.5, the following values are given for each case.

Sigma MUF = standard deviation of MUF in Kg Pu

% Sigma MUF = standard deviation of MUF as percent of throughput

σ_S = systematic error standard deviation of $\hat{D}$ in kg Pu

Sigma (MUF-D) = standard deviation of (MUF-$\hat{D}$) under H_o, in kg Pu

β = non-detection probability for (MUF-$\hat{D}$) test

Q_{max} = maximum probability of non-detection using attributes inspection and (MUF-$\hat{D}$) statistic.

TABLE 7.5. Detection Capability Results for Cases A, B, C

	Case A	Case B	Case C
Sigma MUF	1.711	1.235	0.997
% Sigma MUF	0.112%	0.080%	0.065%
σ_s	2.736	1.853	1.702
Sigma (MUF-$\hat{D}$)	2.738	2.209	2.125
β	0.194	0.120	0.100
Q_{max}	0.192	0.125	0.112

In Chapter 3, Q'_{max} was also reported for various cases. This quantity is similar to Q_{max} except that it is based on attributes inspection, $\hat{D}$, and MUF tests applied individually. Since it has been well established that Q'_{max} is always larger than Q_{max}, only Q_{max} is evaluated here.

It was noted in Chapter 3 that for the base Case A, it was not possible to achieve a β value of 0.05. This statement is not true for Cases B and C, which incorporate the design features. The β values of Table 7.5 assume a variables sample size of 200. By increasing the sample size, β can be driven downward to 0.05 for both Cases B and C. The relationship between variables sample size and β is given in Table 7.6 for Cases B and C.

TABLE 7.6. β Versus Sample Size (SS)

β	Case B (SS)	Case C (SS)
0.12	199	<200
0.11	212	<200
0.10	227	199
0.09	243	213
0.08	262	230
0.07	285	250
0.06	312	273
0.05	345	302

Thus, a β of 0.05 is within reach once the design features for both the operator and the inspector are incorporated. Note that the important feature is to use the same analytical technique in the input and product steams (Case B). Of course, Q_{max} will be driven downward along with β.

7.1.3 Detection Probability with Attributes, $\hat{D}$, Z Tests

In reference (12) (Jaech 1980), the Z statistic was re-introduced as a replacement for MUF, having first been introduced in reference (13) (Jaech 1972). It was indicated in (12) that although the corresponding maximum probability of nondetection for this test combination, designated by Q''_{max}, is slightly larger than Q_{max}, elsewhere in the space of diversion strategies, Q" is appreciably smaller than Q. For Case B, Q and Q" are compared for a number of diversion strategies, with the results again indicating that the test combination involving $\hat{D}$ and Z may, in general, be preferred over (MUF-$\hat{D}$) even though $Q''_{max} > Q_{max}$.

Table 7.7 gives Q and Q" as a function of diversion strategy for Case B. In this table,

a_2 = fractional amount of goal amount diverted into a combination of gross and medium defects (falsifications).

a_3 = fractional amount diverted into small defects (falsifications).

a_4 = fractional amount diverted into MUF.

The values in the last two columns of Table 7.7 are shown on the triangular coordinate plot of Figure 7.1 to give a better perspective of how Q and Q" are related to diversion strategy. Note that only near the region where a_4=0 is Q" greater than Q, and the difference between these two nondetection probabilities is not great. Elsewhere, Q" is considerably smaller than Q. This is visually depicted in Figures 7.2 and 7.3. (Note that the axes have been changed from Figure 7.1 to facilitate the visualization of the response surface.) Additional calculations indicate that Q_{max}=0.126 and Q''_{max}=0.136.

As a final note, it is emphasized that the calculations of this section are again based on a variables sample size of 200. As pointed out in the last section, it is possible to achieve β=0.05 with an additional number of samples once the important design features are incorporated.

TABLE 7.7. Non-Detection Probability as a Function of Diversion Strategy

a_2	a_3	a_4	Q	Q"
0	0	1	.024	.000
0	.25	.75	.062	.000
0	.50	.50	.097	.004
0	.75	.25	.120	.052
0	1	0	.120	.126
.25	0	.75	.067	.000
.25	.25	.50	.096	.007
.25	.50	.25	.114	.068
.25	.75	0	.124	.135
.50	0	.50	.097	.009
.50	.25	.25	.100	.070
.50	.50	0	.102	.114
.75	0	.25	.081	.056
.75	.25	0	.076	.081
1	0	0	.048	.048
.333	.333	.333	.106	.042

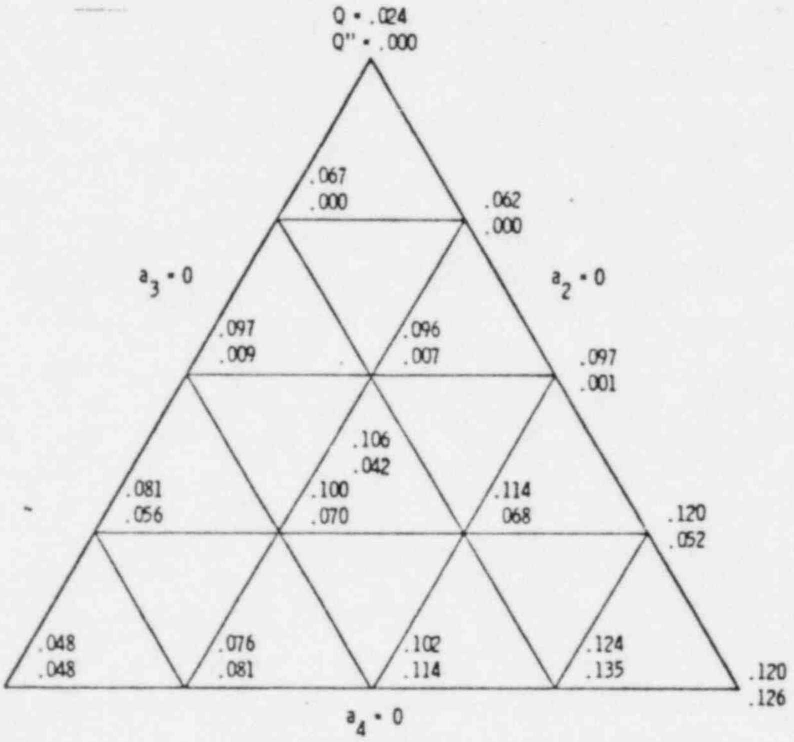

FIGURE 7.1. Q' and Q" as a Function of Diversion Strategy

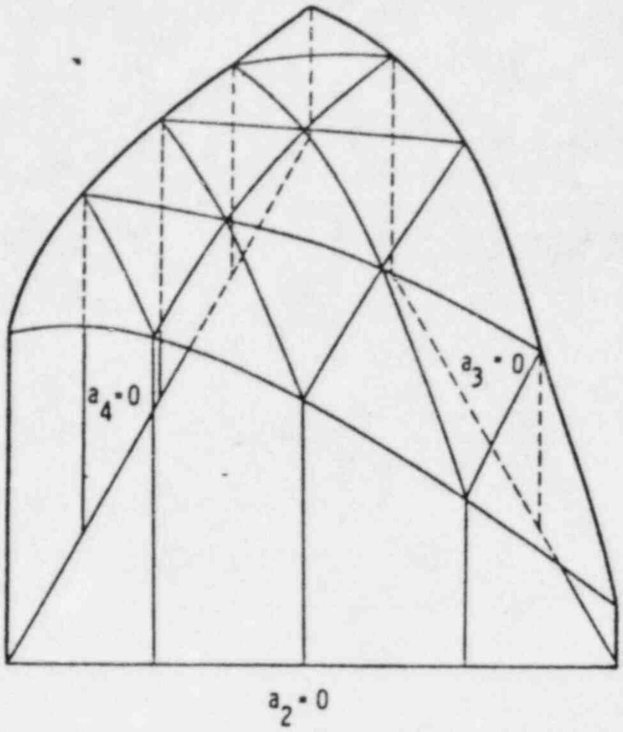

FIGURE 7.2. Non-Detection Probability for Attributes, MUF-$\hat{D}$ Tests

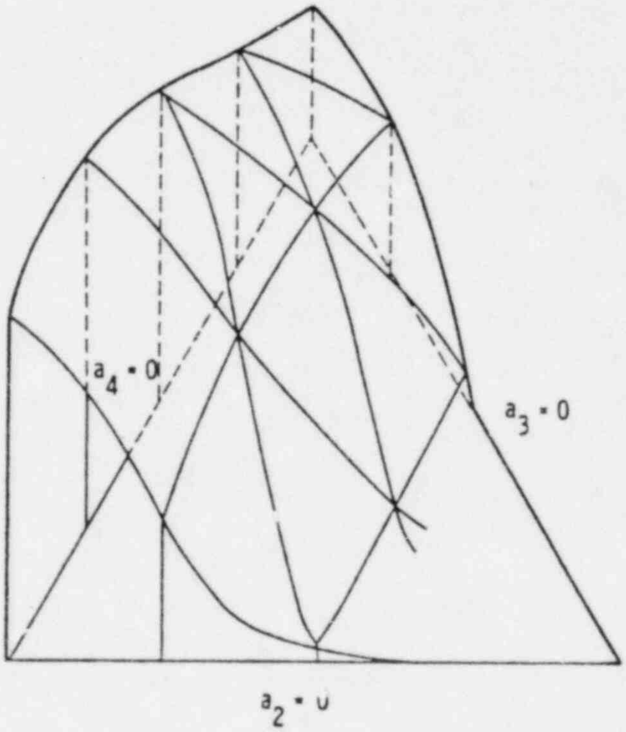

FIGURE 7.3. Non-Detection Probability for (Attributes-$\hat{D}$-Z) Tests

7.2 EVALUATION OF ADDITIONAL DESIGN FEATURES

Each of the design features discussed in Section 5.2 is first evaluated qualitatively for its contribution to the solution of the problems. Subsequently their combined effects on the inspection effort are evaluated. The concept of extended containment and surveillance is also discussed.

7.2.1 Impact on Problem Areas

DF-1: Features Minimizing Volume of Process Equipment and DF-2: Containerization of Transfers Between Process Steps

These features are aimed at achieving adequate measurement accuracy for short detection time inspections. The material is either in small-volume equipment that allows witnessing and measuring of run-out during the periodic visits; or in containers of suitable geometry for accurate verification of the material between process steps by application of quantitative NDA.

DF-3: Quarantined Receiving

This feature eliminates the need for the continuous presence of the inspector in the receiving area to perform verification and sealing of the containers entering storage. With the quarantine, these functions can be performed by the inspector during periodic visits.

DF-4: Walk-Through Vault

This feature makes possible quick verification of sealed items in the vault. There might be several hundred sealed containers and a rate of verification of 2 to 5 minutes per item should be an achievable target. It also provides means for inspection of the integrity of storage containers and thus eliminates vulnerability 1-B not adequately covered by the baseline system.

DF-5: Transportable Inspection Station

This feature makes possible a quick attribute testing of items in quarantine or buffer storage. A rate of 10 minutes per container is desirable since during the 2-week intervals between inspections there might be as many as 160 items accumulated requiring attribute tests.

DF-6: Multitray Sealable Containers for Pellets

This feature reduces the effort for verification of pellet trays. There may be as many as 4,000 trays, 75% in storage and 25% in the process area. If the containers were designed with a capacity of 10 trays per container, only 400 items would require checking. The majority of these checks would be quick seal verifications. Further reduction of the inspection effort could be achieved in attribute tests, if the pellet containers and NDA equipment were designed as a system with this objective in mind.

DF-7: Quarantined Rod Storage Area and DF-8: Fuel Assembly Area for Application of C/S

These features include the arrangement for intermediate rod quarantine and the containment for the assembly manufacturing area. This accomplishes the following goals:

1. Eliminates the need for continuous inspector presence to verify the content of rods during their manufacture. This function can be performed by the inspector during his periodic visits.
2. Provides containment and surveillance of the assembly manufacturing area to assure that no substitution of rods occurs during this process. This eliminates vulnerabilities 3-A and 3-B not adequately covered by the baseline safeguards approach.

DF-9: Tamper-Indicating Sealable Assembly Container

This feature assures that no substitutions take place once an assembly is placed in the container and sealed. It is a potential concept for solving a general problem of preventing substitutions within fresh fuel assemblies in the period between their manufacture and loading into the reactor.

7.2.2 Impact on Inspection Efficiency

The combined effect of these design features on the short detection time manpower requirements in the reference plant is to reduce it from 500 mandays to 300 mandays assuming 26 biweekly inspections per year. Each inspection requires approximately 11 mandays to accomplish as shown in Table 7.8. A team

TABLE 7.8. Summary of Short Detection Time Inspection Effort

Inspection Task	Effort Per Task (Man-Days)
Record Verification	1
Verification of Containment	1
Calibration and Maintenance	2
Receiving Storage Vault (including quarantine transfers)	2.4
Powder Processing and Pellet Fabrication	1.8
Rod Fabrication (including quarantine transfers)	1.4
Fuel Assembly Manufacturing	1.3
Scrap and Waste	0.5
Total Inspection Effort	11.4 man-days per inspection

of 2 to 3 inspectors could perform these tasks in approximately 5 working shifts, thus making is possible to eliminate the need for continuous inspector presence.

Table 7.9 summarizes details of the inspectors' tasks. The first column identifies the area in which the inspection is performed together with the design features required to enable the inspector to perform his verification tasks at the assumed rates. The second column indicates the nature of these tasks and the assumed inspection effort per item, e.g.,

Seal verification - 2 minutes
Attribute test - 10 minutes
Attribute test and sealing - 15 minutes
Other tasks - as indicated

The third column indicates the number of items which must be verified according to sampling plans. The number of items subject to verification is taken from Tables 2.2 and 3.1. The fourth column is the summation of effort estimated for each task. Total effort is summed up in the fifth column.

TABLE 7.9. Bi-weekly, Short Detection Time Inspection Effort (Design Features Included).

Inspection Area and Design Features	Inspection Task	No. of Items		Time Minutes	Total Minutes
Receiving Storage Vault	Counting items in the vault (20 items/min)	Cans, containers, etc.	860	43	43
DF-3 Quarantined area					
DF-4 Walk-through vault	Verification of sealed items (2 min/item)	Pu powder cans	118	236	
		MOX powder cans	41	82	
DF-5 Inspection station		Multi-tray pellet containers	5	10	
		Scrap buckets	2	20	348
DF-6 Multi-tray sealed pellet containers	NDA test and sealing of quarantined items (15 min/item)	Pu powder cans	16	240	
		MOX powder cans	12	180	
		Multi-tray pellet containers	22	330	
		Containers scrap	2	30	780
Process Area	Counting items in process area (20 items/min)	Cans, containers, etc.	70	4	4
DF-1 Small process equipment volume	NDA test (10 min/item)	Pu powder cans	4	40	
		MOX powder cans	27	270	
DF-2 Containerized transfer between process steps		Multi-tray containers (green pellets)	20	200	
		Multi-tray containers (sintering pellets)	20	200	710
DF-5 Inspection stations	Blenders or other equipment run-out observations;			120	
DF-6 Multi-tray pellet containers	sintering pellets run-out observations			60	180
Rod Fabrication	Counting pellet trays and rods	Pellet trays (20/min)	200	10	
		Rods (5-/min)	1500	30	40
DF-7 Fuel assembly area extended surveillance	Attribute test	Pellet trays	20	200	
		Finished rods	44	440	640
Fuel Assembly	Counting rods and assemblies	Rods	300	6	
		Assemblies	24	2	8
DF-7 Fuel assembly area					
DF-8 Tamper indicating assembly container	Verification of sealed assemblies	Sealed assemblies	22	220	220
	Witness packaging of assemblies into containers and sealing (60 min/assy)	Assemblies	6	360	360
	Witness transfer of rod racks and assemblies into and out of the containments			60	60

7.2.3 Impact of Facility Design for Remote Operations on Efficiency

For reasons of safety and radiological protection the process area of the facility may be constructed for remote operations in a shielded canyon. Such an arrangement is illustrated in Figure 7.4. It consists of canyon area A containing nuclear material and processing equipment. The canyon is isolated from

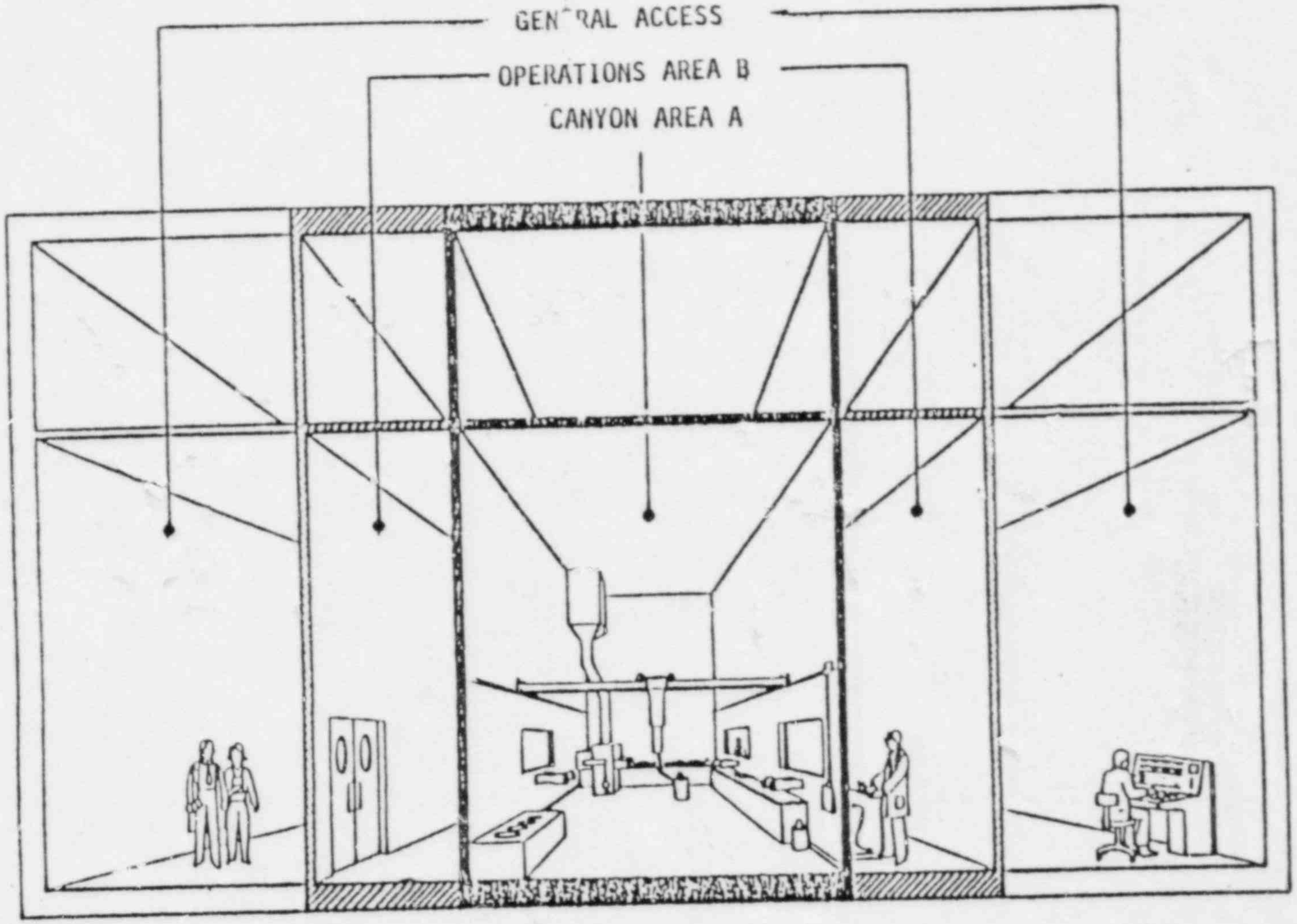

FIGURE 7.4. Cross-Sectional View of Canyon Type Facility. (Reproduced from Westinghouse Electric Corporation report "State-of-the-Art Survey of Residual Holdup in 200 MT/year MOX Fuel Fabrication Facility.")

the surrounding operations area B which contains remote handling and control equipment, glove access ports and viewing windows. The IAEA inspectors would perform their tasks from operations area B. The facility may be a multi-story building with various functional areas located at levels appropriate to their requirements. For example, operations such as dirty scrap recovery and waste processing might be performed in other canyons located at the lower levels of the facility.

The effect on the inspection effort of such a facility design will be to increase the time needed to remotely handle the material for verification. Design features such as DF-5 "Transportable Inspection Station", if appropriately designed for fast coupling to access penetrations and easy retrieval and return of inspected items, could have a very beneficial effect.

The problems associated with fast handling of inspected items in remote facilities have not been investigated in this study. However, it is reasonable to expect that the rate at which containers can be assayed non-destructively will decrease by a factor of 2 to 3, thus increasing the inspector effort required 3 to 6 mandays per inspection.

7.2.4 Costs

The capital and operational costs which are incurred by owner/operator as a result of the introduction of the design features were estimated in a rough order of magnitude bases, using data from References 3 through 6. At best, estimating nuclear facility costs involves a large degree of uncertainty. This is especially true of MOX fuel fabrication facilities, because there are none under construction in the U.S. at present. To simplify the interpretation of the cost data and considering the difficulty of obtaining consensus on the overall cost of the hypothetical reference facility, a capital cost of 50 million dollars was assumed. This provides a reference scale of 1 million dollars equal to 2%, 100,000 dollars equal to 0.2%, etc. A figure of $10 million per year was assumed for operation costs of the reference facility.

Capital Costs

The cost of each design feature was estimated either by comparing the feature to a similar application with a known cost or by estimating the cost of materials, major equipment, construction, labor and engineering. The first method of cost estimating was used whenever possible because the second method requires considerably more effort and a more detailed definition of design characteristics such as sizes of equipment, buildings, etc.

Operational Costs

The second component of cost is that incurred by the facility owner/operator as a result of the introduction of a design feature that may alter his operational functions. For example, there will be an additional effort required on the part of the operators to perform double transfer of items, first into the quarantined storage and then to their final placement in the vault. These kinds of additional costs were calculated from the estimates of man-hours required to perform the tasks.

The detailed cost calculations are presented in Appendix B. A summary of capital and operational costs is given in Table 7.10.

TABLE 7.10. Cost Summary for Design Features at MOX Fuel Manufacturing Facility (1500 Kg Pu per Year)

Identification	Design Feature Description	Incremental Capital Cost (Percent)	Incremental Annual Operating Cost (Percent)
DF-1	Features for verification of in-process material	No change	No change
DF-2	Containerization of transfers	No change	No change
DF-3	Quarantined receiving area	.35	.53
DF-4	Walk-through vault	.10	No change
DF-5	Transportable inspection station	.10	No change
DF-6	Multi-tray sealable containers for pellets	.10	.45
DF-7	Quarantined rod storage area	.44	.18
DF-8	Assembly area designed for containment and surveillance	1.00	No change
DF-9	Tamper-indicating sealable assembly container	.20	No change

7.2.5 Extended Containment and Surveillance

The results of the baseline evaluation indicated that a form of containment/surveillance may be necessary to supplement the baseline safeguards system in medium-size and very large plants. This is a function of insufficient quantitative measurements for these facilities with sufficiently small uncertainty.

Two basic possibilities can be mentioned:

- Path Surveillance. Essentially this involves instrumental surveillance (via portal monitors, for example) of pathways by which nuclear material would be diverted from the facility.
- Human Surveillance (Direct Observation of Actions). This is based on the notion that continuous presence of inspectors would provide some capability of detecting actions and activities associated with the diversion of material. There is also an element of deterrence in this concept. In the limiting case, the concept approaches that of multinational presence or multinational control of sensitive fuel cycle facilities.

Each of these possibilities presents great problems from a practical point of view. The path surveillance approach requires technology that has not yet been developed and demonstrated, although in recent years a considerable theoretical base has been established especially in connection with the safeguarding of reprocessing facilities. The approach based on direct observations of actions has been considered as a possible safeguards technique since as far back as the Acheson-Lilienthal report. It would require a sizable number of inspectors with a much closer involvement in facility operations than is the current inspection practice. It would probably be considered by the plant operators as creating an undue interference in the operation of the facility, a condition to be avoided according to paragraph 4.b of INFCIRC/153.

Nevertheless, it will be made clear in subsequent discussions that a practical concept of extended surveillance may require a combination of both approaches: instrumental surveillance of potential diversion paths and direct observation of at least some activities.

A considerable insight for the potential application of extended surveillance to large plants was obtained in the study of containment and surveillance concepts for the existing Barnwell Nuclear Fuel Plant(2). The proposed C/S approach was to identify containment boundaries which enclose SNM and to monitor all penetrations potentially usable for SNM removal by sensors or other surveillance devices.

The study concluded that such an approach was not practical or useful for the following reasons: 1) the large number of instruments required to monitor some 2200 penetrations would be too costly and could exhibit unacceptably high alarm rates and reliability problems, and 2) the diversion rate that could be carried out under the detection threshold would be about 1 kg of Pu per day, i.e., considerably greater than 8 kg per year goal. It was also noted in the study that the surveillance concept was applied to an existing design that was highly unsuited to this purpose.

It appears to us that the limitations noted in the Reference 1 study may be less severe for the case of MOX fuel fabrication facilities for the following reasons:

1) Fabrication facilities do not require extensive utility services, chemical supplies and instrument lines. Consequently, the number of penetrations to the outside is relatively smaller, perhaps by several orders of magnitude.

2) The materials inside the containment are in solid and powder form and would be more difficult to remove through small diameter pipes than are liquids in a reprocessing facility.

3) The facilities do not yet exist and their designs can be evolved to facilitate the implementation of such a surveillance concept.

A possible way of applying the concept of extended surveillance to the MOX fuel facilities is as follows.

The facility areas that contain nuclear materials, e.g., receiving and storage vault, process areas, waste treatment area, etc., are enclosed within a containment that provides resistance to clandestine penetrations. Surveillance devices are placed on all established penetrations to detect possible transfers of nuclear materials through the containment barriers. Material movements are monitored along the normal routes, e.g., receiving and shipping, to provide relevant information to the accountancy system; movement of material along abnormal routes would create an alarm. The sensors could be connected by the transmission network to a central location to provide integrated real-time overview of their status.

This system must in any case be supported by on-site inspectors for the following reasons: 1) to respond to and resolve causes of alarms, 2) to maintain surveillance instruments, 3) to inspect and provide assurance of the integrity of containment, and 4) to verify the integrity of the seals and witness operations when the seals are removed.

The following are some of the key requirements for the facility design in which extended surveillance could be successfully implemented:

1) Design containment to completely enclose nuclear materials and separate personnel from these materials.
2) Provide for each of verification of containment integrity.
3) Minimize the number of penetrations which must be monitored.
4) Separate high maintenance areas from potential material contact areas.
5) Distinguish between process containment and operations containment. The former can be a hindrance, as noted in connection with the measurement of in-process inventory and containerization vs. continuous transfer. Operations containment is a desirable concept associated with perimeter control.

Some of the requirements described above are already under consideration for future facilities. For example, a canyon-type construction separating operating personnel from nuclear materials, and remote handling, are featured in the conceptual design of a 200 ton per year MOX facility studied by Westinghouse Electric Corporation.

It is important that a unified containment encloses all operations, including treatment of wastes. In the MOX facility probably the largest number of penetrations from process areas are those that are used for the removal of process wastes, operational wastes and failed equipment. These penetrations should not connect to the outside of the containment, but rather to the waste treatment equipment and storage vaults that are located within the containment boundary.

The retention of processed wastes for extended holding periods could be useful for safeguards in cases where verification of the Pu content of the wastes might be required as part of verification of cumulative balances.

Surveillance of the analytical laboratory and the scrap recovery process may require special attention. These operations handle only a small amount of Pu, but the lack of substantial separation between personnel and nuclear material makes this an area of particular concern.

All the penetrations of the containment will be monitored. These include plant ventilation systems, liquid flow lines, gas lines and electrical lines. Seals will be applied to infrequently-used penetrations such as for maintenance access, manipulator and glove penetrations, etc.

The concept of extended surveillance described above applies to the areas where no material transfers across the boundary are expected. It provides the assurance that all material flows occur through the normal routes which are associated with the key measurement points, and thus ties in to the material accountancy. The concept must include the capability to verify the integrity of the containment.

The approach appears to be potentially feasible for application to MOX fuel fabrication facilities provided that surveillance system requirements are included at an early stage of the facility conceptualization process so that an optimal overall system is evolved.

The above analysis of the feasibility of extended surveillance is limited to concept identification. A more detailed and extensive design study, using concepts described in this report as a starting point, would be needed before a definitive assessment of the utility and practicality of the approach could be made.

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REFERENCE NOTES

a) Article XII of the IAEA Statute, as amended up to 1 June 1973, provides that the Agency shall have the right:

> "to examine the design of specialized equipment and facilities, including nuclear reactors, and to approve it only from the viewpoint of assuring that it will not further any military purpose, that it complies with applicable health and safety standards, and that it will permit effective application of the safeguards provided for in this article."

b) The IAEA's safeguards agreements are modelled principally after INFCIRC/153 (corrected), dated 1972, "The Structure and Content of Agreements Between the Agency and States Required in Connection with the Treaty on the Non-Proliferation of Nuclear Weapons;" and INFCIRC/66/Rev.2, dated 16 September 1968, "The Agency's Safeguards System."

c) The report of INFCE Working Group 4 (Reprocessing, Plutonium Handling, Recycle), page 17, for example, states:

> "It is recognized that for future reprocessing and MOX fuel fabrication plants it will be essential to take full account of criteria for effective international safeguards from the inception of plant design, together with the resultant cost. The design stage should include an evaluation of the overall safeguards strategy proposed."

See also INFCE/PC/2/9, Plenary Conference, 25-29 February 1980.

d) In GC(XXIV)/OR.218, 26 September 1980, Ambassador G. C. Smith was reported as stating:

> "INFCE had also concluded that improved international safeguards were essential. Facilities should be designed to make safeguards more effective and to simplify safeguards implementation. Progress in the design and application of safeguards was essential to the expansion of nuclear power."

e) GC(XXIV)/627, July 1980, The Annual Report for 1979, IAEA:

> "There was also progress in developing the methodology for evaluating the effectiveness of safeguards and in working out guidelines on the design of nuclear facilities to make safeguards easier and more effective."

f) The International Working Group on Reprocessing Plant Safeguards was established by the Director General of the IAEA to assist the Agency in undertaking a comprehensive study of the safeguards system and techniques for reprocessing facilities. Recognizing the importance of facility design, Subgroup II on Facility Design Considerations to Facilitate IAEA Safeguards was formed as part of this Working Group.

Ref.4

APPENDIX A

LIST OF DESIGN CRITERIA THAT ENHANCE CURRENT INSPECTION TECHNIQUES (NEAR-TERM FIXES)

This appendix presents a listing of near term design features that either could be added to existing facilities or should be considered in the execution of new designs. These features could be implemented in addition to, or as a part of the safeguards-oriented design approaches described in this study. They have a positive impact both on the effectiveness and the efficiency of safeguards, although their contributions in terms of probability of detection or impact on manpower requirements are difficult to quantity. Many of the features identify auxiliary support requirements of the inspectors to facilitate performance of their tasks.

A.1 SAFEGUARDS DESIGN CRITERIA

DF-1A The facility should have the capability to recycle clean scrap and process dirty scrap to homogeneous, accurately measurable forms within a few weeks after generation of the scrap.

DF-2A To the extent practicable, scrap should be segregated and measured in such groupings that the recovery data can be related either to the lot or lots or to the process operations from which it was produced.

DF-3A Space and electrical supplies for monitoring or placement of surveillance instruments, including IAEA instruments, should be provided in every plutonium access area and entrance and egress points for either personnel or material. (the surveillance instruments may include cameras, CCTV, and radiation detectors.)

DF-4A The processing facilities should be designed to permit most routine maintenance in the processing area without access to the processing enclosure interiors.

DF-5A All parts of the enclosure interiors should be accessible for cleaning. Sufficient glove or manipulation stations should be provided for this. Those areas not used routinely for processing may be sealed.

DF-6A In enclosures and processing equipment, ledges, seams, or flanges that could hold up dry material; tank bottoms or hoppers that have insufficient pitch to permit rapid and substantially complete removal of dry or liquid SNM; pipe sags and taps; and rough surfaces that impair the removal of powders or liquids should be avoided. Provision for washdown or shakedown of such material may be necessary. Generally, complete elimination of holdup of SNM substances will not be possible, but the amount so retained should be minimized and, equally important, should be as reproducible as possible from inventory to inventory.

DF-7A The enclosures should have no interior crevices or seams but should be smooth and polished for ease of sweeping up spilled powders and accumulated dust.

DF-8A Consideration for minimization of SNM holdup should be made in the selection or design of processing equipment.

DF-9A Calcining and sintering furnaces should have seamless linings for easy cleanup of spills.

DF-10A The trays and conveyor mechanisms used to transport material through furnances should be designed so the trays cannot jam, tip, or pile up.

DF-11A If residence times in a calciner or sintering furnace are long (greater than 24 hours), consideration should be given to the use of automatic feeding and egress from the furnace and feeder and receiver capacities of 8 or more hours. In addition, a sealable furnace unit for unattended operation should be considered.

DF-12A Vessels and piping for process liquids should be capable of complete emptying or of emptying to a reproducible holdup, and should be washable.

DF-13A Liquid storage vessels should be provided with the capability for mixing, sampling, and continuous monitoring of liquid level, density, and temperature.

DF-14A All liquid volume measurement systems should have the capability for periodic recalibration using gravimetric or volumetric provers (precision precalibrated batch tanks). Provers permanently installed in the plant should be capable of periodic recalibration.

DF-15A Volume measurement vessels should be of rigid construction with adequate structural support to minimize the possibility of distortions under the conditions of use. They should be right circular cylinders with the axis vertical. Vessels having slab or other noncircular configuration should be avoided unless special provisions are made to ensure uniformity of cross section with height and structural stability during use.

DF-16A If samples are to be taken from a vessel via a fixed sampling point, special attention should be given to the design of the mixing system to ensure that the samples are obtained from a homogeneous mixture.

DF-17A Liquid sampling systems: a) should be designed to drain completely between samples, with provision for flushing the whole system with fresh solution before sampling, or b) should draw the sample from a constantly recirculating loop or process line. Recirculation systems should have means for verifying that the flow rate is adequate to ensure a valid (representative) sample.

DF-18A Space for placement of scales and test weights in processing enclosures should be provided. Consideration should be given to readability in the installation or placement of scales. If necessary for the precise and accurate recording of weights, provisions should be made for supplemental lighting, optical aids, or remote digital readout.

DF-19A Features should be provided that minimize the accumulation of dust or powder on the surfaces of scale pans or platforms and on moveable parts, if any, of the weighing device. Where accessibility to critical parts for cleaning is restricted, dust covers or enclosures should be installed.

DF-20A Provisions should be made to protect scales from drafts, vibrations, corrosive environments, and electrostatic or magnetic forces. To aid in the design, the susceptibility of each weighing system to such sources of error should be determined in advance.

DF-21A Space for location of NDA measurement instruments will be required at certain locations in the processing line. Generally, only the detector unit and shielding will be in the enclosure or attached to it with access to the sample position from within the enclosure.

DF-22A The NDA instruments should be protected from or located away from high and fluctuating radiation background that can affect readings.

DF-23A The design and installation of each NDA system should provide means for frequent calibration in place, as well as for periodic testing and maintentance.

DF-24A Noise-free and stable electrical power for NDA instruments and electronic balances should be provided at all potential meansurement points in the processing operations.

DF-25A Suitable conduits and signal lines for transmission of digitized data from measurement instruments and remote computer terminals to a central computing facility should be provided to every point in the facility where data may be generated for production, process or quality control, or accountability.

APPENDIX B

COST BASIS FOR DESIGN FEATURES (BEST ESTIMATES)

The capital and operating costs presented below for selected design features are best estimates for the reference MOX fabrication facility producing assemblies for light water power reactors (LWRs). In order to account for the effects of inflation, taxes and other factors (e.g., regulatory actions) which would influence the cost of the facility, item costs were normalized to total plant cost and presented as percentages. As a point of reference, the capital cost of the 30 metric tonne MOX/year (i.e., 1500 Kg Pu per year throughput) was estimated from best available information to be $50 million and the annual operating cost was estimated to be $10 million in 1980 dollars. To provide the reader with a perspective of these costs, Figures B.1 and B.2 respectively, denote the estimated capital and operating cost for plants with throughput different from the baseline. Data supporting these figures were taken from References 3 and 4. The costs given below for the design features are estimates only and are not intended to be used for estimating actual design or implementation costs. They are supported by information presented in References 5 and 6.

B.1 DF-1 FEATURES FOR VERIFICATION OF IN-PROCESS MATERIAL

This design feature concerns the volumetric capacity of the process equipment, i.e., blenders, mixers, mills, etc. The requirement is that the volume of this equipment be sufficiently small so that any process operation can be completed and equipment emptied during inspectors periodic on-site presence of about five days duration. The process equipment volume was assumed to be small in the baseline facility (see in-process inventory list in Table 2.2, "Inventory Data for the Model Fabrication Facility). Therefore, no facility cost increase from these requirements is anticipated. Evaluation of typical operations also indicates that there should be no change in operational cost.

At 1500 Kg Pu per year throughput, the facility processes 30 Kg Pu per week. Assuming that equipment is designed to perform a blending of 8 cans of Pu in 3 cycles of 5 hours duration each, the total weekly throughput can be processed in about 30 hours. Therefore, no additional operational costs will be involved.

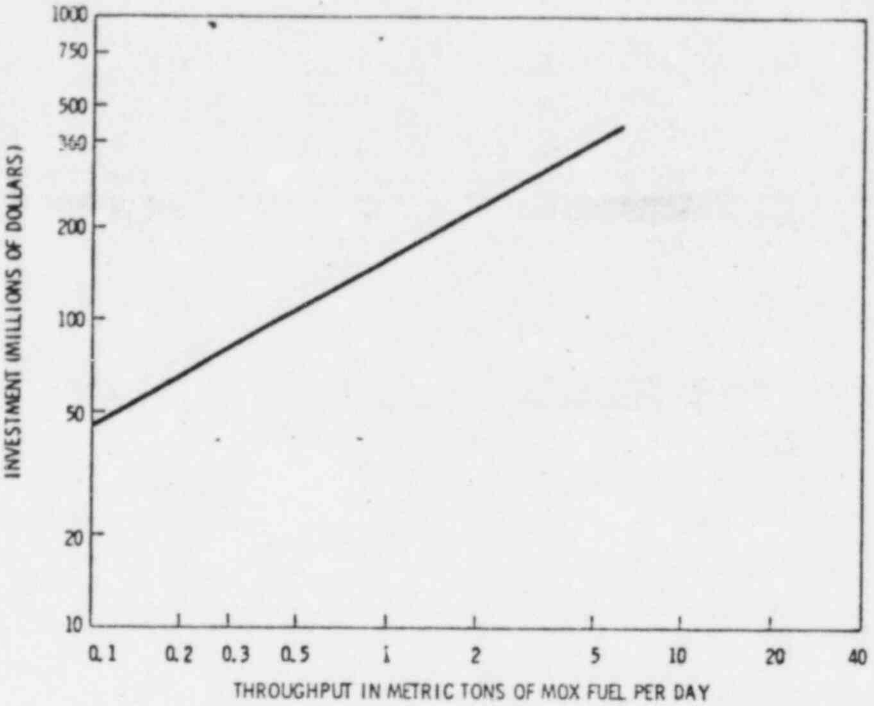

FIGURE B.1. Capital Investment as a Function of Plant Capacity

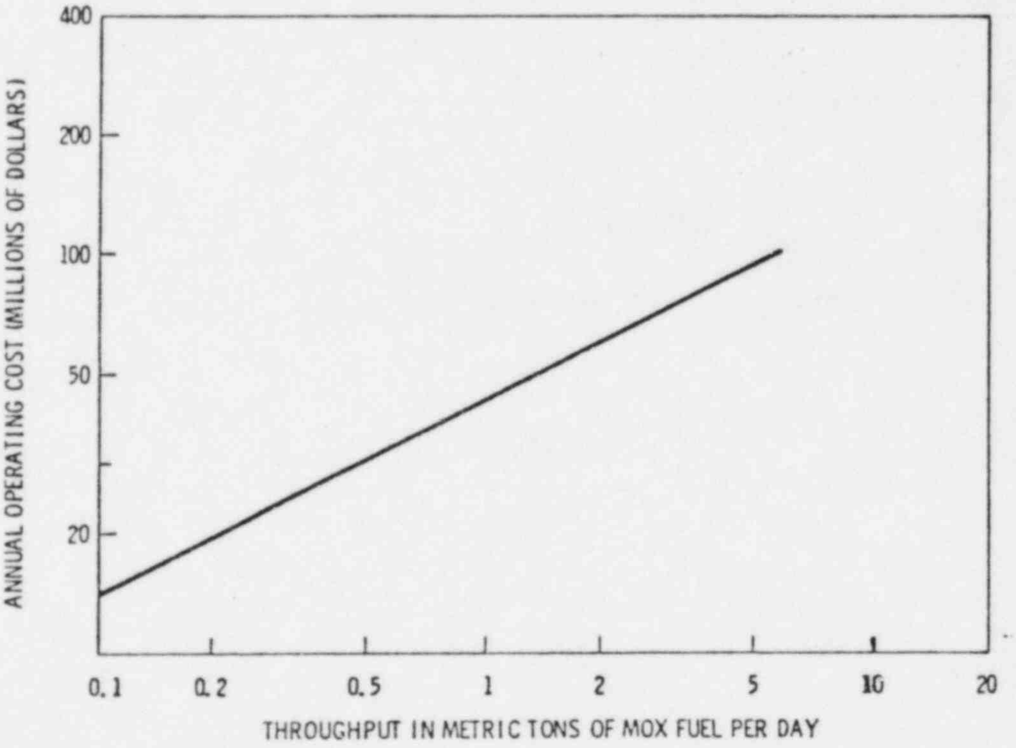

FIGURE B.2. Annual Operating Cost as a Function of Plant Capacity

B.2 DF-2 CONTAINERIZATION OF TRANSFERS

The operation of the reference facility assumed that the processed material (i.e., blended Pu or MOX) will be mostly in containers (2 kg for Pu and 10 kg for MOX). Therefore, this feature should not impact either the capital cost or the operation cost. As was explained in the description of this feature, the size of the container is subject to optimization involving the trade off between the number of containers (time of inspections is proportional to number of containers) and NDA equipment design which may limit the acceptable size. This trade off was not performed in this study and therefore, we assume no change in either capital or operational cost. It is pointed out that PuO_2 and UO_2 received at the facility are probably packaged in industry standard containers and that changing can size for safeguards purposes would impact the business ties between the shipper and receiver.

B.3 DF-3 QUARANTINE RECEIVING AREA

The capital cost is estimated to be $175,000 and the annual operating cost will be approximately $53,000. Table 3.1 indicates that there might be an average of 350 new cans accumulated in the quarantine storage over a period of 2 weeks: 30 Pu cans, 160 MOX cans, 156 multi-tray pellet containers and 6 scrap buckets. Assuming that each container will require approximately 1 cubic foot of space, the size of the vault will increase by 352 $feet^3$. Assuming the cost of additional vault space is 500 x 352 = $175,000. This is .35% of capital construction costs.

The introduction of the quarantine requires that the item be handled twice, i.e., first the process to quarantine, and then quarantine to storage instead of just on an in process to storage.

Assuming the average time for additional handling per item is 10 minutes, it would take an additional 1525 hours/year of a technician to handle 352 items every two weeks. Using a pay scale of $70,000/year and 2,000 hours/year, the extra operating cost is $53,000/year. This is a .53% increase.

B.4 DF-4 A WALK-THROUGH VAULT FOR RAPID SEALS VERFICATION

The number of items stored in the vault may be 2 to 3 times larger than that in quarantine. This indicates a cost of the vault between $400,000 and

$500,000. The provision of walkways and shielding for the storage spaces to protect the personnel may add approximately 10% to the cost of the vault. This will be about $50,000 or .10%.

There are no additional operational costs associated with this feature.

B.5 DF-5 TRANSPORTABLE INSPECTION STATION

The estimate of the cost of the transportable inspection station assumes that it consists of a working enclosure which contains all the necessary NDA equipment and manipulators for the handling of containers with nuclear materials. It also includes the means for easy coupling to the operational glove boxes or process cells. The working enclosure is located in a motorized trolley for easy transport between the inspection access points. The computing equipment is also a permanent pert of the station. The estimate of the cost of such a station includes $25,000 for manipulators (Reference 6), $20,000 for the enclosure and fast disconnect coupler and $10,000 for motorizations. The approximate total is $50,000 or .10% of the cost of the facility. These cost do not include the cost of NDA equipment or the computer.

There is no change to operational costs of the facility arising from this feature.

B.6 DF-6 MULTI-TRAY SEALABLE CONTAINERS FOR PELLETS

The concept of the multi-tray containers includes separation spacers, boats (or trays) and a tie-bolt as shown in Figure 5.3. The boat design in which the pellets are placed at random is fairly straight forward and an estimate for the total cost is $50 to $100 per assembly. The tray design may be more complex since it may need to include provision of mechanisms for unloading into the rod manufacture. The cost of trays is estimated at $200/multi-tray container. For 300 boat containers and for 200 tray container required for the facility the costs will be $50,000. This is .1% of the facility cost.

Operational costs are estimated to increase because the operators will have to build individual trays and boats into assemblies. On average, we estimate that there is a need for about 4,000 containers for handling for green pellets and a similar number of containers with sintered pellets. Assuming 1 minute per container, this will add about 1,300 hours/year at a cost of $45,000, i.e., a .45% incrase in operating costs.

B.7 DF-7 QUARANTINE ROD STORAGE AREA

The room for the storage of quarantined rods should have the capacity for approximately 700 to 1500 rods. For the purpose of calculating its cost, it is assumed that the rods are stored horizontally in layered racks. The length of the quarantine room should be in excess of twice the length of the rod so that rod can be relocated from its normal storage to after-scan storage after passing through the rod scanner. Assuming 40 feet x 10 feet x 10 feet dimensions and \$50 per feet^3 (10% of vault type construction), the construction cost is calculated at \$200,000. To this add \$20,000 for handling equipment for a total quarantine room cost of \$220,000 or .44% of capital costs.

The change in operational cost to the facility will result from additional handling or rods in quarantine. There might be 15,000 additional transfers of rods per year. Assuming 2 minutes per transfer adds 500 hours/year, i.e., equivalent of \$17,500/year or .18%.

B.8 DF-8 ASSEMBLY AREA

Assembly area is assumed to be cube 20 x 20 x 20. A method of constructing a structure which would indicate an attempt to create a clandestine penetration and at the same time be resistant to accidental breaks would be to build the cube of sandwiched glass panels. The two outside layers would be a knock resistant plate glass, containing between them a pannel of easily shatterable glass. This middle panel would visibly indicate a penetration (e.g., an attempt to drill a hole would create a shattered field of large dimensions). Such structures are not presently in use; however, we assume that they are cheaper than the vault construction. Assuming a glass panel cost of \$250 ft^2, this design feature would cost \$500,000 including two portals and internal fixtures. No operational costs should be encountered.

B.9 DF-9 TAMPER DETECTING SEALABLE CONTAINER

There is a need for about 100 assembly containers. These are boxes of 14' by 8" x 8" made from aluminum. The estimated cost for each container is \$1,000. The total cost is \$100,000 or .2% of capital cost.

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