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Vulnerability Analysis of a Mixed-Oxide Plant

Kenneth W. Foster and Howard A. Woltermann

May 8, 1980

Monsanto

MOUND FACILITY
Miamisburg, Ohio 45342

operated by
MONSANTO RESEARCH CORPORATION
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Contents

Abstract

To determine the degree of protection obtainable with the Controllable Unit Approach (CUA) to nuclear material control, a vulnerability analysis was performed on a proposed PuO_2-UO_2 mixed-oxide fuel plant. Diversion scenarios were developed for each potential diversion point in the process with the aid of a "diverter's option" tree. This tree assured that all attractive scenarios were considered and helped to avoid overemphasizing scenarios that would be ineffective or would be redundant. The option tree is based on diversion likelihood factors frequently employed in diversion path analysis. With consideration of all the permutations of pertinent likelihood indexes, as applied to the CUA closure equation network, the number of potential scenarios for the mixed-oxide plant with relative likelihood factors ≥ 0.1 was found to be approximately 1150. By utilizing the time and space spanning effects of the closure equations, one could reject many of these scenarios on the basis of high probability of prompt detection, and many others could be combined with scenarios that were effectively equivalent. This report details 40 diversion scenarios for removing 2.0 kg PuO_2 from the plant that could not be rejected on the basis of low relative likelihood or prompt detection.

From this analysis it was apparent that the CUA closure equation system does provide adequate protection against diversion of 2.0 kg PuO_2 from the mixed-oxide plant from a wide variety of material theft scenarios. Potentially sensitive areas are identified in this report and additional protective measures are suggested.

1. Executive summary

The Controllable Unit Approach to material control and accounting (CUA) has been shown to provide effective material control for any nuclear material processing plant. The CUA control system employs a network of material flow closure equations; each equation provides a periodic material balance within a specific section of a given process, and the network of equations spans the entire process. The network is computer monitored to provide timely control, and the equations are continuously updated by selected plant process control, production control, quality control, and inventory data.

The CUA methodology was recently applied to a proposed high-throughput mixed-oxide fuel plant [1], to determine whether a stated performance criterion for the process could be met with the proposed material measurement system of the plant. The closure equation network developed for this plant has consistently flagged trial single and trickle diversions imposed upon the system by computer simulation tests [2], thereby demonstrating that the plant could meet its stated performance criterion for these relatively simple types of diversion.

To determine the degree of protection provided by the CUA material control system, however, the mixed-oxide plant was studied for its vulnerability to organized material diversion. Vulnerable spots in the plant that were identified by this analysis could then be studied for improved measurement precision, added physical security, and wider inspector involvement.

Figure 1 is a schematic representation of the process, and Figure 2 shows the spans of the CUA closure equations developed for this process. Since one purpose of this study was to illustrate the applicability of CUA to a vulnerability analysis, only those plant areas spanned by the closure equation network were considered in detail. It was assumed that the vulnerability of the shipping and receiving areas, i.e., the only parts of the plant outside the equation network, could be determined by conventional techniques. Potentially vulnerable points in these areas, however, could easily be brought into the CUA control system by adding closure equations where appropriate.

It is useful at this point to introduce a space-time concept to multiple or trickle diversion. All single or multiple diversion scenarios can be placed in one of four categories:

1. Single Space - Single Time (SS/ST)
   A single removal or one-time theft from one point in the process

2. Single Space - Multiple Time (SS/MT)
   Several removals or trickle diversion from one point in the process

3. Multiple Space - Single Time (MS/ST)
   Single removals from several plant locations, not necessarily simultaneously

4. Multiple Space - Multiple Time (MS/MT)
   Multiple or trickle removals from several plant locations, not necessarily simultaneously.

For purposes of this vulnerability analysis, the criterion for a potentially successful diversion has been defined as any single theft (SS/ST) or combination of multiple thefts (SS/MT, MS/ST, or MS/MT) that would

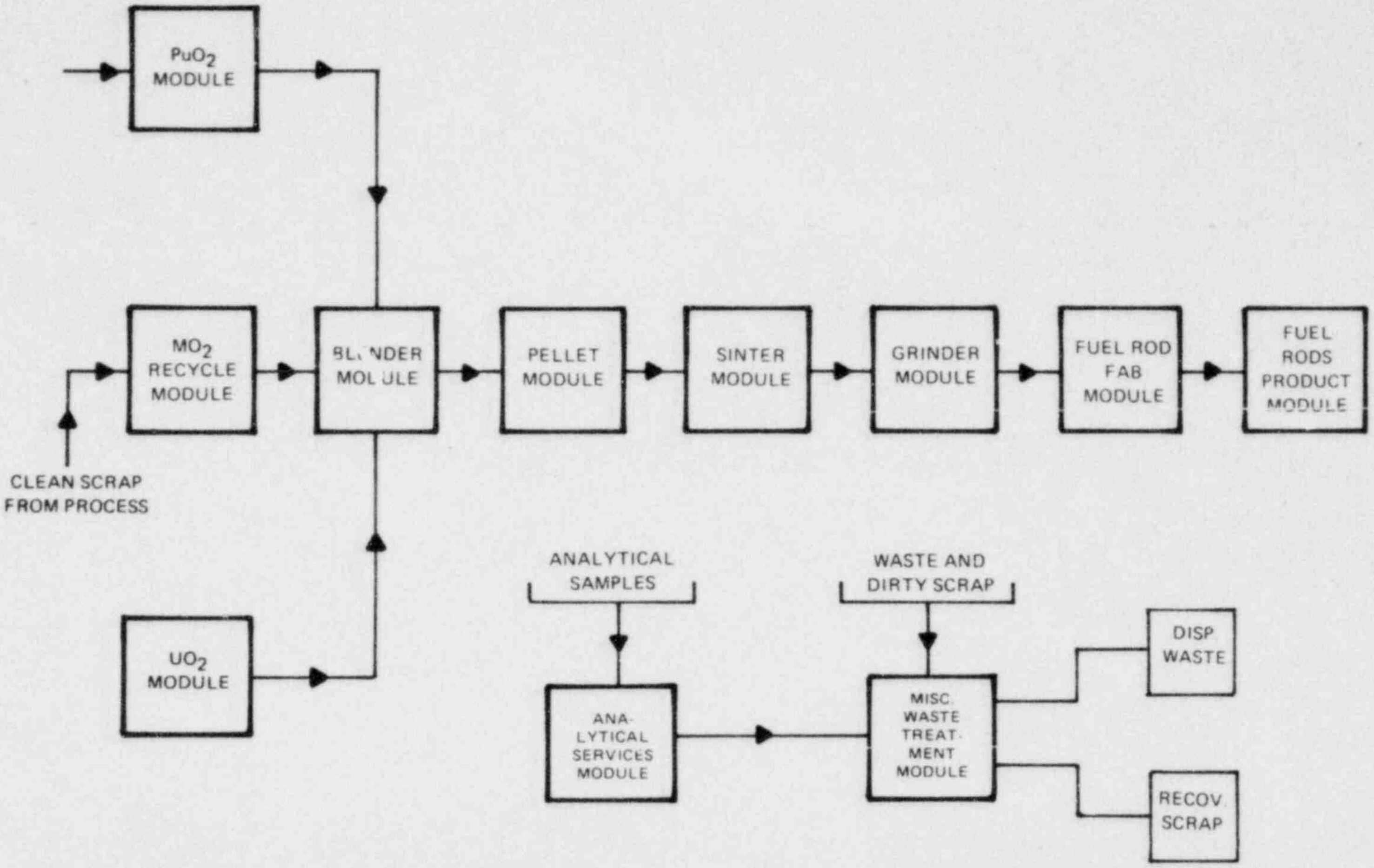

FIGURE 1 - Flow diagram of basic mixed-oxide process.

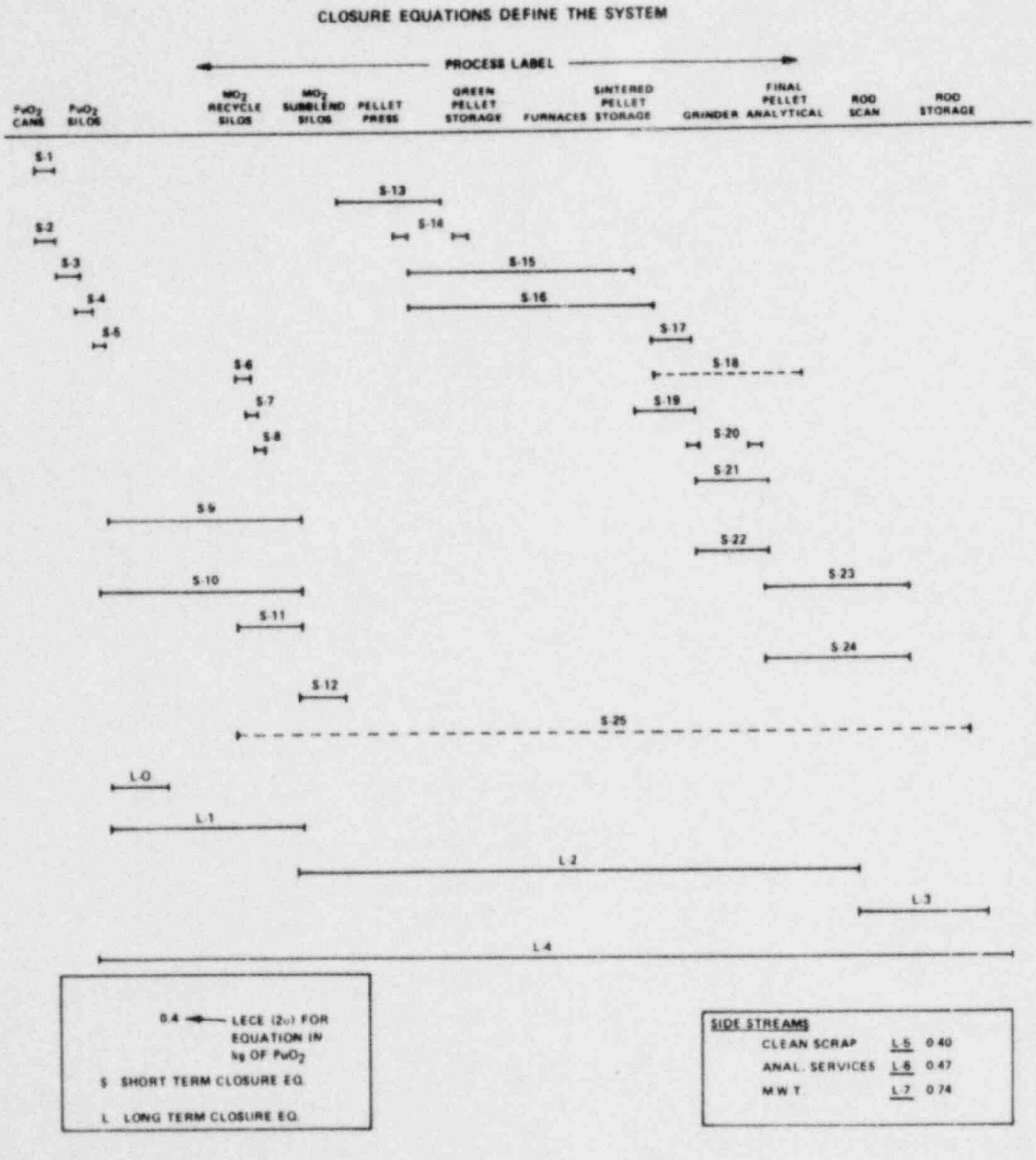

FIGURE 2 - CUA closure equations for the mixed-oxide process.

result in the loss of 2.0 kg or more of PuO_2 from the mixed-oxide plant during any two-month period. If the loss would be detected within 24 hr after reaching the 2.0 kg magnitude, the diversion is considered to have failed. Theft scenarios in which the discovery time would be less than 97.5% would not necessarily be successful, but rather would provide a basis for defining the vulnerable points in the process.

The vulnerability of the plant was assessed by examining possible material theft scenarios for all portions of the plant. Theft scenarios were developed from the standpoint of five relative-likelihood factors that are normally associated with diversion path analysis, i.e., (1) material attractiveness, (2) single or multiple thefts (space-time considerations), (3) material substitution, (4) record falsification, and (5) collusion. Ease of packaging and ease of removal were not considered in detail since these factors would be intimately related to the plant layout and the degree of physical protection. If the vulnerable points of the plant are pinpointed by a technique that is independent of the physical configuration of the plant and its security system, the analysis can then be used to determine effective improvements in the plant layout and to optimize the plant security.

Rather than trying to address the virtually unlimited number of scenarios that would be associated with a complex mixed-oxide plant, techniques were developed to systematically exclude highly unlikely or redundant scenarios from consideration. These techniques employ a "diverter's option" tree (Figure 3) which utilizes the main factors a thief must consider if he hopes to succeed. These factors include single or multiple theft, material substitution, data falsification, and collusion.

If the option tree were applied to each potential material removal point in the plant, the number of potential theft scenarios would still be unmanageably large. However, since each closure equation spans several potential theft points, many of these scenarios become redundant from the standpoint of detectability, and the number of scenarios to be considered can be reduced to a reasonable level. Also, because of the time spanning effect of each closure equation only the total material removed during any closure period will be detected. Thus, many possible multiple diversions from a given area are equivalent and need not be considered individually.

As each scenario was developed, it was examined from the standpoint of detectability and relative likelihood. The detectability of a diversion from a given plant area was determined directly from the closure equation controlling that area, the limit of error of the closure equation (LECE), and the assigned alarm threshold. The relative likelihood of each scenario was determined from established likelihood tables in the USAEC Regulatory Guide [3] and the DPA Handbook [4]. The likelihood factors do not address the probability that a thief will attempt a diversion; such evaluation is beyond the scope of this report.

By consideration of all the scenario formats formed by permutations of the relative likelihood indexes and the interaction

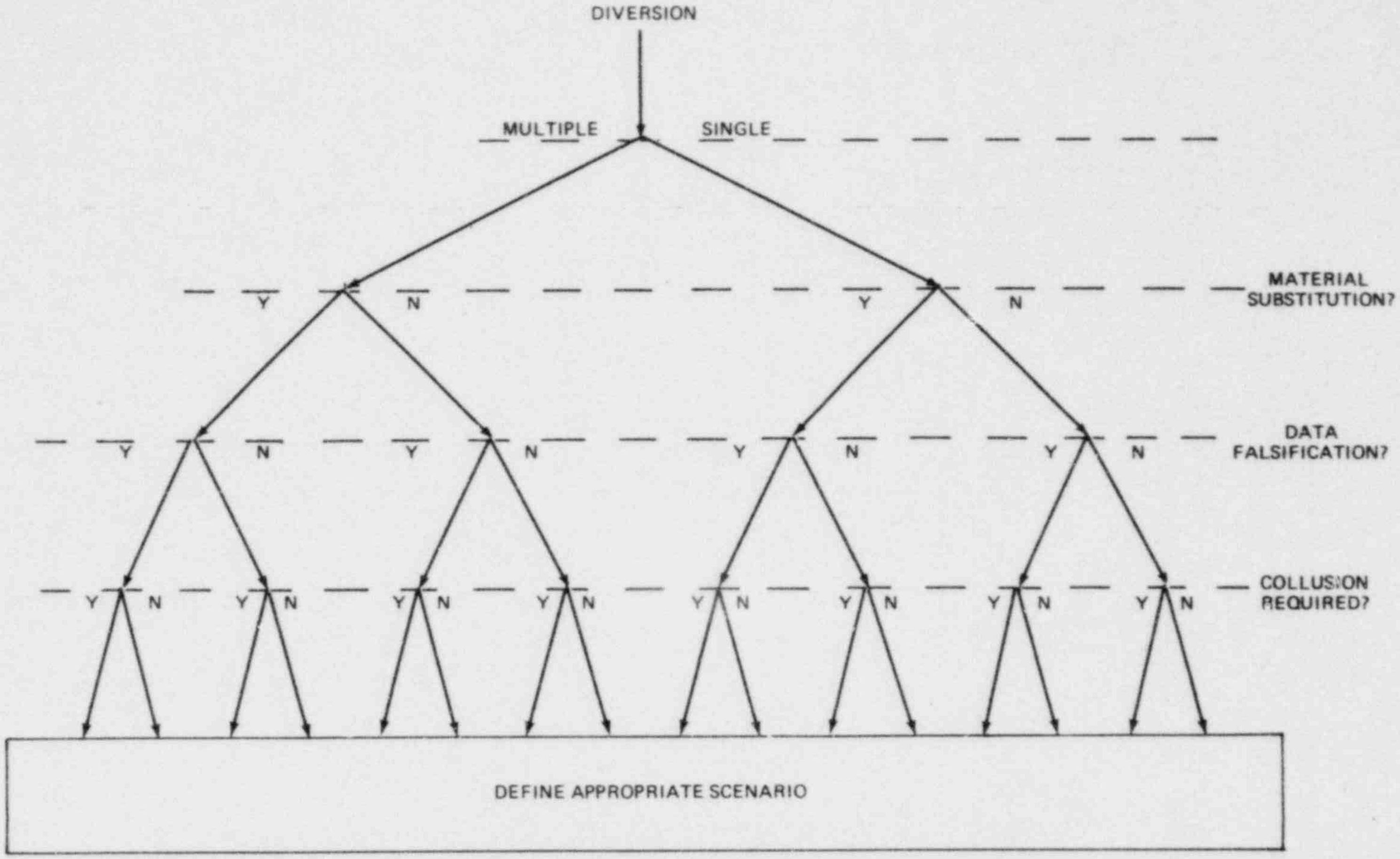

FIGURE 3 - Diagram of diverter's options.

of these formats with the CUA network, it can be shown that there are approximately 1150 generic scenarios with relative likelihood indexes greater than 0.1 in the mixed-oxide plant. Most of these scenarios can be eliminated from serious consideration by preliminary inspection. For example, many such scenarios for diverting 2.0 kg PuO_2 would be detected very promptly with almost 100% certainty, other scenarios can be eliminated on the basis of being members of a family in which all members would be detectable at >97.5%, and still others are effectively equivalent in the context of the closure equation network so that only one member of each family would have to be considered in detail.

In general, scenarios for diverting 2.0 kg PuO_2 having a detectability of 97.5% or greater within 24 hr without an unreasonable false alarm probability or those having a Relative Likelihood Index less than 0.1 were not considered in detail. Forty examples of generic scenarios that do not meet either of these rejection criteria are detailed in this report. These 40 scenarios are used to pinpoint the potentially vulnerable points in the proce.

It should also be noted that theft of 2.0 kg PuO_2 would require the thief to carry only about 4-1/2 lb, and theft of 50 kg MO_2 to acquire 2.0 kg PuO_2 would require that the thief be able to remove approximately 110 lb of material. This added difficulty is reflected in the material attractiveness index for the MO_2. Since control of UO_2 is not part of the specified performance criterion, diversion of UO_2 is not considered in this analysis.

To simplify the preliminary analysis of vulnerability, the mixed-oxide fuel plant was divided into seven major sections. Partitioning of these sections corresponds to major interface points of several of the closure equations in the plant. These sections are:

A. PuO_2 unloading and storage
B. PuO_2-UO_2 blending and subblend storage
C. MO_2 pelletizing and pellet qualification
D. Fuel rod fabrication, inspection, and shipment
E. Clean scrap recycle system
F. Dirty scrap and waste processing system
G. Analytical services facility

Each of these areas is considered in detail below.

A. Potential diversions from PuO_2 unloading and storage

This portion of the plant includes removal of PuO_2 from shipping containers, opening of storage cans, and transferral of the powder to a storage silo. Diversions prior to weigh-in are outside the realm of the closure equation network and are not considered in this analysis. It was assumed that there would be no undetected diversions prior to material weigh-in; i.e., any such diversion would be apparent from shipper-receiver differences.

A single removal (SS/ST) of 2.0 kg PuO_2 from the silo-loading operation is readily detectable at the 99.9%+ level and is not regarded as a threat. Multiple removal during a single silo loading (SS/MT) is also not a viable diversion technique because of the time spanning effect and cumulative monitoring by the controlling closure equation. Single removals of PuO_2 with UO_2 substitution, however, will not be detected by weight measurements alone, but will be detected at the 99.9%+ level by analysis of the contents of the filled silo. Detection time could require as long as one week since the silo contents are not normally analyzed until the silo is filled. Substitution prior to powder transfer would be detected within 8 hours because each can load is sampled for analysis.

Multiple diversion from several sequential silo loads (SS/MT) to accrue 2.0 kg PuO_2 is a slightly more attractive theft mode since the detectability may be reduced to about 92.0% and might require a period of up to a week to detect. Detectability can be improved to 97.5% by added replication of full silo weight measurements.

Each can unloading operation, however, should be monitored to prevent material substitution at the weight hopper and to ensure that each powder batch transferred to the silo is properly sampled for analysis.

Filled PuO_2 silos that are being held for QC certification for the blending operation may be somewhat vulnerable to substitution diversion. Although detectability of a substitution at this point is high (>99.9% in most cases) detection must await analysis of the mixed powders after the blending operation. Since the silo may stand idle for several days before its contents are used, blend analysis may require a week or more. Hence, procedures must be established to ensure that once a silo load is analyzed, tamper-safe seals are applied to the silo to maintain integrity of the load throughout its hold and use periods.

B. <u>Potential diversion from the blending and subblend storage modules</u>

Single removals of 2.0 kg PuO_2 or 50 kg MO_2 (2.0 kg PuO_2 equivalent) are promptly detectable at the 99.9%+ level. The PuO_2 feed system to the blender may be somewhat vulnerable to a multiple diversion (SS/MT) without substitution, provided the material is removed gradually throughout the 8-week operating period. Probability of detection of removal of 250 g per week would be about 20% per theft, so the probability of detection of the trickle removal during at least one week's operation in the eight-week period would be about 80%. Surprisingly enough, substitutional diversion at this point is much more likely to be detected (>99.9%) because of prompt analysis of the prepared subblend (i.e., within four shifts).

The MO_2 recycle feed silo being held for QC certification prior to blending must be sealed to ensure that, once a load is analyzed, its integrity is maintained throughout the hold and use periods.

The powder blending area is even less vulnerable than it appears above. The automated PuO_2 and MO_2 feed and weighing stations provide a considerable physical barrier to removal or substitution between the feed silos and the subblend storage silos. Once a subblend silo is filled and sampled for analysis, however, tamper-safe seals must be applied to preserve the integrity of the subblend batch throughout its hold and use periods.

C. Potential diversion from the MO_2 pelleting module

The only type of theft scenario that appears to be viable for this section of the plant is powder substitution prior to the slugging and pelleting operations. Detection of the substitution is achieved by random analyses of product pellets plus indications from in-line gamma scanners that something is amiss. Detection of substitution is 99.8% certain, but may require as long as one week if the substitution is made near the start of the line.

Multiple removal of slug press wafers (SS/MT), green pellets, or sintered pellets over the 8-week operational period may appear to be attractive because of the relatively high alarm thresholds of the controlling closure equations (4σ). Reducing the alarm thresholds to 2.5 , however, can increase the detectability of multiple theft scenarios that would accrue 50 kg MO_2 to 93.7% within each shift with very small increase in the false alarm rate. To remove material from this point in the plant, the diverter must acquire about 2500 slug press wafers or about 5000 pressed pellets. Substitution for wafers or pellets is not considered to be viable because of the relatively short time before detection and because any scenario introducing substitute wafers or pellets of the proper weight and dimensions would have a relative likelihood factor less than 0.1.

Administrative control of this module must preclude introduction of foreign material to either the slug press or pelleting press to prevent substitute diversion. Also, physical barriers designed to prevent unauthorized removal of wafers or pellets from their respective lines should be considered.

D. Potential diversion from the fuel rod fabrication module

The same problems confronting a diverter in the pelleting module relative to pellet removal and/or substitution would apply also to the fuel fabrication line. Pellet counts are sufficiently accurate to preclude removal of a sufficient number of pellets to constitute a threat. In addition, inert pellet substitution would be detected almost immediately with >99.9% certainty by gamma scanning of fuel rods. After pellets are welded into fuel rods, the welded rods are assigned item numbers and are controlled by item count with normal accountability procedures. Because of the lower material attractiveness and the necessity for a minimum multiple theft of 25 units, any scenario involving the theft of fuel rods would have a relative likelihood factor less than 0.1. When one considers also the difficulty of acquiring 2.0 kg PuO_2 by smuggling 25 fuel rods, each approximately 14 ft long, out of a plant, or the problems involved with clandestine disassembly of 25 fuel rods, it is quite apparent that theft of completed fuel rods is not a viable option for a diverter.

E. Potential diversions from the clean scrap recycle system

Since SS/ST and SS/MT removals are easily detectable, the only apparently viable diversion scenario from the clean scrap system would be the single removal of 50 kg MO_2 with inert substitution. Although the detectability of this type of diversion is >99.9%, the time required may be a week or longer when precise analysis of the recycled MO_2 becomes available.

The dominating error in this system on a shift-to-shift basis is the material holdup in the clean scrap reduction/oxidation step. Additional gamma scanning equipment may be necessary in this system to detect material substitution within a one-shift closure. Also, the alarm point of 4σ on the controlling closure equation may be too restrictive; a 2.5σ alarm point provides significantly improved protection against a trickle diversion with only a modest increase in the false alarm rate from 0.005% to 0.6%.

F. Potential diversions from the waste treatment module

This module is governed by one long-term CUA equation that closes every eight weeks. Although the material attractiveness index of MO_2 wastes is very low, it is possible to remove 2.0 kg PuO_2 as badly contaminated waste. With such a removal there would be a delayed detectability of up to several weeks. If it should appear that some of the waste material is an attractive target it would be necessary to add a short-term closure equation to this module to monitor the weekly plant runoffs.

G. Potential diversions from the analytical services facility

The total amount of material resident in this module at any one time is no more than 0.75 kg, PuO_2 and the total passing through the module is about 6.0 kg PuO_2 per inventory period. Removal of 2.0 kg or more PuO_2 from this area would require that the theft be spread over the entire inventory period. Any such diversions are detectable by closure of the controlling equation at the 99.9%+ level. It is concluded there are no viable options for diversion from this model. Administrative procedures, however, must ensure that the integrity of analytical results is retained and that data falsification in the analytical laboratory is not used to cover an inert substitution somewhere else in the plant.

The option of data falsification to cover removal of material from a CUA-controlled plant was considered, but no viable scenarios were discovered. The diverter can gain some additional time in some areas of the plant by falsifying side stream data to cover removal of material from the main stream. Detection of this type of diversion is covered by the closure equations monitoring the side streams. In some cases, more frequent closures of equations in the scrap or waste areas may be required to achieve more timely detection of this type of diversion.

If a false data entry is inserted within the realm of any closure equation, the discrepancy will be detected with the same probability as any other closure imbalance. If the falsification is made at an interface between two short-term equations, detection will occur by a material imbalance in one or both of the two equations. Likewise, an input-output discrepancy between two equations would be apparent, and any material discrepancy would show up eventually as closure imbalance in the controlling long-term equation.

Because of the interrelation of the closure equations and the use of process control data to drive these equations, any significant discrepancy between input data and plant status would have to be propagated throughout the closure equation network to avoid detection. To be successful, such an attempt would place extreme demands on the diverter's depth of understanding of the plant operations and the closure equation system. In addition, it is not likely that extensive record changes could be accomplished without a several-person collusion, so this option could also be rejected on the basis of low relative likelihood. At best, falsification could prolong the detection time, thereby giving the diverter some leeway to complete his theft. It is concluded that data falsification to conceal a diversion is not a fruitful option for a thief in the CUA-controlled mixed-oxide plant.

From this vulnerability analysis it is apparent that the CUA monitoring system will provide adequate and timely protection against simple material removal scenarios (i.e., SS/ST and SS/MT) anywhere in the mixed-oxide plant, with the possible exception of the waste-processing module. With specific measurement refinements and added physical security in identified vulnerable areas, the plant can meet its specified performance criterion.

It is recognized that a clever thief could succeed in circumventing the material control system in many areas of the plant, but if he has any hopes of escaping detection long enough to complete his diversion, he must introduce more complex secondary factors into his scenarios, e.g., multiple diversion with substitution and perhaps collusion. Such added complications would increase his risk of discovery, as would be evidenced by very low relative-likelihood factors.

This report does not address the problem of detection of one-time diversions from several closure equation realms (MS/ST). A preliminary investigation of this problem has shown that there are no major vulnerabilities of this type in the mixed-oxide plant [5]. The concept of multiple diversions from multiple closure equation realms (MS/MT) will be the subject of a future report.

2. Introduction

The Controllable Unit Approach (CUA) to material control and accounting has been shown to provide effective material control for any nuclear material processing plant and has recently been applied to a proposed high-throughput mixed-oxide process [1].

In the CUA control system, a plant or process is monitored by a series of material flow equations; each equation covers a specific operation or series of operations within the plant. These equations, called "closure equations", employ plant operational data to maintain running material balances. All equations are updated continuously with operational data as they are received, and closure balances are obtained periodically from each equation. Computerized data handling is employed to keep all operational data current and to provide timely alerting to anomalous conditions.

For the mixed-oxide plant, a network of closure equations was developed that spans the entire length of the process. These closure equations have consistently flagged single and trickle trial diversions of special nuclear material imposed upon the system by computer simulation tests at Mound [2].

The control that can be obtained on any process is only as good as the material measuring capabilities at various points throughout the system. Even with careful evaluation of systematic errors, random statistical errors will impose a lower limit upon the amount of material loss than can be detected reliably by any one measurement. If the measuring random statistical errors are normally distributed with a known standard deviation, σ, and if proper allowance is made for systematic errors, any measurement has a probability of 95.4% of being within $\pm 2\sigma$ of its true value. Because of these inherent errors, any material balance equation will generally exhibit a nonzero closure. The size of this closure equation imbalance, "CEI", relative to the standard deviation of the closure equation is a measure of the probability of whether a given CEI represents unaccounted for material movement or is a normal statistical variation of the equation closure.

Random and systematic errors associated with all measurements within the realm of each closure equation were compiled into a composite standard deviation, σ, for the equation. The limit of error of the closure equation, "LECE", is defined as twice the composite standard deviation (2σ) for the equation. Thus, each closure equation has an associated LECE that is the measure of the control precision afforded by the closure of the equation.

To determine the degree of protection the CUA material control system provides, it is necessary to examine the mixed-oxide plant for its vulnerability to organized material diversion. The vulnerability of a plant can be determined by considering the relative simplicity or complexity of possible theft scenarios and the ease or difficulty of detecting material loss, pertinent to each of the various material-handling operations within the plant.

Figure 1 is a schematic representation of the mixed-oxide process, and Figure 2 shows the spans of the CUA closure equations that were developed for this process.

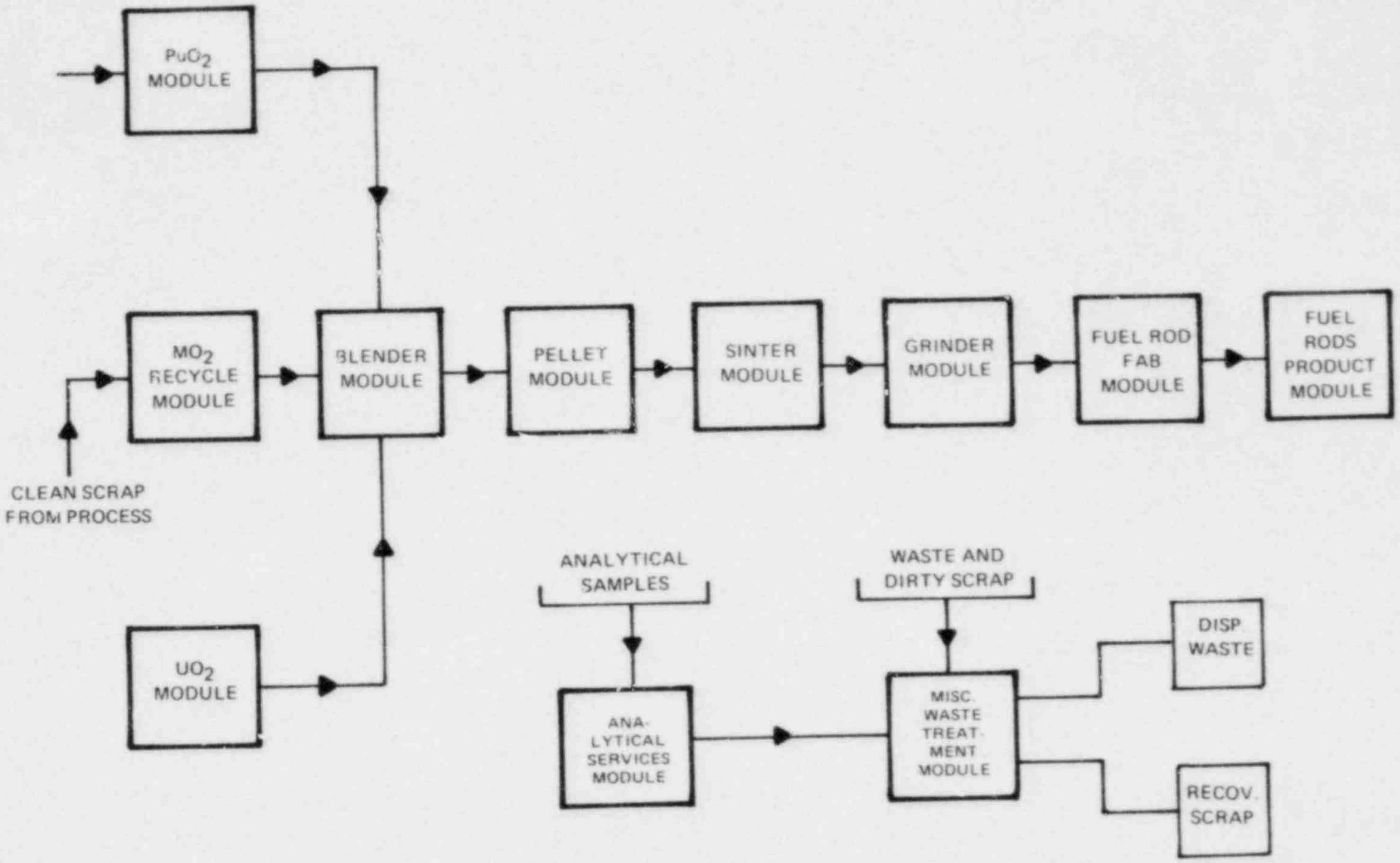

FIGURE 1 - Flow diagram of basic mixed-oxide process.

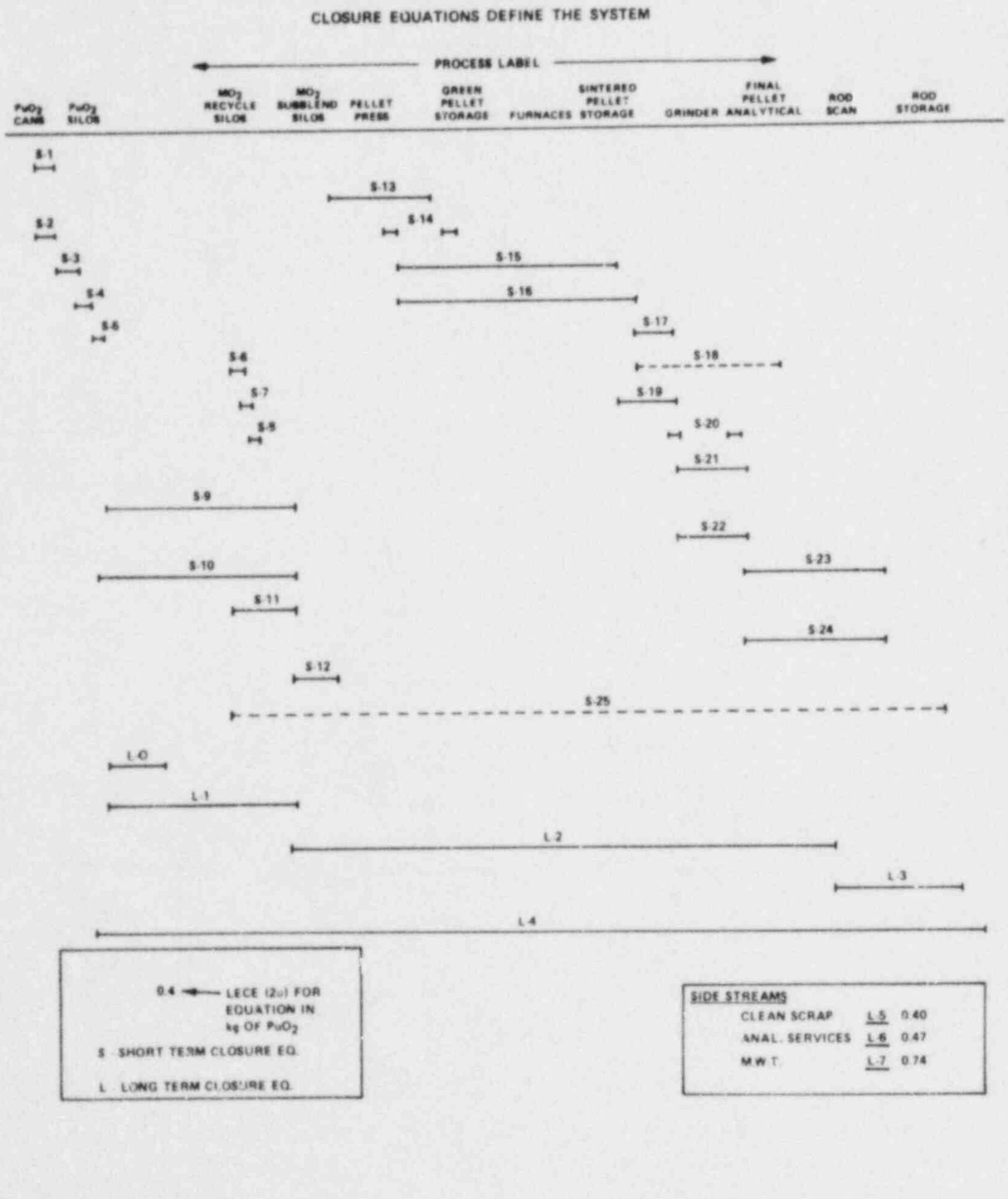

FIGURE 2 - CUA closure equations for the mixed-oxide process.

In a plant as involved as the mixed-oxide plant, the number of conceivable diversion scenarios is virtually limitless. Rather than attempt to define and evaluate thousands of potential theft modes, it is much more productive to examine factors that a thief must consider if he entertains any hope of success, and then use these factors systematically to develop credible diversion scenarios.

Obviously, this study must be systematic to ensure that all attractive scenarios are considered and to avoid overemphasizing those scenarios that would be ineffective or redundant. Also, a method must be provided to rank potentially successful scenarios with respect to ease or attractiveness of implementation. This ranking in no way implies any probability of attempt of theft; it merely serves as a systematic method of prioritizing threats to the material control system.

The factors to be considered are as follows: material attractiveness, accessibility of the material to the thief, ease or difficulty of concealing the diversion, the number of accomplices required, and the probability of detection. Other factors, such as ease of packaging and ease of removal, are not normally considered in this type of vulnerability analysis since these factors are intimately related to the plant layout and its physical security system. Results of a vulnerability analysis, however, can be used to determine where improvements in the plant layout can best be implemented to optimize the physical security system.

All these factors can be evaluated in relation to their impact on the detection of a diversion. For purposes of this report, "detection" implies the discovery of a loss of material by the process measurement system. Discovery of diverted material by scanning devices or other inspection techniques is part of the security system and is not considered in this analysis. The difficulties that would be encountered by a thief in diverting the material, packaging it, and smuggling it out of the plant are addressed by diversion likelihood factors to be discussed in Section 3. Armed attack is outside the scope of this analysis.

For this vulnerability analysis, the criterion for a successful diversion has been defined as any single theft or combination of multiple thefts that would result in the loss of 2.0 kg or more of PuO_2 from the plant during any two-month period. If the loss is detectable at a probability of 97.5% or greater within one day (24 hr) after reaching the 2.0 kg magnitude the diversion is considered to have failed. Any scenario in which the discovery time is longer than 24 hr or the detectability is less than 97.5% is not necessarily successful, but rather provides a basis for defining the vulnerable points in the process.

Since one of the purposes of this study was to illustrate the applicability of CUA to a vulnerability analysis, only those plant areas spanned by the closure equation network were considered in detail. It was assumed that the vulnerability of the shipping and receiving areas, i.e., the only parts of the plant outside the closure equation network, could be determined by conventional techniques. Potentially vulnerable points in these areas could, however, be easily brought into the CUA control system by addition of appropriate closure equations.

3. Development and evaluation of diversion scenarios

For a complete vulnerability analysis of the mixed-oxide plant it is not necessary to consider every possible material handling point; it is sufficient to consider only each CUA closure equation and its realm. To develop potential diversion scenarios, each such realm that was considered was examined in detail by means of a "diverter's option" tree, shown in Figure 3. This tree is derived from likelihood index tables, to be described below, and addresses four of the five factors that are generally sufficient to comprise all likely theft modes of a given material: single or multiple removals, substitution, record change, and collusion. Most scenarios can be represented as "yes-no" combinations of these four factors. The fifth factor, material attractiveness, was not included in this tree since the tree would be applied to all target materials in the plant. Admittedly, a given path through the option tree may describe more than one potential scenario, particularly since the "yes" branch at any one decision point may contain several options. Likewise, there are several questions to be considered at each potential diversion point which are difficult to categorize into simple "yes-no" combinations. These questions are collected into a category of "external factors" which will also be discussed below.

In order to grade the relative seriousness of each scenario as it is developed, the scenario is examined for its probability of detection and its relative likelihood. The probability of detection of a diversion is based on the ability of the controlling closure equation to detect the removal of the amount of material specified by the scenario. In this respect, the probability of detection is determined by the LECE of the closure equation spanning the area involved and its specified alarm threshold.

Because of systematic and random errors associated with the measuring systems, a measurement indicating a loss of material may or may not be realistic indicator of an attempted diversion and may be a false alarm (Type-I error). Likewise, a measurement in which there is no alarm would not be an absolute indication that no removal had occurred; if the removal were small enought it might be lost in the normal statistical variations of the measurement system (Type-II error). With an alarm threshold set at some arbitrary level, there will be a finite probability that some CEI's will exceed the alarm level even though there is no material removal; this probability is known as the "false alarm probability" and is designated by the symbol, α. The false alarm level will normally remain fixed for a given set of equation closures and will depend only upon the threshold setting. With a specified alarm threshold there is also a finite probability that a given loss of material will not be observed (Type-II error). This probability is known as the "nondetection probability" and is designated by the symbol, β. The nondetection probability is not fixed for a given measurement system but depends on the relative magnitude of the amount of material missing and the LECE of the closure equation. With a given LECE and specified alarm threshold, the value for β can be determined from standard statistical tables. It follows that the probability of detection of missing material is $1 - \beta$; this probability is usually expressed in percent.

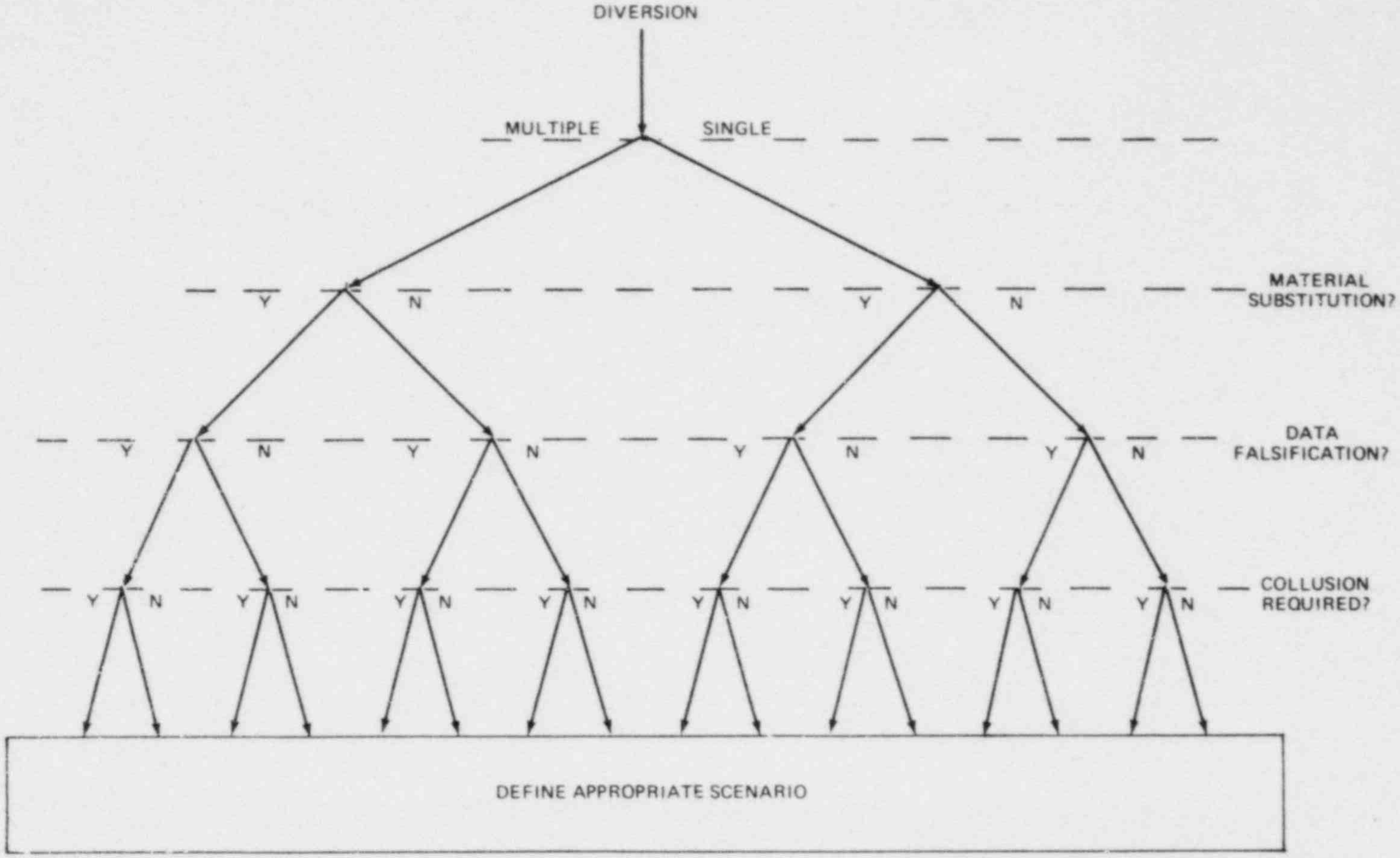

FIGURE 3 - Diagram of diverter's options.

Table 1 - EXAMPLES OF RELATIVE LIKELIHOOD INDEXES FOR THE MIXED-OXIDE PLANT[a,b,c]

Material Attractiveness		Distribution Number		Removal Mode		Record Change		No. of Persons	
PuO_2	1.0	Single	1.0	Simple	1.0	None	1.0	One	1.0
MO_2	0.6	Two	0.9	Inert Subst.	0.7	Weight	0.9[d]	Two	0.3
Clean Scrap	0.6	Three	0.8	Isotopic Subst.	0.1	Concentration	0.5	Three	0.1
Dirty Scrap	0.4	5 - 10	0.4			Non-measurement data	0.45		
Disposable	<0.1	>10	0.1			Limit of Error	0.1		

Notes

[a] NRC Guide #5.24 considers whether the primary thief is operator, other employe with access to the area, or outside personnel. For vulnerability analysis the thief is assumed to have full access to the system, so this factor drops out of consideration.

[b] Any other factor not listed is assumed to have a relative likelihood index of 1.0.

[c] The DPA Handbook lists more detailed likelihood indexes than are given in the above table. Although closer calculation of relative likelihood might be worthwhile in an attempt to define an actual theft, the finer detail does not appear to be warranted for the vulnerability analysis.

[d] NRC Guide #5.24 assumes a likelihood index of 1.0 for weight falsification, while the DPA Handbook lists a value of 0.85. The value in this table represents a compromise of these two indexes.

Because of both Type-I and Type-II errors, selection of an alarm threshold is a tradeoff between a false alarm rate that can be tolerated and a minimized probability of detection of loss that will still provide adequate protection of the process. For the CUA analysis of the mixed-oxide process it was useful to specify for most closure equations that the alarm threshold be set at least one LECE (2σ) greater than the expected mean values of closure equation imbalances. This threshold level corresponds to a false alarm rate of 2.28% for each equation. A diversion of 2σ from one of these equations would have a probability of detection of 50%, and a diversion of 3.96σ would have a probability of detection of 97.5%. For some equations in the process with very low LECE's, the alarm threshold was set to 4σ to reduce the plant over-all false alarm rate. With this alarm threshold, a diversion would have to be at least 5.96σ to be detectable at the 97.5% level.

Relative likelihood indexes for all categories in the option tree are based on listings of likelihood indexes in the USAEC Regulatory Guide [3] and the ERDA/NBS Diversion Path Analysis Handbook [4]. Appropriate likelihood indexes are discussed below and are summarized in Table 1.

3.1. Material attractiveness

Likelihood indexes were assigned to all physical and chemical forms of material expected to be handled in the entire mixed-oxide plant, i.e., PuO_2, MO_2, MO_2 clean scrap, MO_2 dirty scrap, and liquid and solid wastes. These likelihood indexes are based in part on detailed material description factors in the DPA Handbook [6] and in part on experience at Mound in handling various forms and isotopes of plutonium.

3.2. Distribution

- single or multiple theft

All single or miltiple diversion scenarios can be placed into one of four categories:

Single Space - Single Time (SS/ST)
A single removal or one-time theft from one point in the process

Single Space - Multiple Time (SS/MT)
Several removals or trickle diversion from one point in the process

Multiple Space - Single Time (MS/ST)
Single removals from each of several plant locations, not necessarily simultaneously

Multiple Space - Multiple Time (MS/MT)
Multiple removals or trickle diversons from each of several plant locations, not necessarily simultaneously

For purposes of this analysis, a single theft is a one-time removal of 2.0 kg or more PuO_2 from any point in the process (SS/ST). A multiple removal is any number of two or more thefts that would accrue to a total of 2.0 kg or more PuO_2 in any specified period. The distribution number is the number of individual thefts required to achieve the diversion.

Multiple removals may be individual thefts from each of two or more closure equation areas (MS/ST), single removals from each of a sequence of two or more closures of a given closure equation (SS/MT), or any combination of these two modes (MS/MT). Any scenario involving multiple removals within one closure period of a given closure equation is, however, considered to be a single theft since the closure equation will detect the total material removed during the closure period. This feature of CUA methodology eliminates the necessity of considering separately a wide variety of potential multiple diversion scenarios which would be, in fact, CUA equivalents.

In this respect, the number of multiple diversions from a given closure equation realm that must be considered are no greater than the number of equation closures accomplished in the inventory period. If, for example, a given equation is closed 40 times in a given two-month period, either a single theft of 2.0 kg or multiple thefts encompassing anywhere from 2 thefts of 1.0 kg each to 40 thefts of 50 g each from that area are the only candidates for potential diversion scenarios that need be considered.

3.3. Substitution - Yes or No

If there is substitution, two options are available to the thief, i.e., weight substitution and isotopic substitution. The weight substitution includes material that will mix intimately with the powder and transfer around the plant with the powder, solid items that can be added readily to various weighing points but would not normally move with the powder (including false tare weights both internal and external), or solid items approximating the weight and appearance of pressed pellets.

For a plutonium process, isotopic substitution for the purpose of confounding both weight and chemical analysis is not expected to be a viable option for a diverter since plutonium-239 is the only abundant and least radioactive plutonium isotope available. A diverter might consider the use of one of several radioisotopes, such as plutonium-238, or americium-241, in an attempt to create false information in plant areas where material is monitored by gamma scanning techniques. This type of substitution, however, would be detected in subsequent weight measurements. Further refinements of gamma scanning measurement could easily include gamma energy discrimination to differentiate between plutonium-239 and any radioactive substitute.

3.4. Record change - Yes or No

Four types of record change should be considered: weight data falsification; concentration data falsification; falsification of the limit of error of some appropriate measuring system; and falsification of nonmeasurement data, such as deliberate mislabeling of analytical samples, batches, or identification numbers of accountable items. Weight falsification would include falsified weighing data and/or falsified tare weights (as opposed to addition of actual weights to distort tare values). Concentration falsification could be used to conceal gradual substitution of inert material at some point in the process. Analytical sample mislabeling would include submission of false samples for analysis. Data falsification and/or errors can occur by improper recording, improper entry to a computer, and tampering with computer stored files.

3.5. Collusion required - Yes or No

If collusion is required to achieve a successful diversion, the scenario must determine the minimum number of conspirators required. Even if collusion is not required for a potential theft, scenarios in which the chances of success can be enhanced by the addition of one or two accomplices should be considered. As can be seen in Table 1, if more than three conspirators are needed, the scenario can generally be rejected on the basis of low relative likelihood.

3.6. External factors

In addition to the questions addressed by the option tree, additional factors should be considered for their possible impact on reducing the probability of detection or lengthening the time required to detect a loss. These factors would include:

1. Physical damage to key equipment (i.e., accident or sabotage) forcing plant shutdown and preventing CUA equation closure.
2. Distortion of calibration of measuring equipment
3. Attention diverting tactics, such as introduction of a deliberate data error in one part of the plant which would shut the plant down for investigation, then removal of material from another portion of the plant during shutdown.

Table 1 contains three major changes in the relative likelihood indexes from those given in NRC Guide #5.24; namely, types of material that are specific to a mixed-oxide plant were categorized and two indexes in the record change category were modified.

Relative likelihood indexes are not given at this time for any external factors since such factors depend considerably on the physical layout of the plant, the equipment used, and plant security measures. Certainly development of appropriate indexes for these factors should be considered when an actual plant is evaluated.

The relative likelihood factor (RLF) of a given theft scenario is the product of the individual likelihood indexes of the factors comprising the scenario, as obtained from Table 1:

$$\mathrm{RLF} = \prod_{i=1}^{5} I_i$$

In general, scenarios with relative likelihood factors less than 0.1 or with detection probabilities greater than 97.5% within 24 hr for loss of 2.0 kg PuO_2 were not considered in detail. It is assumed that if any abnormality is detected anywhere in the system it can be determined reliably within a reasonable length of time whether the abnormality is a result of physical removal of material or is a false alarm. Scenarios in which the relative likelihood is high and the probability of prompt detection is low were used to pinpoint the most vulnerable locations in the process. In an actual plant, such vulnerable locations would be studied for possible improvements of measuring techniques, added physical security, or monitoring by nonoperating personnel.

4. Vulnerability analysis

For examples of how this analysis can identify vulnerable areas in the plant, potential theft scenarios were applied to all areas of the plant. To simplify this operation, the plant was partitioned into seven sections and scenarios were developed throughout each section. These sections are: PuO_2 powder unloading and storage; PuO_2 blending and subblend storage; MO_2 pelletizing, sintering and grinding; fuel rod fabrication and certification;

clean scrap recovery and reprocessing; dirty scrap and waste processing; and analytical services.

If one considers all the permutations of factors in Table 1 that result in scenarios with relative likelihood factors greater than 0.1, it is possible to calculate the number of generic combinations that would apply to each portion of the plant. Within this limitation, the number of generic formats that can be related to each type of material handled are as follows: 56 formats are PuO_2 related, 41 are MO_2 related, 41 are MO_2 clean scrap related, and 33 are MO_2 dirty scrap related. If these formats are applied to each relevant closure equation, the seven plant areas denoted above would have the following numbers of possible generic scenarios:

1. PuO_2 unloading and storage	168
2. PuO_2-MO_2 blending and sub-blend storage	414
3. MO_2 pelleting, sintering, and grinding.	246
4. Fuel rod fabrication and certification	164
5. Clean scrap recycle	82
6. Dirty scrap and waste processing	33
7. Analytical services	41

Although all these 1148 generic formats were considered for viable diversion scenarios, it was possible, by preliminary inspection, to eliminate a large portion of them from detailed consideration. For many of the scenarios loss of 2.0 kg PuO_2 could obviously be detected very promptly with almost 100% certainty, and frequently it could be shown that families of scenarios could be eliminated on the basis that the least detectable member of the family had a detectability greater than 97.5% for a loss of this magnitude. Also, in other families all members had identical detectabilities, e.g.; multiple and single diversions in the same closure of an equation would be equivalent, so that only one member of the family was examined in detail.

All the generic formats that could not be rejected on the basis of low relative likelihood or prompt detectability are included in the 40 scenarios detailed below in this report. These potentially successful scenarios are ranked according to their seriousness in Section 5 of this report. Any one of these scenarios could permit a diverter to circumvent the performance criterion for the plant. System refinements to override these scenarios to bring the process into compliance with the performance criterion are discussed in Section 6.

4.1. PuO_2 unloading and storage module

This section of the plant, shown schematically in Figure 4, is spanned by short-term closure equations S-1, S-2, S-3, and S-4, and by long-term equation L-0. The realms of these equations, their closure cycles, LECE's, and modes of measurement are given in Table 2.

The PuO_2 unloading and storage section of the plant operates as follows. Pure PuO_2 powder is stored in large shipping casks, which are, in turn, stored in a suitable vault (Location 2, Figure 4). Each cask contains approximately 4.5 kg of powder, divided equally between two welded cans

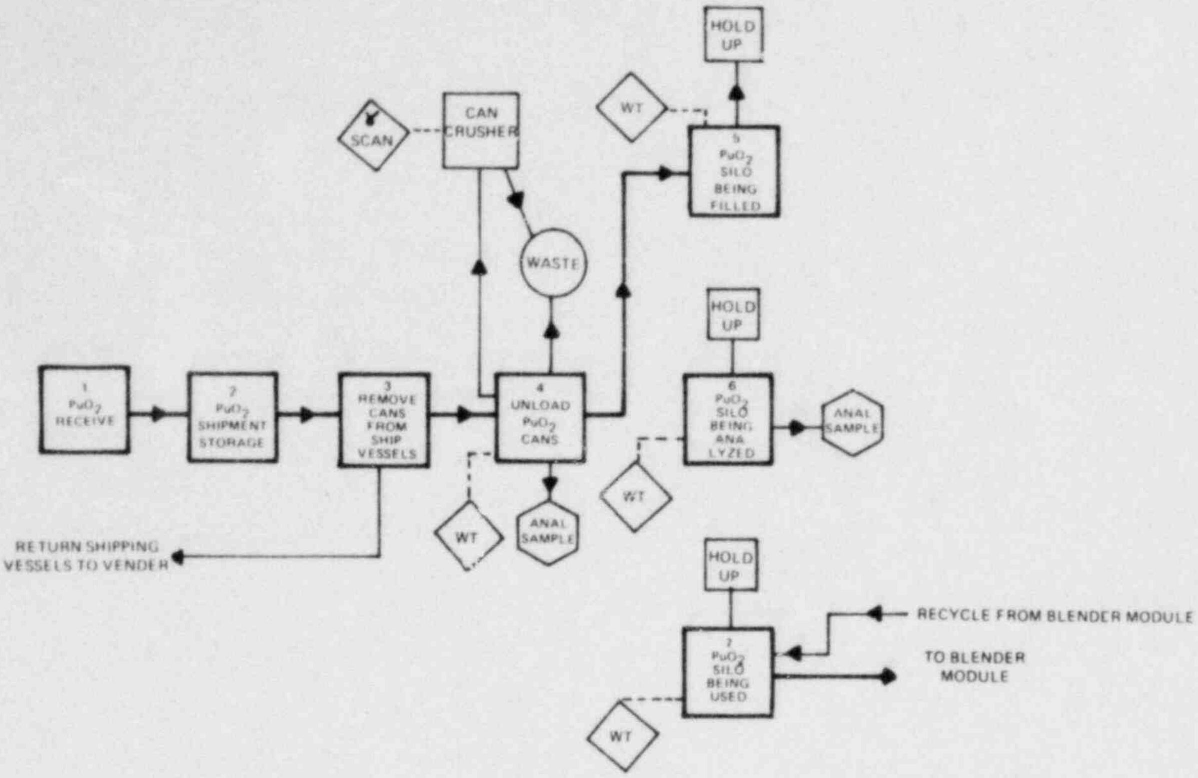

FIGURE 4 - Flow diagram of PuO_2 module.

Table 2 - CUA EQUATIONS GOVERNING PuO_2 SECTION OF THE PLANT

Equation	Process Controlled	Closure Cycle	(2σ) LECE (kg)	Mode
S-1	PuO_2 Cans to Storage Silo	Each Can (∿ 3/shift) & Each Silo Load (1/wk)	0.9 0.36[a]	Wt
S-2	Same as S-1, but adds Pu Analysis	Each Silo Load (1/wk)	1.0 0.63[a]	Wt/Anal
S-3	PuO_2 Silo on Analytical Hold	1/shift	0.9 0.30[a]	Wt
S-4	PuO_2 Silo to Feed Hopper	1/shift	0.9 0.43[a]	Wt
L-0	PuO_2 Cans to Storage Silo	1/inventory Period	1.46	Wt/Anal

[a] LECE improved by rolling average data filter.

Note: Alarm threshold is 1 LECE (2σ) for each equation.

(i.e., there is nominally 2.25 kg PuO_2 or 2.0 kg Pu per can). As each cask is opened, the two cans are identified, suitably logged, and weighed (Location 3).

After being weighed, each storage can is then opened, an analytical sample is weighed out, and the contents of the can are dumped into a hopper for pneumatic transfer to the storage silo (Location 4). The empty can and lid are tared and transferred to waste storage for ultimate decontamination and disposal.

The plant is operated continuously on a three-shift per day basis; there is a total of 21 8-hr shifts per week. Every two months (approximately eight weeks) the plant is shut down for cleanup, material holdup removal, and complete nuclear material balancing.

There are three identical storage silos for PuO_2 (Locations 5,6,7). In any one week of operation one silo is being filled, the second silo is being held for analysis, and the third silo is being used to supply PuO_2 powder to the rest of the plant. Each silo holds the contents of 74 cans, or approximately 166 kg of PuO_2. All 21 shifts in one week are required to load one silo, so that either three or four cans are processed in any one shift. The gross silo weight is monitored closely throughout the entire loading process and loading weight data are compared to can unloading data by means of CUA equation S-1. With this schedule, each silo is cycled every three weeks during the two-month operation cycle. Short-term equations, S-1, S-2, S-3, and S-4, are closed on batch-to-batch, shift-to-shift, and load-to-load bases, and the long-term equation, L-0, is closed at each two-month shutdown.

Material in receiving (Location 1), storage (Location 2), and cask opening (Location 3) is outside the CUA equation network. Proper initiation of the CUA network requires assurance that the initial input weights in Location 4 (unloading station) accurately reflect the amount of material handled by Location 4. Weighings at this location are used to verify shipper-receiver agreement, so that standard item accountability procedures and physical protection are required for all operations prior to this point in the process. Evaluation of the vulnerability of the plant prior to Location 4 is outside the scope of this analysis; it is assumed, for purposes of this report, that there have been no diversions prior to opening the shipping casks.

Physical removal of material from this section of the plant is possible by means of the following operations at the locations indicated in parentheses:

- Removal of sealed can prior to weighing (4)
- Removal of sealed can after weighing (4)
- Removal of PuO_2 powder from opened can (4)
- Removal of PuO_2 powder from silo being filled (5)
- Removal of PuO_2 powder from full silo (6)

Examples of potential scenarios for theft from these areas are given below. These examples are not all inclusive, but rather were selected to indicate the various factors addressed by the option tree. The list does, however, include all scenarios that could not be eliminated by low RLF or high detectability.

EXAMPLE 1: Removal of Sealed Can Prior to Weighing

Since the plant would be maintaining an adequate item accountability system, a missing can would be detected with virtual certainty prior to the end of the same shift, and probably within an hour, so that the simple theft of a can would not be viable option to a diverter. There is, however, one scenario of this type that can escape detection for at least 24 hr.

SCENARIO - Steal one can of PuO_2 (2.25 kg) prior to weighing and replace with identical can of UO_2 (also 2.25 kg).

Decision	Relative Likelihood Index
Material Attractiveness	1.0
Single Removal	1.0
Inert Substitution	0.7
No Record Change	1.0
No Collusion	1.0
Relative Likelihood Factor	0.7

This is an attractive scenario from the diverter's point of view since the material is already packaged and contains enough material to be a significant loss to the plant. The can substitution would avoid problems with item accountability and there would be no discrepancy in empty can counts or in the number of powder batches transferred to the storage silo. The scenario would, however, require that the diverter have prior knowledge of the precise weight of a given can so that he could prepare the substitute accurately and thereby avoid raising problems with shipper-receiver reconciliation.

EXAMPLE 2: Single Removal During Silo Filling

SCENARIO - Steal a sealed can after weighing but before opening.

Decision	Relative Likelihood Index
Material Attractiveness	1.0
Single Removal	1.0
No Substitution	1.0
No Record Change	1.0
No Collusion	1.0
Relative Likelihood Factor	1.0

The diversion of 2.25 kg PuO_2 is approximately 5σ of a single closure of CUA equation S-1. With an alarm threshold of 2σ, the probability of detecting the removal of this quantity of material is 99.3% within one shift.

This scenario would also be detected by an imbalance between the number of powder batches transferred and the number of cans logged into the system. Because can and batch counts are considered to be errorless, the probability of detection of this type of diversion by the end of the same shift is virtually certain.

EXAMPLE 3: Single Removal During Silo Filling with Inert Substitution

SCENARIO - Substitution of one sealed can of UO_2 for a sealed can of PuO_2 after weighing at the unloading and weighing station.

Decision	Relative Likelihood Index
Material Attractiveness	1.0
Single Removal	1.0
Inert Substitution	0.7
No Record Change	1.0
No Collusion	1.0
Relative Likelihood Factor	0.7

This scenario would not be detected by any can or batch count, nor would any weight abnormalities be detected by closure equation S-1 upon closure. Also, the substitution would result in a concentration of approximately 1.3 at. % uranium in plutonium in the filled silo; the scenario is virtually 100% detectable by closure of equation S-2, but could require as long as one week to detect. One refinement to regain timeliness control would be inclusion of a closure equation covering daily analytical sample submissions.

EXAMPLE 4: Single Removal of Powder During Silo Filling with Inert Substitution and Record Falsification

SCENARIO - Substitute 2.0 kg UO_2 for 2.0 kg PuO_2 removed from an opened can at the weighing station, and take the analytical sample from the 0.25 kg PuO_2 remaining in the opened can.

Decision	Relative Likelihood Index
Material Attractiveness	1.0
Single Removal	1.0
Inert Substitution	0.7
Change of Nonmeasured data	0.45
No Collusion	1.0
Relative Likelihood Factor	0.32

This is a slightly modified version of Example 3, and is designed to avoid a prompt alarm from an improper analytical sample. The diversion would not appear as a weight abnormality in equation S-1, but would appear as improper plutonium concentration (1.2 at. % U in Pu) by closure of S-2. Detection is virtually certain for this scenario, but would require as long as one week since there would be no apparent anomaly in any of the batch analyses. In this respect, this scenario circumvents the timeliness requirement of the performance criterion.

The chances of success of this type of scenario could be enhanced by additional collusion and data falsification in the analytical laboratory. Such added complications, however, would reduce the likelihood index to <0.1. This scenario does point out, however, the necessity of maintaining close control over analytical specimens and records.

EXAMPLE 5: Multiple Removal During Silo Filling

Closure equation S-1, which monitors the material balance between the can unloading operation and the storage silo, is closed with each powder batch transfer and thereby provides prompt detectability of any single diversion. Also, since each S-1 closure in sequence considers the cumulative total of material handled in the silo loading operation, a variety of multiple diversion scenarios are equivalent if they result in the same total material removed during the entire loading period. Therefore, it makes no long-run difference from the standpoint of detectability whether a single diversion of 2.0 kg is made from any one of the batches or if 0.027 kg is removed from each of the 74 cans processed or any other multiple removal from this location. With any combination of multiple removals during any one loading operation the loss to the silo load is 2.0 kg, which would be detected no later than the final closing of S-1, with a probability of detection of 99.3% or better. Thus, any multiple diversions totaling 2.0 kg during the silo filling operation can be reduced to equivalent of Examples 2, 3, or 4.

One type of multiple diversion from this area is unique, however. There are eight sequential silo loads in any two-month inventory period, and each load has its own independent material balance.

SCENARIO - Remove 250 g of PuO_2 powder from each of eight sequential silo loadings to total 2.0 kg during the two-month inventory period.

Decision	Relative Likelihood Index
Material Attractiveness	1.0
Distribution (8)	0.4
No Substitution	1.0
No Record Change	1.0
No Collusion	1.0
Relative Likelihood Factor	0.4

Although the LECE of the governing closure equation is 0.9 kg, for a single weighing, the effective LECE can be reduced to 0.36 kg by the use of a rolling average data filter (a statistical technique that utilizes a moving average of eight can weights during the loading process, see Table 2) [7], so that 1σ would be 180 g. The probability of detecting removal of 250 g (1.39σ) would be 27.1% within two shifts. This is a low enough probability to consider the scenario more in detail. It can be shown, however, that the probability of detection of at least one removal of 250 g from each of eight sequential silo loads is 92.0% $[(1-\beta^8) \times 100\%]$. Also, with this type of diversion, one would expect to see an average of 2.2 alarms out of a sequence of eight loadings; the number of false alarms expected for the same period would be 0.2, so any alarm would be grounds for a detailed investigation. Since this scheme has a less than desirable probability of detection, may require up to a week to discover, and has a relatively high likelihood factor, it is a candidate for a realistic diversion scenario. This operation, however, is also protected by long-term closure equation, L-0, which has an LECE of 1.46 kg PuO_2. The probability of detection of this scenario by at least one of the short-term equations or the long-term equation is 98.1%. Added short-term protection can be achieved by replication of full silo weighings to compare more precisely the actual silo load with its value determined from statistical predictors.

It is interesting to note that if the data filtering technique is not used, 1σ would be 450 g, the probability of detection of removal of 250 g from the silo would be 7.5%, and the probability of detection of at least one removal of this magnitude from each of eight silo loadings would be only 46.4%. Obviously, the sophisticated data treatment is required at this point in the process to alleviate the vulnerability.

EXAMPLE 6: Record Change - Data Falsification During Silo Loading

The only viable theft scenario based on record change in this section of the process would involve falsifying the scrap or waste stream data to cover removal of material from the main stream and thereby force the controlling equation to close within alarm limits. Such diversions, however, would be detected by improper closure of the equations governing the scrap recovery and waste process modules; these are discussed in Sections 4.5 and 4.6.

Otherwise, if all input data are assumed correct, any weight falsification used to conceal a diversion during loading would have to be propagated throughout the plant by the diverter and his accomplices to avoid detection by improper closure of one or more downstream equations. Such a scenario would place severe demands on a potential diverter. He must understand the plant thoroughly, he must understand the operation of the closure equations thoroughly, he must be aware of equation closure schedules, and he would probably have to acquire several accomplices to effect appropriate data falsification at the right times and places throughout the plant. At best, data falsification during silo loading would delay detection time for only a few days.

Weight data at the input weighing station could conceivably be falsified downward to cover a proposed downstream theft. The thief would have to achieve his diversion before the next closure of the first equation in the system so that the falsification of initial weight would then match the weight of material entering the process and throughout all subsequent closure equations with no indication of abnormality. It has already been assumed for this analysis that storage-can weights will be reconciled with shipper-receiver values; therefore, any discrepancy between material removed from storage and material processed would be cause for alarm. Can and batch records are not currently part of the closure equation network, so falsification of such records is outside the scope of this analysis. The equation network can be expanded to include item counts of can and batches, however, if it appears advantageous to do so.

EXAMPLE 7: Single Removal of 2.0 kg PuO_2 From Loaded Silo

Material control of loaded storage silos on analytical hold is governed by closure equation S-3. Since this equation has approximately the same LECE as Equations S-1 and S-2, theft scenarios similar to those noted above would have approximately the same levels of detectability. One exception would be inert substitution; there is no secondary analysis of the silo contents prior to the blending operation, so that detection would await analysis of the subblend batch.

SCENARIO - Removal of 2.0 kg PuO_2 from silo on hold and substitution of 2.0 kg UO_2.

Decision	Relative Likelihood Index
Material Attractiveness	1.0
Single Removal	1.0
Inert Substitution	0.7
No Record Change	1.0
No Collusion	1.0
Relative Likelihood Factor	0.7

This scenario would not be detected by any subsequent weight measurements on the silo or by any subsequent closures of equations S-3 or S-4. It is, however, virtually certain of detection by closure of equation S-10 in the blending section of the plant, but such detection could take as long as two weeks. In this respect, this scenario would circumvent the timeliness requirement of the performance criterion.

EXAMPLE 8: Single Removal of 2.0 kg PuO_2 from Loaded Silo with Tare Weight Distortion

SCENARIO - Remove 2.0 kg PuO_2 from silo on hold and add 2.0 kg false tare weight to the silo.

Decision	Relative Likelihood Index
Material Attractiveness	1.0
Single Removal	1.0
Silo Tar Weight Substitution	0.7
No Record Change	1.0
Two-person Collusion	0.3
Relative Likelihood Factor	0.21

As in Example 7 above, this scenario will not be detected by any subsequent weight measurements on the loaded silo. The diversion would, however, be detected upon emptying the silo by an imbalance of the final closure of equation S-4. The refined LECE of S-4 is 0.43 kg, so the probability of detection is greater than 99.9%. Detection could take as long as two weeks since the anomaly will not appear until the silo is empty. The added tare weight would appear to be an abnormal amount of material holdup which would be an adequate cause for investigation.

With this scenario it is assumed the thief would not be able to remove the added tare during the silo unloading cycle without detection. Any sudden weight discrepancy would be detected within one shift by closure imbalance of equation S-4.

EXAMPLE 9: Multiple Removal from Loaded Silos with Tare Distortion

SCENARIO - Remove 250 g PuO_2 from each of eight on-hold silo loads, and add 250 g false tare weight to each silo.

Decision	Relative Likelihood Index
Material Attractiveness	1.0
Distribution (8)	0.4
Silo Tare Weight Substitution	0.7
No Record Change	1.0
Two-person Collusion	0.3
Relative Likelihood Factor	0.08

If the thief tries to remove the excess weight during the silo emptying operation, he will be detected by a closure imbalance of equation S-4. The refined LECE of S-4 is 0.43 kg, or 1σ is about 215 g. The probability of detection of removal of 250 g from any one silo is 20.3%, and the probability of detection of at least one removal from each of eight silo loads is 83.7%.

If the thief is not able to retrieve his added weights from the emptied silo, the anomaly will show up as added tare and would be interpreted as an abnormal amount of holdup. With eight calibration weighings of the silo tare [7., 1σ is approximately 173 g. The probability of detection of at least one such weight anomaly in eight loads is 93.6% or greater.

4.2. MO_2 blending subblend storage module

In Section 4.1. all the alarm thresholds were set at one LECE (2σ) greater than the expected mean value of the CEI's. In the ensuing plant sections many of the LECE values are small enough to permit their alarm thresholds to be set to 2 LECE (4σ), thereby reducing the false alarm probability to approximately 0.005%.

The MO_2 blending module is shown schematically in Figure 5. Each powder blend prepared in this section of the plant consists of approximately 227 kg homogeneously mixed PuO_2 and UO_2; the nominal concentration of PuO_2 in the blend is 4%. This mixture is attained by blending approximately 7.7 kg PuO_2, 185 kg UO_2 (new powders obtained from respective storage silos), and 34.3 kg MO_2 (nominally 4% PuO_2 and obtained from recycle storage). To prepare the blend, each feed hopper, shown in Figure 5, is loaded with approximately 120% of the material required for the subblend; i.e., the amount required for the subblend is added from respective storage silos to 20% heels remaining in each feed hopper from the previous subblend preparation. To accomplish this weight distribution, the PuO_2 feed hopper (Location 8, Figure 5) is loaded to 9.0 kg PuO_2, the MO_2 feed hopper (Location 23) is loaded to 41 kg MO_2, and the UO_2 feed hopper (Location 14) is loaded to 185 kg UO_2.

Depending upon the composition of the MO_2 obtained from recycle, precise quantities of PuO_2, MO_2 and UO_2 are metered into their respective weighing hoppers to achieve the desired mix of PuO_2 and UO_2 in the blending operation. Certified analytical data on each material are used to compute the exact amount of each powder type required. Computer-controlled metering operations from each feed hopper ensures delivery of the proper proportions of these powders to the blender. Powders that are not used for a given subblend are retained in their respective feed hoppers for the next batch.

The feed hoppers and weighing hoppers for both the PuO_2 and the MO_2 systems are capable of returning the material to respective storage areas in the event the material cannot be blended or the moisture content of the powder is too high. In general, to avoid possible contamination of feed stock, UO_2 will never be returned to storage. Scrap UO_2 will normally be shipped offsite for recovery.

The operational mechanics of the blender (Location 25) are not discussed here; it is assumed that a completely homogeneous powder is ultimately transferred to the reduction mill (Location 26). The function of the reduction mill is to break up particle aggregates that may have formed during the blending operation. Analytical samples are removed from the reduction mill while the bulk of the powder from each load is transferred to an appropriate MO_2 subblend storage silo.

There are nine MO_2 subblend storage silos. During normal plant operations, these silos are in various stages of being loaded, being held for analysis, being used to feed the pelleting module, or being weighed for holdup and tare verification. MO_2 batches that are rejected or are not fed to the pelleting operation for one reason or another are returned to the MO_2 recycle storage silo, directly rather than being passed through the clean scrap recycle system.

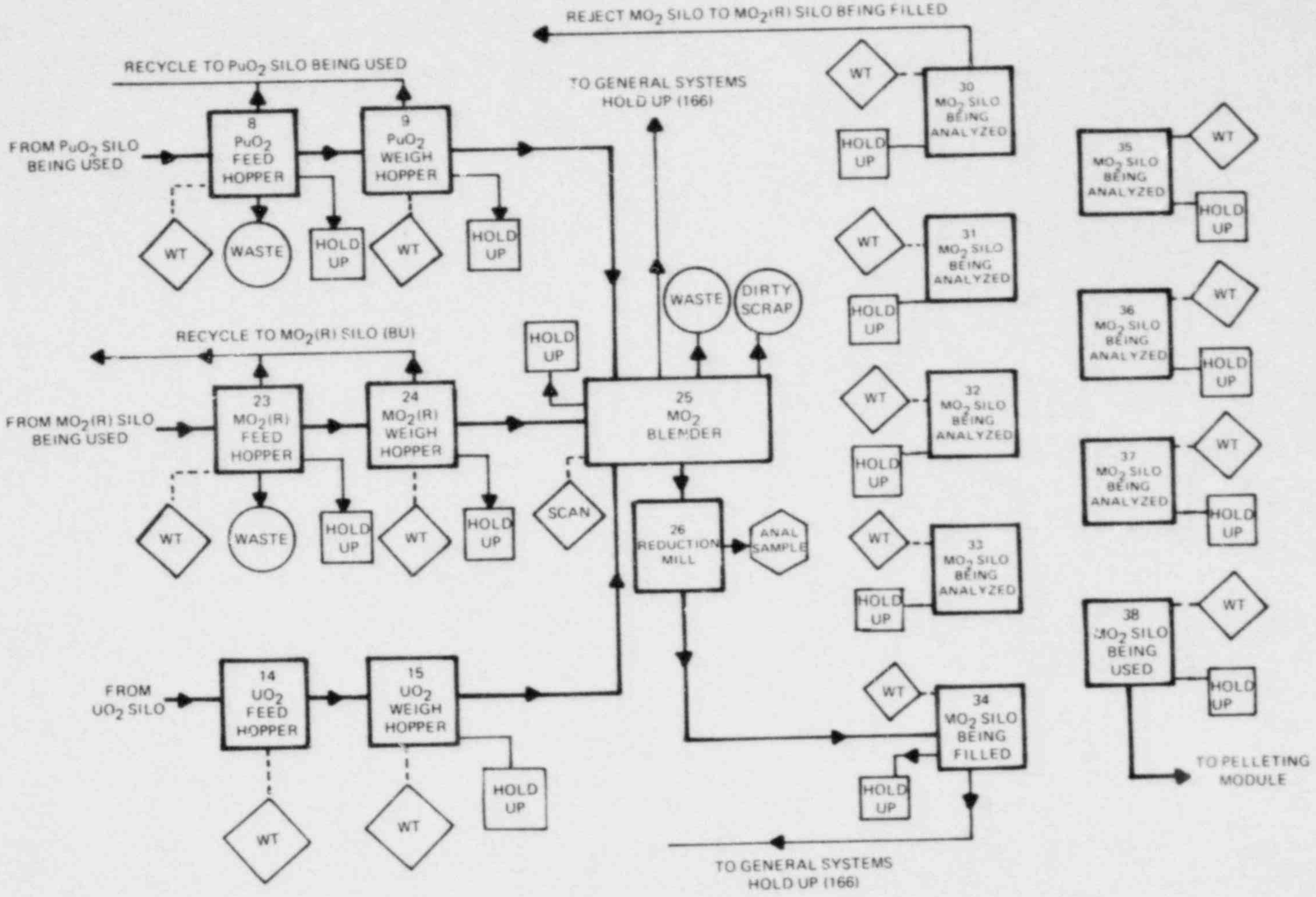

FIGURE 5 - Flow Diagram of blending module.

Approximately one blend is prepared per shift so that each PuO_2 storage silo load will feed a total of 21 blends. This would mean also that each MO_2 subblend storage silo would be recycled two or three times per week, or approximately 19 times in a two-month inventory period.

CUA closure equations controlling this section of the plant are:

S-4	Transfer of PuO_2 from storage to PuO_2 feed hopper
S-5	Transfer of PuO_2 from feed hopper to weighing hopper
S-6	MO_2 recycle silos on hold (i.e., after filling, before use)
S-7	Transfer of MO_2 from storage silo to MO_2 feed hopper
S-8	Transfer of MO_2 from feed hopper to weighing hopper
S-9	Transfer of PuO_2, MO_2, and UO_2 from weighing hoppers through the blender and reduction mill to the subblend storage silos
S-10	Same as S-9, but additional control of plutonium by analysis
S-11	Controls reject of MO_2 from subblend silo
S-12	Controls seven subblend silos on hold (i.e., after filling, before use)
S-25	Controls clean scrap and rejected MO_2 subblend recylced to MO_2 recycle storage silo
L-1	Opening PuO_2 cans, addition of UO_2 to subblend storage.

LECE's and alarm thresholds for these 11 equations are given in Table 3.

The reason for the overlapping of equations S-9 and S-10 is immediately apparent from this table. Equation S-9 has a large LECE and is relatively vulnerable to any multiple diversion or to any diversion with substitution. These two potential diversion modes would be detectable by equation S-10, but at the expense of additional time required for detection. The LECE for equation S-9 is large because, in the absence of analytical data, all closure equation imbalance in the blender module (Location 25) must be considered to be PuO_2. Equation S-10, however, uses analytical data to compute the MO_2 imbalance in terms of actual PuO_2 discrepancy.

Modes by which it is physically possible to remove material from the locations indicated in parentheses are:

- Removal of PuO_2 from storage silo being used (5,6,7)
- Removal of PuO_2 from feed hopper (8)
- Removal of PuO_2 from weigh hopper (9)
- Removal of MO_2 from storage silo being used (20,21,22)
- Removal of MO_2 from feed hopper (23)
- Removal of MO_2 from weigh hopper (24)
- Removal of MO_2 from reduction mill (26)
- Removal of MO_2 from subblend silo being filled (30-38)
- Removal of MO_2 from subblend silo on analytical hold (30-38)

Removal of unblended UO_2 is not considered in the current analysis since control of uranium is not part of the performance criterion.

Table 3 - ALARM SETTINGS AND CLOSURE TIMES OF CUA EQUATIONS[a]

Equation No.	LECE (2σ) (kg PuO_2)	Alarm Level (kg PuO_2)	Time Required (shifts)	Measurement Mode
S-4	0.4	0.4	< 1	wt
S-5	0.07	0.14	< 1	wt
S-6	0.06	0.12	< 1	wt
S-7	0.05	0.10	< 1	wt
S-8	0.01	0.02	< 1	wt
S-9	1.2	1.2	< 1	wt
S-10	0.07	0.14	~2	wt/assay
S-11	0.05	0.10	< 1	wt
S-12	0.06	0.12	< 1	wt
S-25	0.2	0.4	< 1	wt
L-1	0.94	0.94	168	wt/assay

[a] Reference 3.

On the following pages examples are given of scenarios that illustrate the degree of protection afforded by the closure equation network at potentially vulnerable points in the mixed-oxide blending and storage section of the plant. It is assumed that the contents and analysis of each PuO_2 storage silo being used to load the feed hopper have been verified and certified for use. Likewise, it is assumed the contents and analyses of the MO_2 and UO_2 storage silos have been verified and certified.

The scenario examples are not all-inclusive, but were selected to illustrate means of identifying vulnerable points in the blending process.

4.2.1. Examples of Diversion of PuO_2 from the Blender Module

EXAMPLE 10: Single removal from PuO_2 Storage Silo In Use

SCENARIO - Remove 2.0 kg PuO_2 from the system during transfer of the powder from the storage silo to the feed hopper.

Decision	Relative Likelihood Index
Material Attractiveness	1.0
Single Removal	1.0
No Subsitution	1.0
No Record Change	1.0
No Collusion	1.0
Relative Likelihood Factor	1.0

The controlling closure equation is S-4 with a refined LECE of 0.43 kg PuO_2. A diversion of 2.0 kg is 4.44σ; with an alarm threshold of 2σ, the probability of detection would be 99.3% within one shift.

EXAMPLE 11: Multiple Diversion from PuO_2 Silo In-use

SCENARIO - Remove 250 g PuO_2 from each of eight sequential silo loads over a two-month period.

Decision	Relative Likelihood Index
Material Attractiveness	1.0
Distribution (8)	0.4
No Substitution	1.0
No Record Change	1.0
No Collusion	1.0
Relative Likelihood Factor	0.4

Again, the controlling equation is S-4. The diversion is 1.16σ per silo load, and it would occur in one of the 21 closures seen by equation S-4 during each silo unloading operation. The probability of detection of a 250-g removal during silo unloading is 20.3%; the probability of detection of at least one such removal in eight sequential silo unloadings is 83.7%, so the scenario can circumvent the performance criterion.

EXAMPLE 12: Multiple Removal from One PuO_2 Silo Load

SCENARIO - Remove approximately 95 g from each blend loading in the feed hopper (i.e., one removal per shift).

Decision	Relative Likelihood Index
Material Attractiveness	1.0
Distribution (> 10)	0.1
No Substitution	1.0
No Record Change	1.0
3-man Collusion Required	0.1
Relative Likelihood Factor	0.01

A minimum three-man collusion is required since removals must be accomplished during every shift. Normally, this scenario would be rejected on the basis of low relative likelihood, but it is included here to illustrate how apparently dissimilar scenarios can be CUA equivalents. Since equation S-4 also monitors the cumulative closure imbalance throughout the 21 shifts, positive detection of this trickle diversion would be achieved sometime prior to the end of the unloading process. Under the worst conditions, the total material removed by the end of the run would be 2.0 kg and the loss would be equivalent to a one-time removal with a detectability of 99.3% (identical to Example 10).

EXAMPLE 13: Multiple Diversion from Multiple CUA Closures

SCENARIO - Remove approximately 12 g PuO_2 from each blend load, thereby totaling 250 g per silo load and 2.0 kg over a two-month period.

Again, because of cumulative monitoring of equation S-4, this scenario becomes equivalent to Example 11, i.e., a relatively simple eight-part diversion. The probability of detection would be at least equal to and probably greater than that given for Example 11, 83.7%. The relative likelihood factor, however, would be 0.01 or less because of a minimum three-person collusion, so the scenario is not an attractive alternative for a diverter.

EXAMPLE 14: Single Removal with Substitution

SCENARIO - Remove 2.0 kg PuO_2 from the feed hopper and substitute 2.0 kg UO_2.

Decision	Relative Likelihood Index
Material Attractiveness	1.0
Single Removal	1.0
Inert Subsitution	0.7
No Record Change	1.0
No Collusion	1.0
Relative Likelihood Factor	0.7

This scenario would not be detected by weight measurement, so that neither Equation S-4 or S-9 would give an indication of material removal. The scenario would be detected by S-10, however, since this equation includes analysis of the subblend powder. Normally about 9.2 kg PuO_2 is loaded into the feed hopper to provide 7.7 kg for each subblend. If 2.0 kg UO_2 were substituted in one of these loads, the subblend would be short by about 1.67 kg PuO_2, and the concentration of PuO_2 would be about 3.3% instead of the nominal value of 4.0%.

The LECE of S-10 is 0.07 kg PuO_2, so the loss would be approximately 48σ, which is certain of detection approximately one shift after the blending is completed. Likewise, the remaining 0.3 kg of UO_2 in feed hopper would contaminate the next subblend to the extent of about 8σ, which would also be virtually certain of detection within one shift after blending. Concealment by a SS/ST removal with mass substitution at this point in the process is not a viable alternative.

EXAMPLE 15: Multiple Removal of PuO_2 with Substitution

SCENARIO - Remove 95 g PuO_2 from each of 21 subblend preparations with UO_2 substitution.

Decision	Relative Likelihood Index
Material Attractiveness	1.0
Distribution (21)	0.1
Inert Subsitution	0.7
No Record Change	1.0
3-Person Collusion	0.1
Relative Likelihood Factor	0.007

Although this scenario has a probability of detection of 88.7% in the one-week loading period, it is rejected on the basis of having a very low relative likelihood factor.

SCENARIO - Remove 200 g PuO_2 from each of 10 subblends in a week with UO_2 substitution (i.e., 10 shifts).

Decision	Relative Likelihood Index
Material Attractiveness	1.0
Distribution (10)	0.4
Inert Substitution	0.7
No Record Change	1.0
2-Person Collusion	0.3
Relative Likelihood Factor	0.08

This is a diversion of 5.7σ per subblend. With a 4σ alarm threshold, the probability of detection of any one such theft is 95.3%. Also, with 10 such thefts there would be an average of 9.5 alarms during the week; without material loss there would be no expected alarms.

It is apparent from these two scenarios that multiple removal of PuO_2 from the blender module with subsitution is not a viable theft mode. The thief is limited by relatively high detectability if his removals are too large, and the difficulty in achieving a large number of smaller removals is reflected by very low likelihood factors.

EXAMPLE 16: Removal of PuO_2 with Tare Weight Subsitution

SCENARIO - Remove 2.0 kg PuO_2 from the storage silo in use and add in 2.0 kg false tare weight.

Decision	Relative Likelihood Index
Material Attractiveness	1.0
Single Removal	1.0
Inert Subsitution	0.7
No Record Change	1.0
No Collusion	1.0
Relative Likelihood Factor	0.7

This scenario will not normally become apparent from successive closures of equation S-4. This discrepancy would appear as a significant difference of tare determinations between sequential loads. Each tare determination is the mean of eight weight measurements. The standard deviation of the mean is 0.087 kg, so the standard deviation of the difference of two sequential tare determinations would be 0.122 kg. Therefore, a 2.0 kg discrepancy in tare weight would be essentially 100% detectable.

4.2.2. Examples of Diversion of MO_2 from the Blender Module

Because of the nominal concentration of 4 wt % PuO_2 in the mixed oxide, it would be necessary for the diverter to remove 50 kg MO_2 to achieve the defined diversion of 2.0 kg PuO_2.

EXAMPLE 17: Single Removal of 50 kg MO_2

SCENARIO - Remove 50 kg MO_2 from MO_2 recycle storage silo on hold.

Decision	Relative Likelihood Index
Material Attractiveness	0.6
Single Removal	1.0
No Substitution	1.0
No Record Change	1.0
No Collusion	1.0
Relative Likelihood Factor	0.6

The MO_2 recycle on hold is controlled by closure equation S-6, which has an LECE of 0.06 kg PuO_2 and an alarm threshold of 0.12 kg. A diversion of 50 kg MO_2 (2.0 kg PuO_2) is essentially 100% detectable within one shift.

EXAMPLE 18: Single Removal of MO_2 with Weight Substitution

SCENARIO - Remove 50 kg MO_2 from MO_2 storage silo on hold and replace with 50 kg UO_2.

Decision	Relative Likelihood Index
Material Attractiveness	0.6
Single Removal	1.0
Inert Substitution	0.7
No Record Change	1.0
No Collusion	1.0
Relative Likelihood Factor	0.42

If the diversion occurs prior to removal of the MO_2 analytical sample, the PuO_2 concentration in the silo would drop from an expected value of 4.0% to approximately 3.72%, which is virtually certain of detection by the analysis. If the diversion occurs after the silo contents have been analyzed, it would not be detected until the resultant subblend is analyzed; this subblend would have a PuO_2 concentration of 3.95%. The diversion would be detected after blending within one shift by a closure imbalance in equation S-10; the probability of detection is 71.6% for any one blend. The probability of detection of at least one change of concentration of this magnitude would exceed 97.5% after three blends had been prepared.

In practice, the PuO_2 concentration in recycled MO_2 will vary somewhat from a nominal 4%, depending on concentration of rejected and recycled subblends, so that a small concentration deviation from 4% does not, per se, indicate something is amiss. In this respect, a careful material balance of the recycled MO_2 must be maintained via equations S-11 and S-25 (See Clean Scrap Cycle, Section 4.5).

EXAMPLE 19: Single Removal of MO_2 During Feed Hopper Loading Operation with Substitution

SCENARIO - Remove 50 kg MO_2 from storage silo and feed hopper and refill hopper with 41 kg UO_2.

Decision	Relative Likelihood Index
Material Attractiveness	0.6
Single Removal	1.0
Inert Substitution	0.7
No Record Change	1.0
No Collusion	1.0
Relative Likelihood Factor	0.42

Since only 41 kg of material can be removed from the feed hopper, the extra 9 kg MO_2 must be removed from the storage silo leading to a 9.0-kg weight discrepancy. The 9.0-kg (0.36 kg PuO_2) imbalance occurring upon closure of equation S-9 would have a probability of detection of 8.1%. The lower plutonium concentration in the subblend resulting from the uranium substitution would be detected, however, by closure of S-10. In this respect, this scenario is approximately equivalent to the post analytical diversion in Example 18.

It can be summarized that a single diversion of 2.0 kg PuO_2, either as PuO_2 or as 50 kg MO_2, from Locations 9, 24, 25, 26, and the subblend silo (shown in Figure 5), along with removal from any side stream, would be detected within one shift by a closure imbalance of equation S-9. Likewise, a single diversion with substitution from any of these locations would be detected by a closure imbalance of equation S-10 within two shifts. In effect, all such potential diversions are equivalent and are detectable at > 99.9%

EXAMPLE 20: Multiple Diversion of MO_2 from Subblend Preparation

SCENARIO - Remove 10 kg MO_2 from every third subblend (i.e., the same shift every day) to total 50 kg in a one-week load.

Decision	Relative Likelihood Index
Material Attractiveness	0.6
Distribution (5)	0.4
No Substitution	1.0
No Record Change	1.0
No Collusion	1.0
Relative Likelihood Factor	0.24

The quantity of PuO_2 removed with each theft is 400 g. By closure equation S-9, the probability of detection is 9.13% per theft, so that the probability of detection of at least one diversion of this magnitude in five blendings is 38.0%. Utilizing equation S-10 and waiting an extra shift for analytical results will, however, result in a probability of detection of any one of the diversions (i.e., $>10\sigma$) of greater than 99.9%.

EXAMPLE 21: Multiple Diversion of MO_2 from Subblend Preparation with Substitution and/or Collusion

SCENARIO - Same as Example 20, but with UO_2 substitution and removal of material during more than five shifts.

Inert substitution is not a viable option for this example because of the extreme sensitivity of equation S-10 to plutonium concentration in the blend. If the scenario in Example 20 is expanded to include removal of material from more than five shifts, a minimum two-man collusion would be required, and the relative likelihood factor would be reduced to less than 0.07. Since this refinement would not result in a significant decrease in the detection probability, this option is rejected.

4.2.3. Examples of Diversion from Subblend Silos On Hold

In addition to the subblend silo being filled and the subblend silo being used to feed the pelleting line, seven of the subblend silos are either empty or have been previously filled and weighed and are awaiting analytical results from the sample taken during loading operations. Subblend batches must be accepted by QC prior to their use in the pelleting module. Closure equations controlling the subblend silos on hold are S-11 and S-12.

EXAMPLE 22: Single Removal from MO_2 Subblend silo On Hold

SCENARIO - Remove 50 kg MO_2 (2.0 kg PuO_2) from silo on hold.

Decision	Relative Likelihood Index
Material Attractiveness	0.6
Single Removal	1.0
No Substitution	1.0
No Record Change	1.0
No Collusion	1.0
Relative Likelihood Factor	0.6

The LECE of the controlling equation is 0.1 kg PuO_2. The silos are continually monitored by instrumented load cells, so that a diversion of 50 kg MO_2 (c.a. 40) would be almost instantaneously detectable with a probability > 99.9%. A simple theft at this point is a negligible threat.

EXAMPLE 23: Single Removal from Subblend Silo with Substitution

SCENARIO - Remove 50 kg MO_2 from subblend silo on hold and substitute with 50 kg UO_2.

Decision	Relative Likelihood Index
Material Attractiveness	0.6
Single Removal	1.0
Inert Substitution	0.7
No Record Change	1.0
No Collusion	1.0
Relative Likelihood Factor	0.42

Substitution diversion from the on-hold silo prior to removal of the QC analysis sample is equivalent to Example 18. If this scenario can be performed after removal of the QC sample without alerting the continuous load cell information system, it is virtually undetectable in the prescribed length of time; there are no further plutonium concentration analyses downstream from this point until the final pellet inspection station. This emphasizes the necessity for sealing a silo after it is sampled for quality control.

EXAMPLE 24: Multiple Removal from Subblend Silo On Hold

SCENARIO - Remove 7.2 kg MO_2 (288 g PuO_2) from each of the seven silos in on-hold mode.

Decision	Relative Likelihood Index
Material Attractiveness	0.6
Distribution (7)	0.4
No Substitution	1.0
No Record Change	1.0
No Collusion	1.0
Relative Likelihood Factor	0.24

With an LECE of 0.06 kg PuO_2 and an alarm threshold of 0.12 kg, the detectability of any one of these diversions (9.6σ) is > 99.9%, so this scenario is rejected on the basis of rapid detectability.

Further refinements of this type of diversion would likely require at least one accomplice for the diverter, which would reduce the RLF below 0.1. It is expected that the silo would be sealed after removal of the QC sample, so that inert material would have to be substituted before the sample removal. This scenario would be equivalent to Example 23. The only viable record-change-based scenario in this section of the plant would be falsification of scrap or waste-stream data to desensitize a loss of main-stream material. The unlikelihood of this type of scenario was discussed in Example 6.

4.3. MO_2 pelleting, sintering, and QC module

4.3.1. Pelleting Module

The pelleting module described in this section is shown schematically in Figure 6.

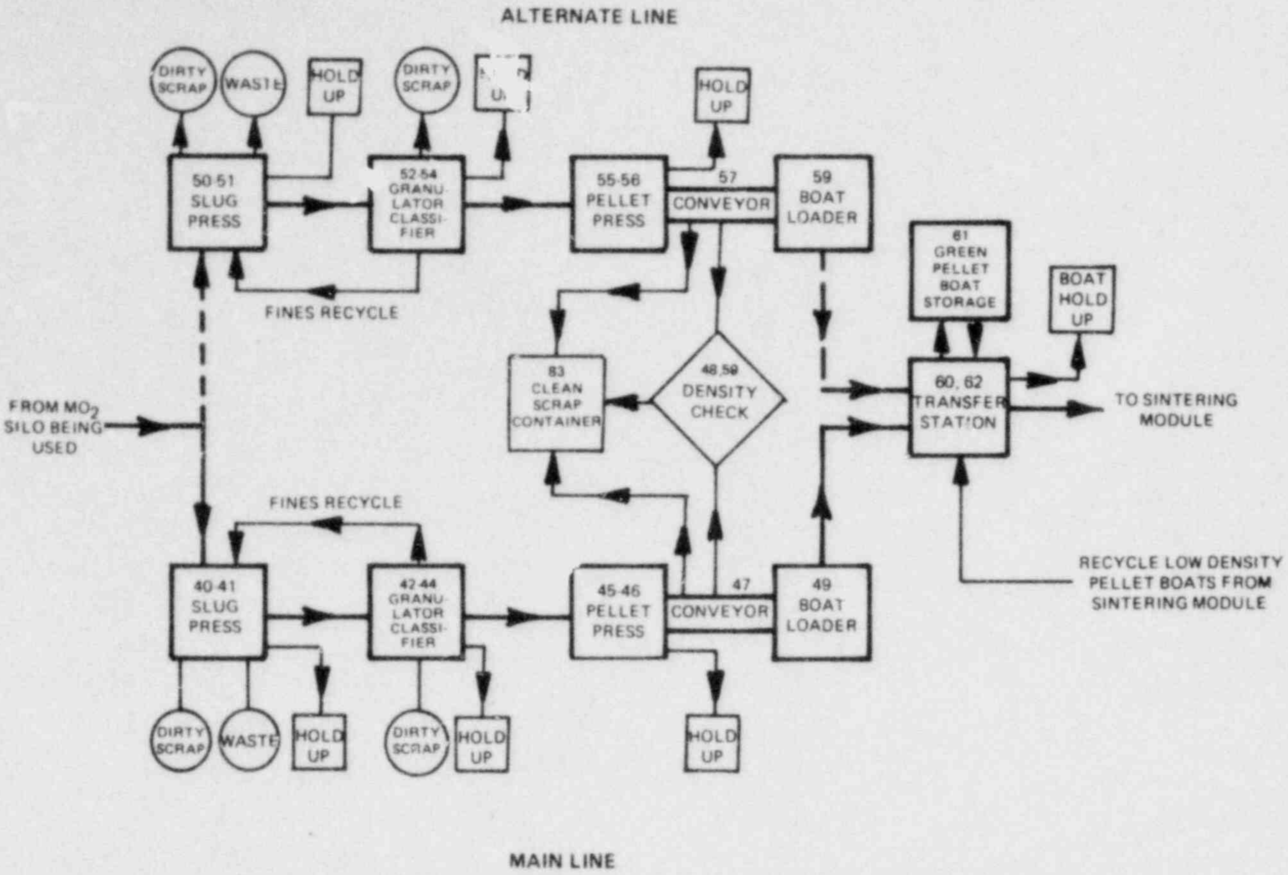

FIGURE 6 - Flow diagram of pelleting module.

Mixed-oxide powder for this section of the plant is obtained from QC-released MO_2 storage silos, described in Section 4.2.3. Each silo contains approximately 225 kg of homogeneously mixed PuO_2 and UO_2, with a nominal concentration of 4 wt % PuO_2. The pelleting module consists of duplicate independent process lines, either of which is capable of supporting the plant production rate. This feature makes it possible to continue operation in the event of a malfunction in the operating pellet line. There is a buffer storage area for green pellets at the end of the pelleting module that is common to both lines. Total input to the pelleting line is one subblend silo load per shift or about 225 kg MO_2. With normal operations, an average of about one subblend silo load per week can be expected to be rejected by QC and thereby returned to recycle storage.

The slugging and pelleting line is fully automated. The mixed-oxide material is fed upon demand into a slug press (Locations 40-41 or 50-51 in Figure 6) and precompacted into wafers weighing approximately 20 g each. These wafers are then crushed, ground, and sieved to achieve a uniform particle size (Locations 42-44 or 52-54); oversized particles are recycled to the grinder, and fines are recycled to the slug press hopper. Properly sized powder material is transferred pneumatically to the pellet press hopper (Location 45 or 55) where die lubricant is added. The lubricated powder is then compacted into cylindrical pellets weighing approximately 10.4 g each. Compacted green pellets are placed on a conveyor (Location 47 or 57) and are moved single-file past an inspection station to a boat loader (Location 49 or 59). Broken or cracked pellets are removed at the inspection station and placed in clean-scrap storage. Also, pellets are randomly selected from the stream and transferred to an in-line density check station (Location 48 or 59). If this check indicates improper compaction is occurring, the line is shut down and in-line pellets are placed in clean-scrap storage. Otherwise, all acceptable pellets are loaded into molybdenum sintering boats and placed in a transfer station (Locations 60, 62) to await sintering. The transfer station is common to both pelleting lines. Each boat holds 900 pellets or about 9.4 kg MO_2.

With the exception of the inspection station, these operations are completely automated; each feed hopper operates a level sensor which controls the upstream feed to the hopper. Thus, a tie-up at any point in the process will automatically shut down the operation preceding it, thereby avoiding flooding of material.

The transfer station is computer controlled to route loaded boats either into the sintering module or into boat storage (Location 61). The system is programmed to process loaded boats in order of the fabrication of the pellets. Thus, recycled pellets from the sintering module will have priority over freshly compacted pellets.

Material control in this section of the process consists of weight measurements at the loading end, pellet counts at the conveyor, and pellet counts in each sintering boat. Pellet counts are related to material weight by average weight per pellet. These counts are obtained by gamma scanners using the natural radiation of the plutonium-239. Scrap accountability in this section is governed by weight.

This portion of the process is controlled by closure equations S-13 and S-14.

4.3.2. Sintering Module

The green-pellet sintering module is shown in Figure 7. This line consists of five sintering furnaces (Locations 64, 67, 70, 73, 76) that are operated continuously in parallel. Boats are fed to each furnace by a conveyor system (Location 63) which is controlled by the transfer station computer. The capacity of each furnace is 24 boats; each hour one boat is removed from the downstream end of each furnace, and a fresh boat is passed into the upstream end. The residence time of a given boat in a furnace is nominally 24 hr.

Following sintering, each boat load of pellets is conveyed (Location 79) to an inspection station (Location 80) where sample pellets are removed for density check. Boat loads accepted as the result of the density check are transferred to sintered boat storage (Location 85) to await final grinding. Rejected boat loads are recylced through one of the sintering furnaces or are placed in clean scrap storage (Location 82) for reprocessing.

Material control in this section is by pellet count for each boat and by boat count. Scrap control is by weight. This section is controlled by closure equation S-15 and, in part, by S-16.

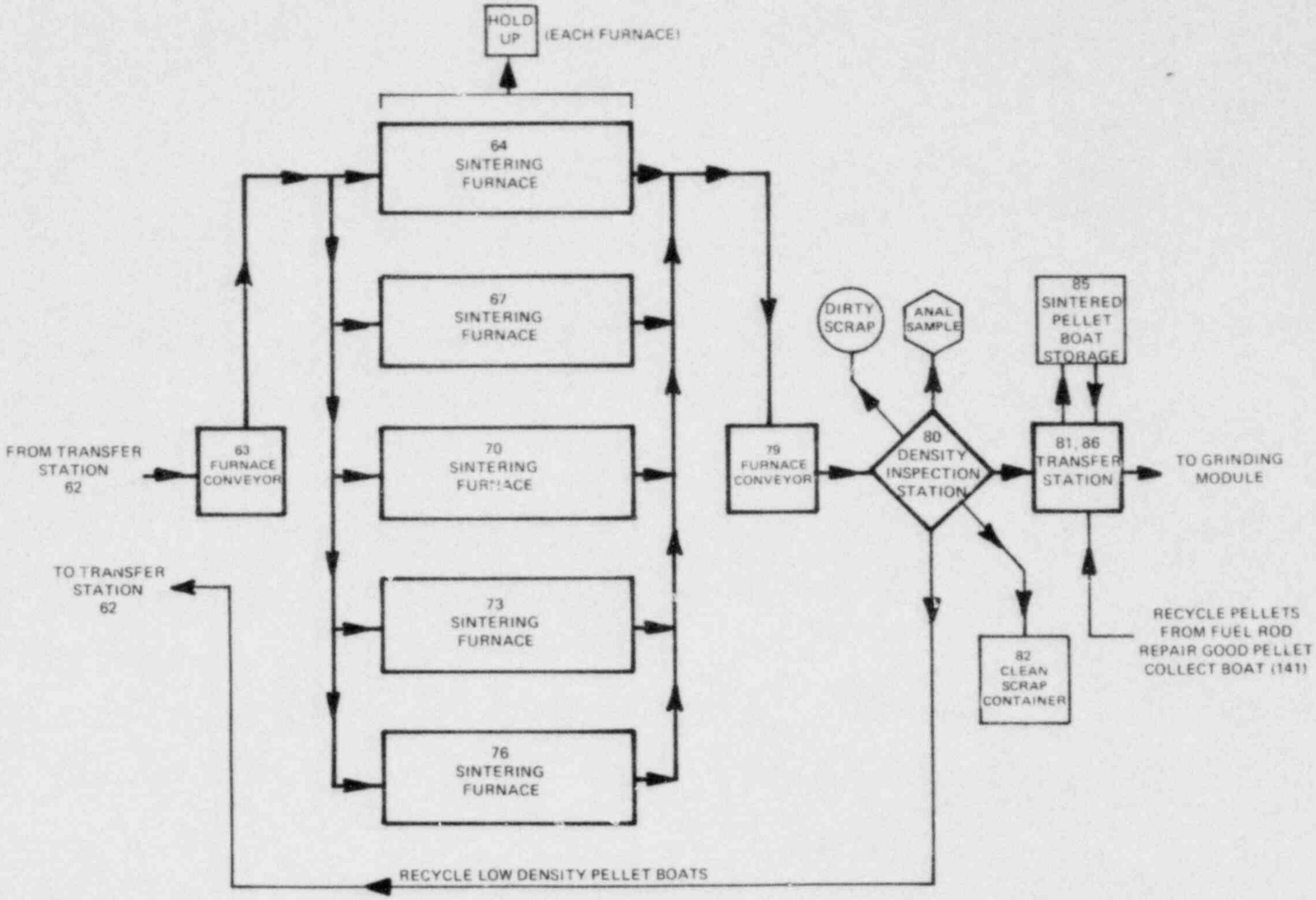

FIGURE 7 - Flow diagram of sintering module.

4.3.3. Grinding Module

The pellet grinding module is shown in Figure 8. The purpose of this module is to grind each pellet to a precise diameter, remove grinding dust, accept or reject individual pellets based on diameter tolerances, and load pellets into handling trays.

The grinding module consists of two parallel lines; each line can carry the full production load of the plant. As in the case of the pelleting module, this feature permits the plant to continue operating in the event of a malfunction in the operating line. These grinder lines are also fully automated, and the throughput rate is self regulated.

Individual pellets are unloaded from the molybdenum sintering boats and placed in single file on one of the conveyor lines (Locations 90, 100). Residual dust, broken pellets, or other material remaining in the boats is placed in clean scrap, and the empty boat is returned for another load of green pellets to be sintered.

Each pellet is ground to a precise diameter on a centerless grinder (Locations 91, 101), then sprayed with water to remove grinder dust and sludge and dried with high-velocity hot air (Locations 92, 102). Each pellet is then inspected for nicks, crack, or breaks, then checked for proper diameter (Locations 94, 104). Accepted pellets, weighing approximately 10.0 g each, are loaded end-to-end in rows on special

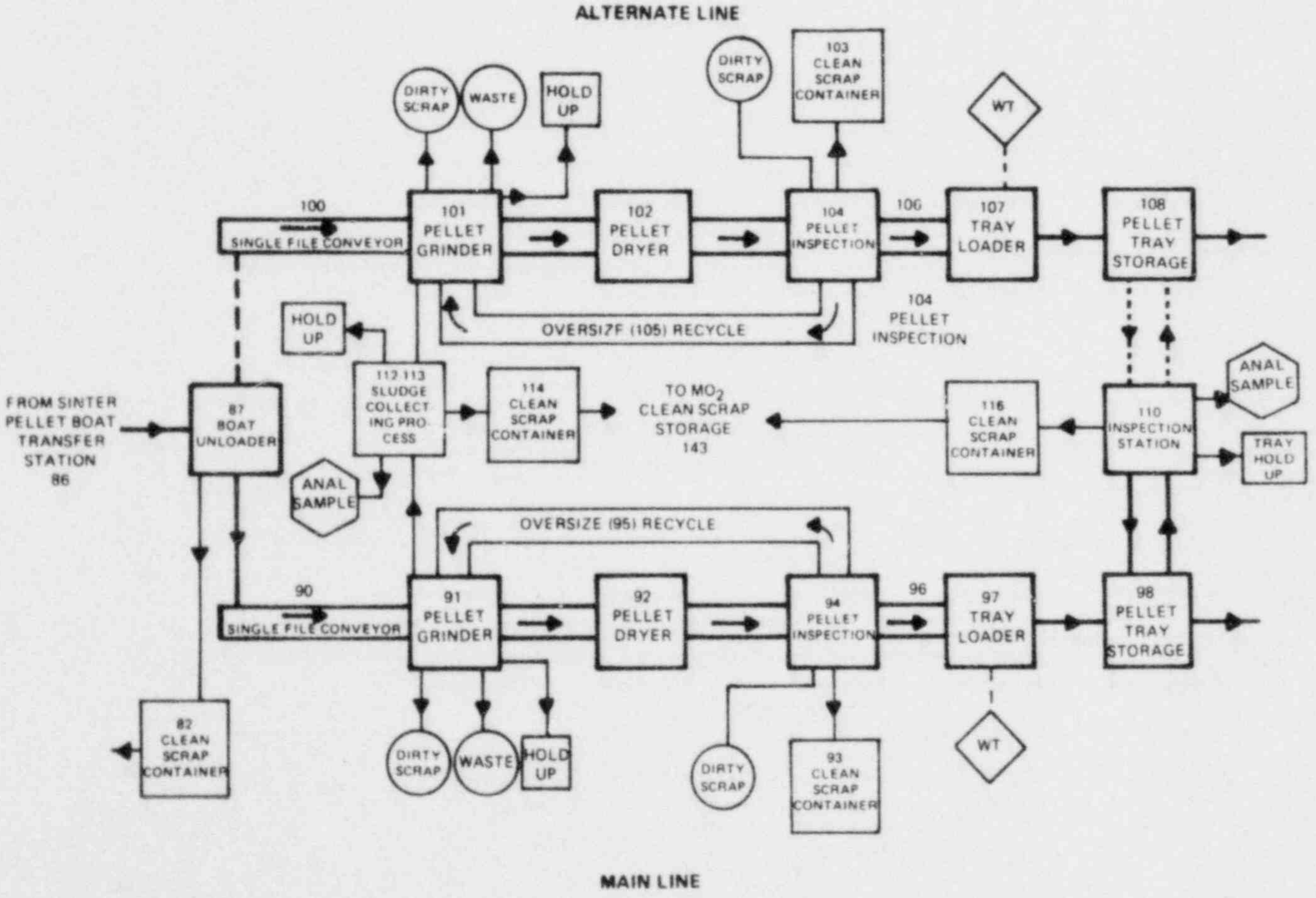

FIGURE 8 - Flow diagram of grinding module.

handling trays (Locations 97, 107). Each tray holds 900 pellets, or about 9.0 kg of MO_2, and is considered, for accountability purposes, a single item. Reject pellets are either returned for additional grinding if they are oversized or are placed in clean scrap (Locations 93, 103) if they are undersized or otherwise damaged.

Tray loads of pellets are then placed in storage (Locations 98, 108) to await QC qualification for assembly into fuel rods (Location 110).

Material control in this section of the plant is by boat count and pellet count; control of clean scrap, waste, and grinder sludge is by weight. CUA closure equations covering this portion of the plant are S-16, S-17, S-18, S-19, S-20, S-21, and long-term equation L-2. In addition, equation S-16 spans the entire time a set of pellets resides in a given boat, i.e., from green-pellet loading to sintered-pellet unloading.

These equations span the following section of the process:

S-13	Transfer MO_2 from subblend silo through green-pellet press
S-14	Single file conveyor to sintering boat loading
S-15	Monitoring of pellets on sintering boats per shift
S-16	Monitoring of each boat from loading to unloading; overlaps S-14, S-15, and S-17
S-17	Boat unloader through pellet grinder to single file conveyor
S-18	Monitoring of grinder sludge
S-19	Monitoring of pellets from boat unloader, through inspection to storage tray loading; overlaps S-17, S-18, and S-20
S-20	Monitoring of pellets from grinder single file conveyor to storage tray loading
S-21	Monitoring of pellets from tray loading, through storage and quality control certification to tray unloading in the fuel-rod fabrication module
L-2	Covers filling of MO_2 subblend silos to final pellet inspection.

Alarm settings, LECE's, and closure schedules for these CUA equations are given in Table 4.

Possible theft modes in this section of the plant (locations in parentheses) are:

- Removal of MO_2 powder from the slug press hopper (40,50)
- Removal of MO_2 wafers from the slug press effluent (41,51)
- Removal of green pellets from pellet press conveyor (47,57)
- Removal of green pellets during density check (48,58)
- Removal of green pellets from loaded boats or removal of loaded boats during transfer and storage operations (60,61,62)
- Removal of pellets or boats at entrance or exit of sintering furnaces (63,79)
- Removal of sintered pellets at sintering density check station (80)
- Removal of pellets or boats from transfer station and storage (81,85, 86)

Table 4 - ALARM SETTINGS AND CLOSURE TIMES OF CUA EQUATIONS

Equation No.	LECE (2σ) (kg PuO_2)	Alarm Level (kg PuO_2)	Time Required (shifts)	Measurement Mode[a]
S-13	0.1	0.2	< 1	wt/P.C.
S-14	0.1	0.2	< 1	P.C.
S-15	0.02	0.04	< 1	B.C./I.D.
S-16	0.02	0.04	< 4	B.C.
S-17	0.03	0.06	< 1	P.C.
S-18	0.03	0.06	< 1	wt/P.C.
S-19	0.1	0.2	~ 2	wt/P.C.
S-20	0.03	0.06	< 1	P.C.
S-21	0.01	0.02	< 1	T.C.
L-2	0.84	0.84	168	wt/P.C./Anal

[a] P.C. Pellet Count
B.C. Boat Count
T.C. Tray Count
I.D. Identification #

- Removal of pellets from grinder conveyor (90,100)
- Removal of pellets during pellet final inspection (94,104)
- Removal of pellets during tray loading (97,107)
- Removal of pellets or trays from storage (98,108)
- Removal of pellets from inspection station (110)
- Removal of clean scrap (83,82,93, 103,114)
- Removal of grinder sludge (112,113)
- Removal of waste, dirty scrap from various points throughout the process

Discussion of the last three of these items will be deferred to Sections 4.5. and 4.6. of this report.

Examples of scenarios that illustrate the degree of protection afforded by the closure equation network in the pelleting, sintering, and pellet QC module are given in the following pages. Scenarios that do not meet the 97.5% detectability for loss of 2.0 kg PuO_2 or relative likelihood rejection criteria are listed along with some other examples of typical theft scenarios that might appear attractive to a naive diverter.

EXAMPLE 25: Single Removal from Slug Press Hopper

The capacity of the slug press hopper is about 20 kg, so a single theft of 50 kg MO_2 from this area is not possible. The hopper of the slug press is, however, kept full continuously from the feed silo, so that a diverter could, over the period of one shift, remove 50 kg MO_2 from the 225 kg handled by the hopper during the shift. To keep the likelihood factor greater than 0.1, the thief can made no more than 10 removals in the course of one shift.

SCENARIOS - Remove 5 kg MO_2 (0.2 kg PuO_2) from the slug press feed hopper at 10 times during one shift.

Decision	Relative Likelihood Index
Material Attractiveness	0.6
Distribution (10)	0.4
No Substitution	1.0
No Record Change	1.0
No Collusion	1.0
Relative Likelihood Factor	0.24

This portion of the process is controlled by closure equation S-13, which closes once per shift. The diversion would appear to the governing equation as a single removal; in this respect, the number of removals is immaterial. The total diversion is 2.0 kg PuO_2 which is about 40σ; detection of this diversion upon closure is virtually certain.

EXAMPLE 26: Multiple Removal from the Slug Press Hopper

The thief can reduce the probability of detection by trickling the diversion over several sequential closures of the governing CUA equation. In Example 25, it was seen that more than 10 individual thefts would reduce the relative likelihood factor below 0.1, so scenarios of this type are conveniently limited to a maximum distribution number of 10.

SCENARIO - Remove 5.0 kg MO_2 (0.2 mg PuO_2) from the slug press hopper every third shift over a two-week period, i.e., 10 shifts.

Decision	Relative Likelihood Index
Material Attractiveness	0.6
Distribution (10)	0.4
No Substitution	1.0
No Record Change	1.0
No Collusion	1.0
Relative Likelihood Factor	0.24

The diversion per closure is 0.2 kg PuO_2 which is 4σ. The alarm threshold for S-13 is 4σ, so the probability of detection of any one diversion of this magnitude is 50%. The probability of detection of at least one of these diversions in the 10 shifts is 99.9%. With this scenario one would expect an average of five alarms in the two-week period; with no diversion the number of expected false alarms in this period is essentially zero.

EXAMPLE 27: Multiple Removal from the Slug Press Hopper with Substitution

SCENARIO - Remove 5.0 kg MO_2 from the slug press hopper every third shift and replace with 5.0 kg UO_2.

Decision	Relative Likelihood Index
Material Attractiveness	0.6
Distribution (10)	0.4
Inert Substitution	0.7
No Record Change	1.0
No Collusion	1.0
Relative Likelihood Factor	0.17

Since there are no additional analytical steps until the final pellet inspection, such a diversion is difficult to detect on a timely basis. If it is assumed that the UO_2 is homogeneously mixed in the slugging hopper, the substitution would result in pellets with nominal 3.91% PuO_2 rather of the final pellet analysis. With a 4σ alarm threshold on this analysis, the probability of detection of a change in concentration of this magnitude would be about 99.8%. It is more likely that the UO_2 substitution in the slugging hopper would not be homogeneous, so the resultant pellets would indicate a relatively wide variation of PuO_2 content, which would be easier yet to detect.

Even though a week or more could elapse between the initial substitution and its detection in the final pellet inspection stage, the diverter cannot be successful because he must spread his diversion out over a two-week period. If he increases the size of theft per shift, he stands the chance of being detected by improper response of the gamma scanning pellet counters. If he spreads his diversion out among any more shifts, he must add accomplices into the diversion, and the RLF would be reduced below 0.1. It is apparent that careful monitoring of the input hoppers for this section of the plant should be performed to ensure prompt detection in the event of a gross substitution.

EXAMPLE 28: Removal of Wafers from the Slug Press Effluent

A single theft (SS/ST) from the grinder-classifier hopper is not possible since the hopper holds a maximum of 20 kg of material at one time. The diverter, however, could remove 2500 wafers (50 kg MO_2) over the course of a shift to achieve a SS/MT diversion of 2.0 kg PuO_2.

SCENARIO - Remove 2500 wafers from the slug press effluent over the period of one shift.

Decision	Relative Likelihood Index
Material Attractiveness	0.6
Distribution (10)	0.1
No Substitution	1.0
No Data Falsification	1.0
No Collusion	1.0
Relative Likelihood Factor	0.06

The LECE for the controlling closure equation, S-13, is 0.1 kg PuO_2, so this diversion would be detected upon closure at the end of the shift with >99.9% probability. Reducing the number of individual thefts to keep the RLF above 0.1 will have no effect on the detectability. The number of multiple thefts is immaterial since the equation closes on the cumulative total at the end of the shift.

EXAMPLE 29: Multiple Removal of Wafers from Slug Press Throughout Inventory Period

SCENARIO - Remove approximately 63 wafers from the slug press effluent in each of 40 shifts throughout the inventory period to total 2500 wafers.

Decision	Relative Likelihood Index
Material Attractiveness	0.6
Distribution (40)	0.1
No Substitution	1.0
No Data Falsification	1.0

No Collusion	1.0
Relative Likelihood Factor	0.06

Because of low relative likelihood, this scenario would not normally be considered in detail. There are, however, some significant restrictions on detectability. This diversion is equivalent to approximately 50 g PuO_2 removed in a given shift. The LECE for equation S-13 is 0.1 kg, so the diversion is 1σ. The alarm threshold for this equation is 4σ, so the probability of detection of a single diversion of this magnitude is 0.1%. The probability of detection of at least one diversion of this magnitude during the 40 shifts is 5.3%. To improve the detectability, the alarm threshold could be reduced to 2.5σ; the probability of detection of removal of 50 g of wafers in one shift would be 6.68%, and the probability of detection of at least one such removal in the 40 shifts would be 93.7%. The number of true alarms expected in the period would be 2.7, and no false alarms could be expected if there were no diversion. Any further reduction in alarm threshold to enchance detectability would have to be balanced against a tolerable false alarm rate.

Since the RLF for this diversion is already <0.1, added diversion refinements will only reduce the RLF still further. Although the diversion is possible, it is not believed to be viable. Physical protection around the press system can reduce the vulnerability still further. This scenario would ultimately be detected by closure of long-term equation L-2, which has an LECE of 0.84 kg for the two-month period. Probability of detection by equation L-2 with a 1-LECE alarm threshold would be 99.7%.

Substitution diversion at this point in the process would require that the diverter have in his possession a supply of 2500 UO_2 wafers weighing, on the average, 20 g each. Although the likelihood table does not reflect the added difficulty of obtaining material of this type for substitution, there is no doubt that obtaining such wafers would represent a significant reduction in likelihood index. Also, the same detectability of UO_2 substitution as described in Example 27 would apply.

EXAMPLE 30: Removal of Green Pellets from the Pellet Press Conveyor or During the Pellet Density Check

Both these areas are within the realm of closure equation S-13, so that all the diversions described in Examples 25 through 29 are generic to any scenarios for removing material from this section of the module. All the likelihood factors and probabilities of detection are the same.

EXAMPLE 31: Removal of Pellets During the Boat Loading Operation

This section of the module is controlled by overlapping CUA equations S-13 and S-14. The counting input data that open S-14 are the same data that helped close S-13. Any removal during the actual boat loading will result in an imbalance in S-13, which may or may not be detectable. However, S-14 compares the actual pellet count on a boat with the measured number of pellets fed to a boat. The controlling error (LECE) in this operation is a 1% counting error. If it is assumed that a boat is loaded until all 900 slots are filled, a 2σ counting error would be 9 pellets. With an alarm threshold at 4σ (18 pellets), a descrepancy of 6σ (27 or more pellets) would be detectable at the 97.5% level. At this stage of the process, a diversion would require removal of 4812 pellets at 10.4 g MO_2 each to achieve 2.0 kg PuO_2. With 900 pellets per boat, this would require removal from a minimum of five boats. If only 27 pellets can be removed from any one boat, thefts would have to be made from a minimum of 178 boats. For a multiple diversion of MO_2, the maximum RLF would be 0.06. Any attempt to cut down the distribution number would result in increased detectability; and any attempt to reduce detectability would further lower the relative likelihood factor. It is also assumed that if any pellets were removed from a loaded boat after closure of S-14, the empty spaces would be immediately apparent. Likewise, removal of the entire contents of a boat or removal of the boat itself would be immediately detectable. It is concluded that there are no viable diversion scenarios for this operation, other than pellet substitution.

The question of material substitution in this section of the plant was discussed in Example 27.

EXAMPLE 32: Removal of Pellets from Loaded Boats During Transferring, Green Pellet Storage, Sintering, Density Check, Sintered Pellet Storage, and Boat Unloading Operations

This entire range of operations is covered by closure equations S-15 and S-16; equation S-15 controls the number of boats processed, and S-16 controls the total number of pellets processed. A diversion at any point within this span will have the same effect on closure imbalance as the same diversion at any other point in the span, so that specification of location within the span is not necessary. There are no generic differences between diversions from this area and those discussed in Example 31. The LECE's for these two equations are 0.02 kg PuO_2, as opposed to LECE's of 0.1 kg PuO_2 for equations S-13 and S-14, so that diversion detection sensitivity in this section is higher for the same generic scenarios in Example 31. It is concluded there are not viable diversion scenarios for the S-15 and S-16 area.

EXAMPLE 33: Removal of Pellets from Grinding, Cleaning, Inspection, and Storage Tray Loading Operations

This section of the plant is controlled by closure equations S-17, S-18, S-19, and S-20; equation S-17 controls the pellets from the boat unloader through the grinder by pellet count, S-18 controls the material removed from each pellet during grinding (grinder sludge) by weight, S-20 controls the grinder conveyor to tray loading by pellet count, and S-19 controls the entire operation by weight. The largest LECE of the four equations is S-19 with a value of 0.1 kg PuO_2; other LECE's are all 0.03 kg PuO_2. Removal of pellets prior to grinding would have the same restrictions as were noted in Examples 31 and 32. After grinding, the average weight per pellet is 10.0 g, so that to achieve a diversion of 50 kg MO_2 (2.0 kg PuO_2), a total of 5000 pellets would have to be removed. For detection by S-19, which has an alarm threshold of 0.2 kg, a diversion of 0.3 kg PuO_2 per closure would be detectable at the 97.5% level. This is equivalent to a maximum allowable removal of 750 pellets per shift; or a minimum of seven shifts to achieve the diversion. The RLF for MO_2 with a distribution number of 7 is 0.24, so this might appear to be an attractive option to a diverter. With the smaller LECE's for S-17 and S-21, however, the maximum number of pellets that can be removed in one shift with detection less than 97.5% is 112. Removal of 5000 pellets would then require at least 45 shifts. Even if there is no collusion, the RLF would be reduced to 0.06. With 45 shifts, a minimum two-person collusion would be required, and the RLF would be further reduced to 0.018.

Substitutional diversion from this section of the plant would require that the diverter have available 5000 pellets of UO_2 for replacement of removed pellets. This places some rather severe demands on the attractiveness index, in addition to the diversion being detected within two or three shifts by final pellet inspection.

Another possible diversion from this section would be the collection of grinder sludge. With an LECE of 0.03 kg for controlling equation S-18 and an alarm threshold of 0.06 kg, no more than 0.09 kg can be removed in any one shift with less than 97.5% detectability. Diversion of 2.0 kg PuO_2 would then require a minimum of 22 shifts. The RLF for MO_2 diversion with a distribution number of 22 is 0.06. Substitution of UO_2 for grinder sludge would reduce the RLF to 0.042.

It is concluded that the optimum point for substitutional diversion in this section of the plant is at the feed hopper to the sludging process; although the detectability of this diversion is relatively high, the thief can gain the most time by diverting from this point. If this location can be physically controlled, substitutional diversion is not a viable option for the diverter.

One potentially attractive scenario based on record change in this portion of the process would be falsification of scrap and waste stream data to desensitize loss of main stream material. Such a scenario would be detected by improper closure of the equations controlling the scrap and waste processing operations, which are discussed in Sections 4.5. and 4.6. The likelihood of this option was addressed in Example 6.

4.4. Fuel rod fabrication module

The fuel rod fabrication module is shown schematically in Figure 9. In this section of the plant, trays of pellets that have been qualified by QC are received from tray storage (Location 98 or 108 in Figure 5) and are directed into either of the two rod-loading stations (Location 99 or 109). Each tray will be missing one pellet for QC analysis, so that any additional missing pellets would be immediately evident. Likewise, any trays with more than one pellet missing in the event of additional QC samples being taken would be properly documented and identified.

Preweighed empty fuel rods are loaded automatically from the storage trays. Each rod nominally holds 200 pellets, so each tray can load approximately 4.5 fuel rods. An average of 22 trays are unloaded per shift, leading to a production rate of about 100 rods per shift. Material control in the rod-loading operation is by pellet count.

Once a rod is loaded and welded (Locations 120-122), it is carried as an inventory item. Inspection of the completed fuel rods includes helium leak (Locations 126-127) and x-ray inspection (Location 130) to determine weld integrity, gamma scanning

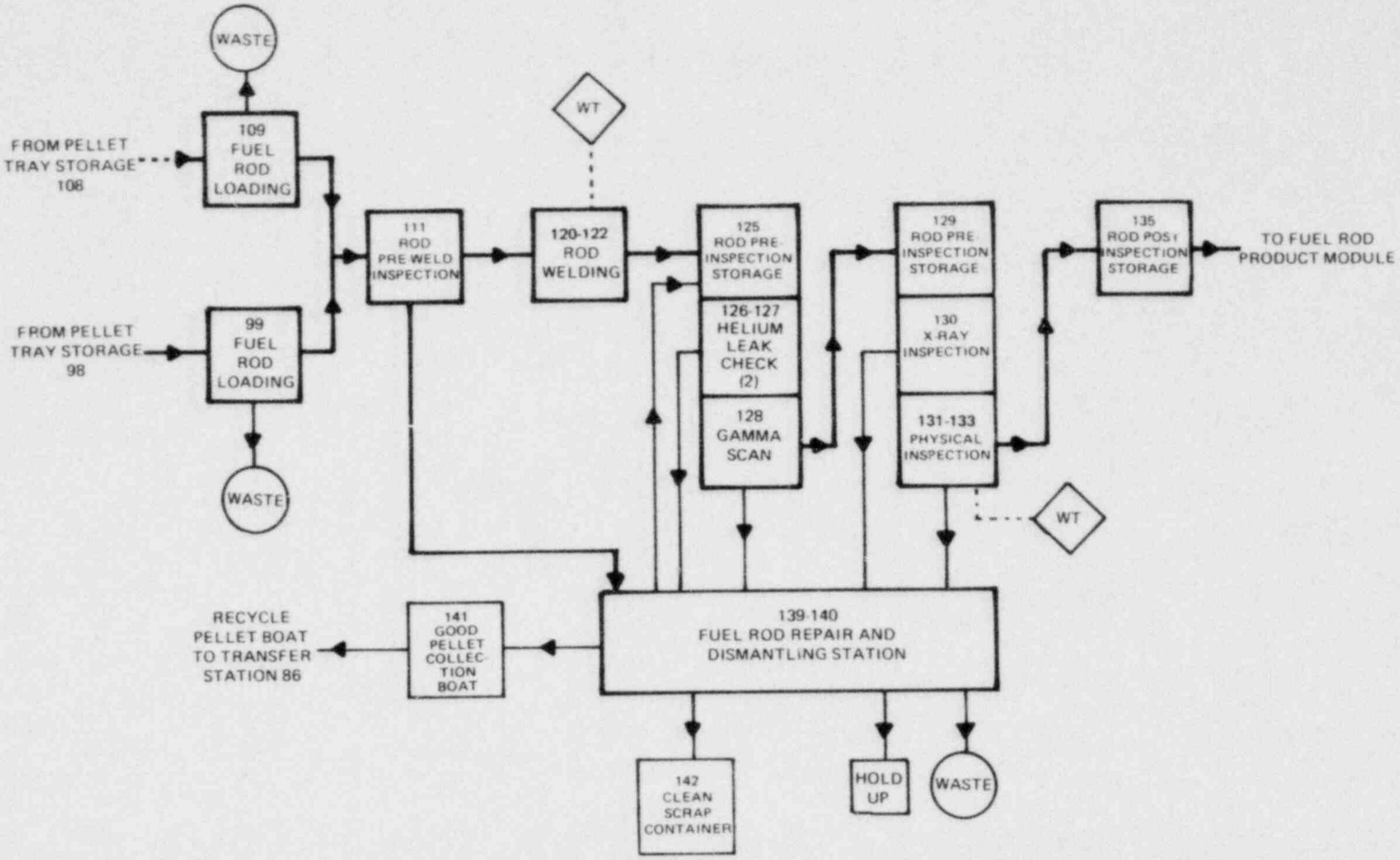

FIGURE 9 - Flow diagram of fuel rod fabrication module.

(Location 128) to verify that all internal pellets contain plutonium and that no pellets are missing, and physical inspection (Locations 131-133) for straightness and dimensional compliance. Rods that meet all inspection criteria are weighed to verify the MO_2 content and are placed in post-inspection storage (Location 135).

Rejected rods are transferred to a repair and dismantling module (Locations 139-140) for service. Rods that are repaired are returned to the rod inspection module for reinspection. Rods that cannot be repaired are cut open, and the pellets are removed. Pellets that appear to be undamaged are placed in a sintering boat for recycle through the pellet qualification steps. The boat is recycled when it is filled with 900 pellets (i.e., the contents of about 4.5 rods). Pellets that appear to be damaged are placed in clean scrap (Location 142).

Short-term closure equations that control this module are S-21, S-22, S-23, and S-24. Euqation S-21 controls the pellets from the tray-loading to rod-loading operations. Control is by pellet count, and the time span may cover several shifts for a given tray. S-22 controls the residence of pellets in a tray within a shift; control is by pellet count. S-23 controls the rod-loading operation through rod inspection; control is by pellet count and final weight of the rod, and the time span may cover several shifts for a given rod. S-24 controls the shift-to-shift flow of rods through this module; control is by rod count.

Once rods have passed inspection and are given item numbers, it is assumed that item counts are essentially errorless. From this point in the process through rod channel assembly, packaging, and shipment, control is by conventional accountability techniques since these operations were not included in the original CUA closure equation network. Equations can easily be written, however, and implemented to cover these operations if it should appear necessary to do so.

Closure equations span the fuel fabrication portion of the plant as follows:

S-21	Monitors unloading of pellets at rod loader
S-22	Monitors number of pellets in tray during storage
S-23	Monitors loading of pellet into rods and follows control rods through physical inspection
S-24	Monitors number and location of completed rods
L-3	Monitors final pellet inspection to rod physical inspection
L-4	Monitors entire process-PuO_2 unloading to fuel rod inspection

Alarm thresholds and closure times of these equations are given in Table 5.

Possible theft modes in the rod fabrication and inspection module are:

- Removal of pellets from tray storage
- Removal of pellets during loading
- Removal of assembled rods
- Removal of recycled pellets from disassembled rods
- Removal of discarded pellets from clean scrap or from waste.

Table 5 - ALARM THRESHOLDS AND CLOSURE TIMES OF CUA EQUATIONS

Equations No.	LECE (2σ) (kg PuO_2)	Alarm Level (kg PuO_2)	Time Required (Shifts)	Measurement Mode[a]
S-21	0.01	0.02	< 4	T.C.
S-22	0.01	0.02	< 1	T.C./I.D.
S-23	0.02	0.04	< 4	Wt/I.C.
S-24	-	0.01	< 1	I.C./I.D.
L-3	0.37	0.37	168	Wt/Anal.
L-4	0.97	0.97	168	Wt/Anal.

[a] T.C. Tray Count
I.D. Identifier Number
Wt Weight
I.C. Item Count (Rods)

The last item in this list will be discussed in Section 4.5. Since the only items handled in this module are MO_2 pellets or completed fuel rods, thefts can be defined in units of number of pellets or number of rods. To divert 50 kg MO_2 (2.0 kg PuO_2) it is necessary for a thief to remove 5,000 pellets or 25 rods.

EXAMPLE 34: Removal of Pellets from Certified Storage

Extra pellets could be removed from the storage trays at the time the QC pellets are being removed. The removal of 5,000 pellets at one time without detection, however, is not possible, nor is the removal of an entire tray of pellets possible. Removal from storage would be detected immediately, either visually or by weight sensors in the storage area. For MO_2, the maximum distribution that would retain the RLF >0.1 would be 10; for 10 diversions of MO_2 the RLF would be 0.24. (For more than 10 diversions the RLF would be 0.06) A scenario involving 10 thefts of 500 pellets each from the storage area would be immediately detectable since the storage area is set up for visual audit on a shift-to-shift basis. The minimum number of pellets that can be removed from storage during 40 shifts (two months of operation by a given shift) and still achieve a total of 5,000 pellets is 125 per shift. With 24 trays being handled per shift, this would be a discrepancy of 5.2 pellets per tray, which would be immediately detectable visually. Also, such a scenario would have an RLF much less than 0.1 since the distribution number would be 40.

Substitutional diversion would involve the same difficulties in obtaining proper UO_2 pellets as were encountered with UO_2 wafers. Detection of substituted pellets would be ensured upon gamma scanning completed fuel rods.

EXAMPLE 35: Removal of Pellets from the Loading Module During Loading

Transfer of pellet trays to the fuel fabrication line and pellet loading is completely automated, so that removal of pellets during this operation does not appear to be physically possible. Even if removal by this mode were physically possible, there does not appear to be any attractive scenario available to a diverter.

SCENARIO - Remove 500 pellets per shift for 10 shifts.

Decision	Relative Likelihood Index
Material Attractiveness	0.6
Distribution (10)	0.4
No Substitution	1.0
No Record Change	1.0
No Collusion	1.0
Relative Likelihood Factor	0.24

If the pellets are removed during the same shift each day, no collusion is required. The LECE's for the governing equations, S-21 and S-22, are 0.01 kg PuO_2 per shift. Five-hundred pellets is 0.2 kg PuO_2, or about 40σ, so that prompt detection by pellet count is essentially certain.

SCENARIO - Remove 125 pellets per shift over 40 shifts during one inventory period.

Decision	Relative Likelihood Index
Material Attractiveness	0.6
Distribution (40)	0.1
No Substitution	1.0
No Record Change	1.0
No Collusion	1.0
Relative Likelihood Factor	0.06

A group of 125 pellets represents 0.05 kg PuO_2, which would be a diversion of about 10σ. Even with a 4σ alarm threshold, detection within the shift is virtually certain.

Substitutional diversion at this point is not believed to be a viable option because of physical difficulties in overriding the automation equipment. Also, UO_2 substitution would be apparent upon gamma scanning of completed fuel rods.

EXAMPLE 36: Removing Fuel Rods

SCENARIO - Remove 25 fuel rods from anywhere in the completed rod module.

Decision	Relative Likelihood Index
Material Attractiveness	0.6
Distribution (25)	0.1
No Substitution	1.0
No Record Change	1.0
No Collusion	1.0
Relative Likelihood Factor	0.06

This diversion will be detected by a discrepancy in daily inventory. If records are falsified to conceal the disappearance of an accountable item, the RLF is reduced by an additional factor of 0.45 to 0.027; this would be considered a very unlikely scenario. Falsification of scrap or waste stream data from the rod repair module to desensitize loss of main stream material was discussed earlier in Examples 6 and 33.

In addition, when one considers the difficulty in smuggling 25 accountable items, each approximately 14 ft long, out of a plant or in disassembling the rods in a clandestine environment to recover the pellets, it is quite apparent that theft of fuel rods is not a viable option for a diverter.

4.5. Clean scrap recovery and storage facility

Clean scrap processing and storage for the mixed-oxide plant is shown schematically in Figure 10. This process is governed by closure equations S-25 and L-5 which cover the processing and storage of all reprocessed mixed oxide in the plant. This reprocessed material was, for one reason or another, rejected from the final product, and it includes subblend powders, green pellets, sintered pellets both ground and unground, dried grinder sludge, and pellets recovered from reject fuel rods. Clean scrap consists only of those materials that can be used to prepare new subblends with minimum reprocessing. Dirty scrap and waste materials that are likely to be contaminated physically or chemically, such as spillage, completed analytical samples, liquid wastes, and cleanout materials, are not included in the clean scrap category. Waste materials will be discussed in Section 4.6., the waste treatment module.

The clean scrap module processes material from the following plant locations:

- Reject subblend lots from the subblend storage area (Locations 30-34, Figure 5)

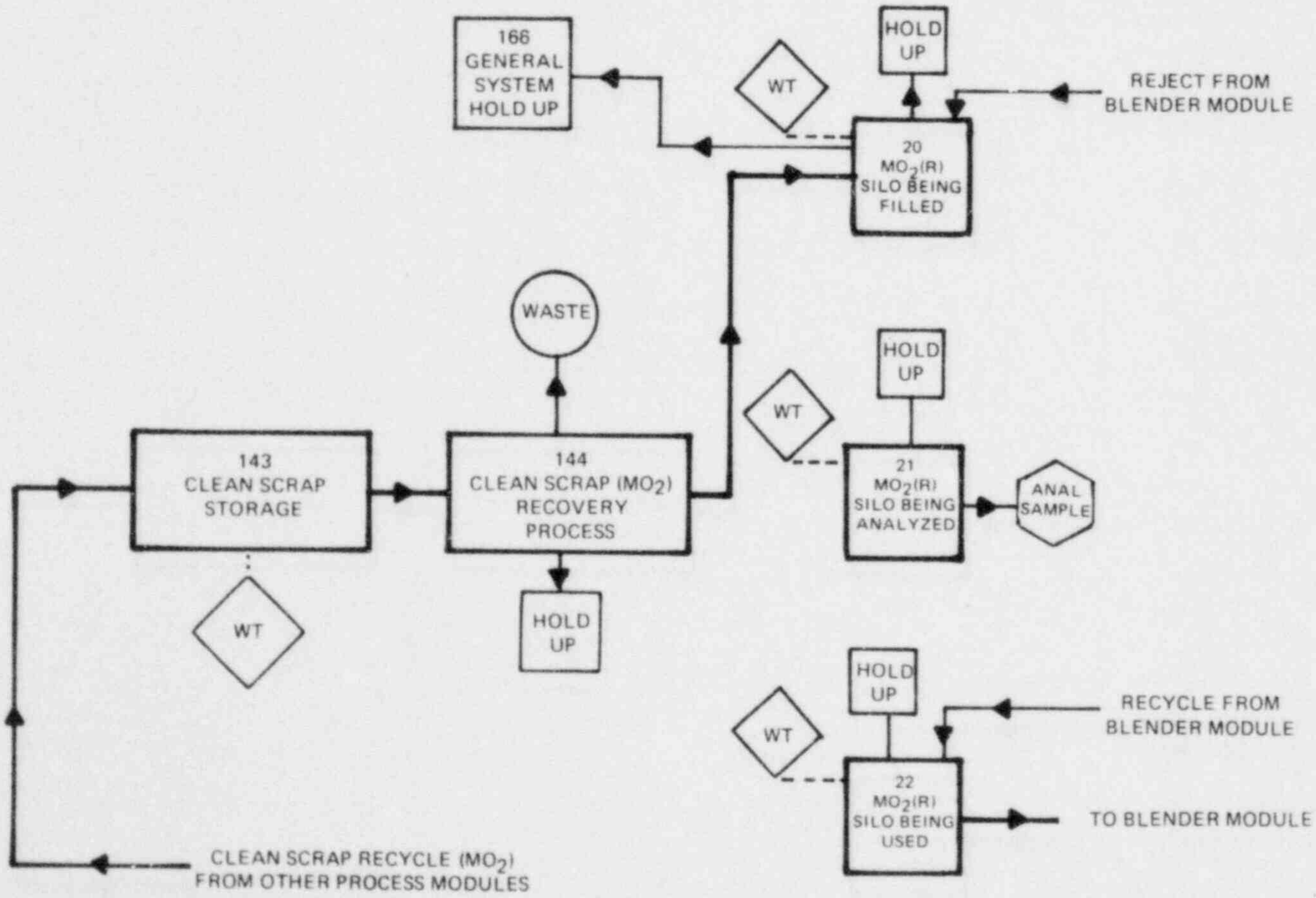

FIGURE 10 - Flow diagram of MO_2 (recycle) module.

- Broken pellets and residual powder from pellet pressing operations and/or boat loads of green pellets of improper density (Location 83, Figure 6)
- Boat loads of sintered pellets rejected because of improper density (Location 82, Figure 7)
- Dried grinder sludge (Location 114, Figure 8)
- Undersized pellets from the grinder lines (Locations 93, 103, Figure 8)
- Rejected tray loads from final pellet inspection (Location 216, Figure 8)
- Rejected pellets from fuel rod repair and dismantling station (Location 142, Figure 9).

All clean scrap to be processed is transferred to the clean scrap storage facility (Location 143, Figure 10). Clean scrap material control is by weight; scrap containers are weighed before material transfer and are tared after emptying. In the clean scrap recovery module (Location 144), all material is crushed to granular size or smaller, then is subjected to several reduction/oxidation steps to adjust the material to stoichiometric UO_2 and PuO_2 and to remove excess moisture. Treated material is then transferred pneumatically to one of the MO_2 blender feed silos (Locations 20, 21, 22). If there is insufficient silo storage available, material is packaged and returned to clean scrap storage (Location 143) until silo space becomes available.

Possible modes of physical removal of material from the clean scrap recovery system include:

- Removal of powder from subblend silo load being returned to MO_2 feed silo
- Removal of clean scrap container or containers from any of the in-plant locations (including pellet grinder sludge)
- Removal of scrap or reprocessed MO_2 from clean scrap storage
- Removal of reprocessed MO_2 during feed silo filling operations.

Closure equation S-25 spans the entire clean scrap system, so it is not necessary to consider removal from any specific locations within the scrap processing operations. It is necessary to consider only the effect of any removal on the closure imbalance of S-25.

The LECE for S-25 is 0.2 kg PuO_2 and the alarm threshold is set at 0.4 kg (4σ). Closure is on a shift-to-shift basis.

EXAMPLE 37: Single Removal of Clean MO_2 Scrap

SCENARIO - Select a reject subblend and remove 50.0 kg from it as it is returned to the MO_2 scrap recycle system.

Decision	Relative Likelihood Index
Material Attractiveness	0.6
Single Removal	1.0
No Substitution	1.0
No Record Change	1.0
No Collusion	1.0
Relative Likelihood Factor	0.6

A single removal of 50 kg MO_2 (2.0 kg PuO_2) would be a quantity approximately 8σ greater than the alarm threshold and would thereby be virtually 100% certain of detection within one shift.

EXAMPLE 38: Single Removal of MO_2 Scrap with Substitution

SCENARIO - Remove 50 kg MO_2 from the scrap recycle system and substitute 50 kg UO_2.

Decision	Relative Likelihood Index
Material Attractiveness	0.6
Single Removal	1.0
Inert Substitution	0.5
No Record Change	1.0
No Collusion	1.0
Relative Likelihood Factor	0.3

This scenario would not be detectable by weight alone, and therefore would not appear as an imbalance of equation S-25. Acceptance or rejection of a given MO_2 batch, however, depends on the analysis of the subblend. Likewise, the MO_2 storage silo to be used is also analyzed so that if there were a significant change of plutonium concentration, detection would be virtually certain. Analytical results could require periods from several days to one week, however.

EXAMPLE 39: Multiple Diversion from the Scrap Recycle System

Multiple removals from different parts of the scrap recycle system within one shift would be equivalent to a single removal, as far as equation S-25 is concerned, and would therefore hold no advantage for the diverter other than the time required for detection. The diverter must then consider multiple removals from different shifts. In order to avoid reducing the likelihood factor below 0.1, the diverter is limited to a maximum distribution number of 10.

SCENARIO - Remove 5.0 kg MO_2 (0.2 kg PuO_2) during each of 10 different shifts during an inventory period.

Decision	Relative Likelihood Index
Material Attractiveness	0.6
Distribution (10)	0.4
No Substitution	1.0
No Record Change	1.0
No Collusion	1.0
Relative Likelihood Factor	0.24

A removal of 2.0 kg PuO_2 would be approximately 2σ of equation S-25. With an alarm threshold of 4σ the probability of detection would be 2.28% per shift. The probability of detection of at least one such removal in 10 shifts would be 20.6%. This would appear to be an attractive scenario, but the diverter would be tripped up by the long-range closure equation, L-5. This equation has an LECE of 0.4 kg and an alarm threshold of 0.4 kg, so that a 2.0 kg (PuO_2) diversion (c.a. 10σ) would be detectable with > 99.9% probability. Timeliness, however, may be a problem since as long as six weeks could elapse between the diversion and its detection.

More rapid detection or removal from the clean scrap area can be achieved by setting the alarm threshold of S-25 to 2.5σ (1.25 LECE). With this limit, the probability of detection of removal of 0.2 kg

PuO_2 is 30.9% within one shift; the probability of detecting at least one such removal in 10 shifts is 97.5%. At this alarm level the false alarm probability is 0.62%, so that one would expect approximately one false alarm in two inventory periods. If this diversion scenario were being followed, however, there would be an average of 3.1 alarms per period. Investigation of one false alarm in two periods does not appear to be an unreasonable trade-off to provide protection against this type of scenario.

4.6. Waste treatment module

The flow diagram for the waste treatment module is shown in Figure 11. This module is established to process all liquid wastes, dirty scrap, and solid waste materials from the plant production operations and cleanouts. Dirty scrap is "material that is too impure to recycle and is in the judgement of the operator rich in SNM concentration" [7]. Waste is "material which is too impure to be directly recycled and is in the judgement of the operator very dilute in SNM" [7].

Cans of waste are received from the various process locations at the close of each shift and placed in storage (Location 150). All cans are quickly gamma scanned (Location 152) to estimate the plutonium content. If the plutonium concentration is higher than accepted limits, the can is passed

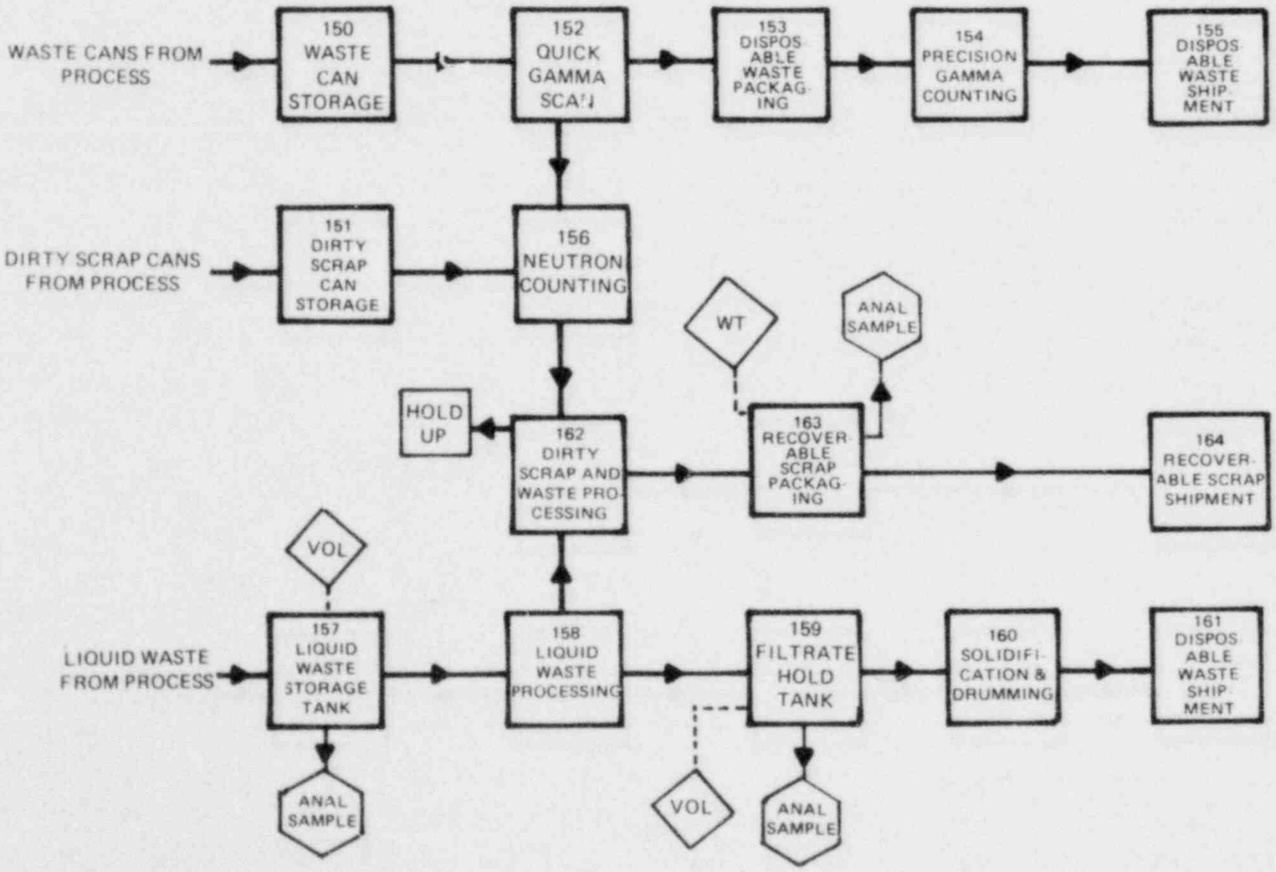

FIGURE 11 - Flow diagram of miscellaneous waste treatment module.

into the dirty scrap line (Location 156) for processing. Otherwise, waste materials are packaged (Location 153), precision gamma scanned to assay the plutonium content (Location 154), and shipped for disposal (Location 155).

Dirty scrap is received from the various plant locations and placed in storage (Location 151). Each can is assayed for plutonium content by neutron counting (Location 156), then passed to the processing module (Location 162).

Liquid waste is collected in a storage tank (Location 157) where it is analyzed chemically for plutonium content. The liquid is then processed chemically to precipitate the plutonium (Location 158), and the precipitate is transferred to the processing module (Location 162). The filtrate is assayed for residual plutonium (Location 159), mixed with a solidifying agent (Location 160), packaged, and shipped for disposal (Location 161).

Dirty scrap, recoverable waste, and liquid waste precipitate are calcined in the processing module (Location 162) to a stable ash form, packaged for shipment, assayed (Location 163), and shipped to a material recovery site (Location 164).

The controlling closure equation for this operation is long-term equation L-7. Since this equation spans the entire waste treatment module, it is not necessary to consider removal from any specific locations in the module. This equation normally closes at the end of each inventory period with an LECE of 0.74 kg PuO_2. To maintain timeliness, the equation also closes once per week, but since the process is dominated by largely unknown holdup in the calcining module, the LECE's for shorter term closures contain much larger uncertainties.

Theft of disposable waste (either the solid wastes or the liquid filtrate) is not regarded as a viable option for the diverter; this material has a relative likelihood index < 0.1, so any scenario involving this material would have a very low relative likelihood factor.

EXAMPLE 40: Single Removal of 2.0 kg PuO_2 as Dirty Scrap

Decision	Relative Likelihood Index
Material Attractiveness	0.4
Single Removal	1.0
No Substitution	1.0
No Record Change	1.0
No Collusion	1.0
Relative Likelihood Factor	0.4

With an alarm threshold of 2σ (1 LECE), a diversion of 2.0 kg PuO_2 (5.56σ) would be detectable with a probability of 99.9% at the two-month closure of L-7. Also, any combination of multiple thefts totalling the 2.0 kg would be detected identically; however, detection could take as long as two months for the final closure. Some interim protection is obtainable by weekly closures of L-7, but the detectability is difficult to calculate because of the large uncertainty in the LECE. In this respect, the dirty scrap treatment system may be potentially vulnerable from a timeliness of detection viewpoint.

Substitutional diversion also does not appear to be a viable option in this section of the plant; all effluent materials are assayed by gamma counting or by chemical analysis.

4.7. Analytical services module

The analytical services module is shown schematically in Figure 12. This module processes all analytical samples obtained throughout the mixed-oxide plant. Only one long-term closure equation, L-6, is required to monitor this module.

All sample movement in the module is governed by the analytical material control station (Location 148). Incoming samples are weighed and apportioned to appropriate analytical laboratories for analysis. After analysis, all samples are disposed of as dirty scrap, solid waste, or liquid waste; no material is returned directly to the fuel fabrication process.

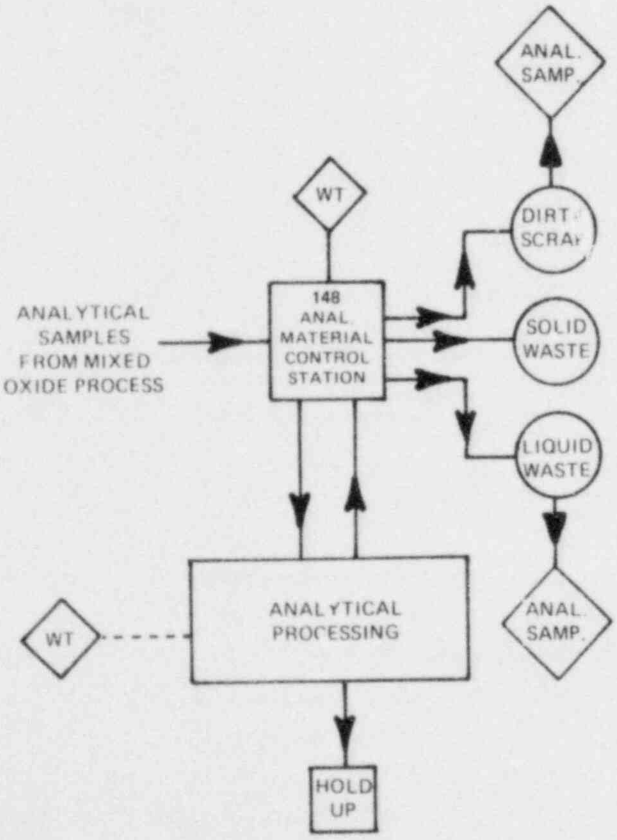

FIGURE 12 - Flow diagram of analytical service module.

The total material throughput of the analytical module is approximately 6.0 kg PuO_2 per inventory period. Since used material is transferred regularly to the waste processing facility, there is never more than about 0.75 kg PuO_2 in all forms in the module at any one time. Hence a single theft to acquire 2.0 kg is not possible. Since any removal of large amounts of material from this area would be immediately obvious, the diverter must spread his thefts over the entire inventory period. Thus, the two-month closure cycle of equation L-5 is sufficiently timely to thwart a diversion attempt.

The LECE and alarm threshold of L-6 are 0.47 kg PuO_2, so a 2.0 kg diversion would be approximately 9σ and would be detectable at virtually 100% probability.

It is concluded that there is no viable way for a diverter to accrue 2.0 kg PuO_2 from the analytical services module.

5. Diversion scenario ranking

In considering potential theft scenarios for the mixed-oxide plant, a diverter must assess any time advantage he may be able to gain in addition to the probability that his theft will be detected, the difficulty of setting up the diversion, and the material attractiveness (Relative Likelihood Factors). It is assumed the diverter's organization has available adequate facilities for concentrating and utilizing the plutonium. It is also assumed the diverter is capable of packaging his theft and removing it from the plant without discovery. For MO_2 this would involve smuggling approximately 110 lb of material.

With these factors in mind, the scenarios developed in Sections 4.1. through 4.7. are ranked into an order of descending relative attractiveness for each plant section. These rankings are given in Tables 6-12. In general, those scenarios with high probability of detection but requiring longer detection times are given higher rankings than scenarios with lower probabilities of detection in a shorter time. These tables do not list all the scenarios developed in Section 4; scenarios in which the probability of detection in 24 hr is 97.5% or greater are not listed, nor are most of the scenarios with RLF's less than 0.1. Remedial action for vulnerabilities identified in these tables is discussed for each area of the plant in Section 6.

Table 6 - POTENTIAL DIVERSION FROM THE PuO_2 STORAGE SILO LOADING OPERATION

Scenario No.	Type	Relative Likelihood Factor	Probability of Detection	Time of Detection
5	8-time Multiple	0.4	92.0%	Up to 1 wk
4	Single w/UO_2 Substitution & Record Change	0.32	>99.9%	<4 shifts
3	Single w/UO_2 Substituion	0.7	>99.9%	<4 shifts

Table 7 - POTENTIAL DIVERSIONS FROM THE PuO_2 STORAGE SILOS ON HOLD

Scenario No.	Type	Relative Likelihood Factor	Probability of Detection	Time of Detection
7	Single w/UO_2 Substitution	0.7	>99.9%	2 wk
8	Single w/tare Substitution	0.21	>99.9%	2 wk
9	8-time Multiple w/tare substitution	0.08	93.6%	1 wk

Table 8 - POTENTIAL DIVERSION OF PuO_2 SILO IN USE (BLENDER FEED AND WEIGH HOPPERS)

Scenario No.	Type	Relative Likelihood Factor	Probability of Detection	Time of Detection
11	8-time multiple	0.4	83.7%	1 wk
16	Single w/tare Substitution	0.7	>99.9%	1 wk + 1 shift

Table 9 - POTENTIAL DIVERSIONS OF MO$_2$ FROM THE BLENDER CYCLE

Scenario No.	Type	Relative Likelihood Factor	Probability of Detection	Time of Detection
18	Single w/UO$_2$ Substitution (MO$_2$ feed silo on hold)	0.42	71.6% 97.5%	< 2 shifts 4 shifts
19	Single w/UO$_2$ Substitution (Blender feed & weigh hopper)	0.42	71.6% 97.5%	< 2 shifts 4 shifts
23	Single w/UO$_2$ Substitution (Subblend silo on hold)	0.42	99.9%	2 wk + 1 shift

Table 10 - POTENTIAL DIVERSIONS OF MO$_2$ FROM THE PELLETING MODULE

Scenario No.	Type	Relative Likelihood Factor	Probability of Detection	Time of Detection
27	10-time Multiple w/UO$_2$ Substitution (slug press feed hopper)	0.17	99.8%	$\leq$ 1 wk
29	40-time Multiple (slug press wafers)	0.06	5.3% 93.7%[a]	1 shift 1 shift[a]

[a] The nominal alarm threshold for equation S-14 is 4σ[8]; the higher detectability shown here is obtained if the alarm threshold is set at 2.5σ.

Table 11 - POTENTIAL DIVERSIONS FROM THE CLEAN SCRAP RECYCLE SYSTEM

Scenario No.	Type	Relative Likelihood Factor	Probability of Detection	Time of Detection
38	Single w/UO$_2$ Substitution	0.3	> 99.9%	1 wk +
39	10-time multiple	0.[illegible]	> 99.9% 97.5%[a]	6 wk 1 shift[a]

[a] The nominal alarm threshold for equation S-25 is 4σ [8]. At this alarm level the diversion cannot be detected by S-25, only by the long-term equation, L-5. If the alarm threshold on S-25 is reduced to 2.5σ, however, the short-term equation can be used, and detection now will meet the timeliness requirement of the performance criterion.

Table 12 - POTENTIAL DIVERSION FROM THE WASTE PROCESSING MODULE

Scenario No.	Type	Relative Likelihood Factor	Probability of Detection	Time of Detection
40	Single (Dirty Scrap)	0.4	99.9%	8 wk

Note: No short-term equations were written for this module.

6. Conclusions

From the above analyses it is apparent that a material monitoring system based on a CUA closure equation network will provide adequate and timely protection against simple material removal scenarios (i.e., simple SS/ST or SS/MT diversions without substitution or record change) from all areas of the plant, with the possible exception of the waste processing module. It is recognized that a clever thief could succeed in circumventing the material control system, but if he were to have any hope of escaping detection long enough to complete his diversion he must introduce complex secondary factors into his mode of theft. In most cases examined, these secondary factors will reduce the likelihood factor to below 0.1. Potential vulnerabilities noted in Section 5 can be controlled as follows:

1) PuO$_2$ Silo Filling Operation
Although substitutional diversion will be detected with high reliability, the time scale of detection is long enough to be attractive to a potential diverter. Each can unloading operation should be monitored to prevent material substitution at the input weighing station. Also, to protect against a multiple diversion from sequential silo loads, replicate weight measurements of full silos can be used to reduce the LECE of the filling equation.

2) Filled PuO$_2$ and MO$_2$ Silos on Analytical Hold
There is no immediate method for detecting material substitution in a filled silo. Tamper-safe seals must be used on full silos to ensure that, once a silo is analyzed, its integrity will be maintained throughout its hold and use periods. Otherwise, secondary analyses would be required.

3) Blending Module
The PuO$_2$ silo in use is somewhat vulnerable to multiple diversions, primarily because of scenarios with a less-than-desirable detectability and the possibility that several shifts may pass before the trickle removal is discovered. This problem can be alleviated by added replication of silo weight measurements to reduce the LECE of the controlling equation. Substitution is readily detected by subblend analysis which is usually available 24 hr after completion of the subblend. Controls are needed, however, to ensure that once a subblend silo load is sampled for analysis and quality control the silo is sealed to preserve the integrity of

its contents throughout its hold and use periods.

4) Pelleting Module
Although detection of substitution diversion from this module is ultimately detectable with high reliability, the possibility of an elapsed time of a week or more between diversion and detection makes such a diversion relatively attractive. Physical and administrative control of this system must preclude introduction of foreign materials to either the slugging press or the pelleting press.

5) Fuel Rod Fabrication
Although it appears that there are no viable theft scenarios for this module, proper procedures are required to maintain accurate records of the hundreds of fuel rods handled in this section of the plant to ensure there are not record changes.

6) MO_2 Scrap Recycle System
Although any sizeable diversion from this section of the plant would have a high probability of detection, a sufficiently dedicated diverter might be attracted by the substantial time lag required for analyses. The largest source of error contributing to imbalances in shift-to-shift closures in this section of the plant is uncertainty in material holdup. Additional gamma scanning instrumentation can be used to more accurately estimate this holdup at closure times. Also, it is apparent that setting the alarm threshold at 2 LECE (4σ) may not be restrictive enough; a 1.25 LECE alarm threshold would result in much tighter control with only a modest increase in the false alarm rate to 0.62 per inventory period.

7) Waste Processing Module
If it appears possible to physically remove material from this section of the plant, it will be necessary to consider implementing a short-term closure equation for regular run-out modes (approximately once per week).

8) Analytical Services Module
Although removal of material from the analytical module is not a viable theft option, administrative procedures must ensure the integrity of analytical results so that data falsification in the analytical laboratory is not used to cover an inert substitution somewhere else in the plant.

The option of data falsification to cover removal of material from a CUA-controlled plant was considered, but no viable scenarios were discovered. The diverter can gain some additional time in some areas of the plant by falsifying side stream data to cover removal of material from the main stream. Detection of this type of diversion is covered by the closure equations controlling the side streams. In some cases, more frequent closures of the scrap or waste equations may be required to achieve more timely detection of this type of diversion.

Data falsification to conceal a diversion is not a fruitful option for a thief in the mixed-oxide plant. Because of the interrelation of the CUA closure equations and the use of process operational data to drive these equations, any significant discrepancy between input data and plant status would have to be propagated throughout the closure equation network in a carefully controlled manner to avoid detection. To be successful, such an attempt would place extreme demands on the diverter's depth of understanding of the plant operations and the closure equation system. In addition, it is not likely that extensive record changes could be accomplished without a several-person collusion, so this option could also be rejected on the basis of low relative likelihood. At best, data falsification could prolong the detection time, thereby giving the diverter some leeway to complete his theft.

Another conclusion that can be reached from this analysis is that, by spanning several material handling points simultaneously and by computing material balances within this span on a periodic basis, each closure equation permits treating a large number of potential theft scenarios as identities. This "pruning" effect of both time and space has permitted a detailed study of the vulnerability of the mixed-oxide plant without having to consider literally thousands of potential theft scenarios. Utilizing the cumulative effects of closure equation imbalances makes it possible to pinpoint "worst-cases" scenarios for most of the plant areas.

The problem of detection of scenarios employing diversions from two or more closure equation realms (MS/ST) is beyond the scope of this report. A preliminary investigation of this problem has shown there are no major vulnerabilities of this type in the mixed-oxide plant [5]. The concept of multiple diversions from various areas of the mixed-oxide plant (MS/MT) will be the subject of a future report.

7. Acknowledgements

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