MLM-2957
NUREG/CR-2831

A Test of the Controllable Unit Approach (CUA) Concept in a Low-Enrichment-Uranium Fuel-Fabrication Facility

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Monsanto

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Miamisburg, Ohio 45342

operated by
MONSANTO RESEARCH CORPORATION
a subsidiary of Monsanto Company

for the
U. S. DEPARTMENT OF ENERGY
Contract No. DE-AC04-76-DP00053

Printed in the United States of America
Available from
National Technical Information Service
U. S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

NTIS price codes
Printed Copy: A06
Microfiche copy: A01

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NUREG/CR-2831
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Prepared for: The United States
Nuclear Regulatory Commission
Office of Nuclear Regulatory Research

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Contents

Executive summary

Introduction

The Controllable Unit Approach (CUA) to nuclear material control and accounting (MC&A) was developed by Monsanto Research Corporation staff at Mound Facility for the Nuclear Regulatory Commission, Office of Standards Development*, to demonstrate the feasibility of controlling any nuclear material process to a specific performance criterion [1-4]. The term "performance criterion" refers to any set of performance control parameters imposed upon a process for safeguards purposes. For example, the current MC&A system, as contained in 10 CFR - Part 70, has a performance criterion that the uncertainty associated with material balance be controlled to within 0.5% of the total plant SNM throughput during any one inventory period.

The NRC is giving consideration to more stringent performance criteria [5]. These criteria would focus on detection of smaller amounts of material losses over shorter periods of time.

The CUA methodology was applied successfully to a proposed mixed-oxide fuel-fabrication process [2]. It was demonstrated in this application that the proposed measurement system for this process could control the process to a maximum loss of 2.0 kg of PuO_2 in any two-month inventory period.

The next logical step in the development of CUA was to apply the concept to an actual process of sufficient complexity to provide a convincing demonstration of the applicability of the CUA methodology to any process requiring material control and accounting. Results of the study were expected to provide a strong statistical and scientific authenticity to the information base that will be used to support Regulatory Guides and Rules and to provide greater assurance that proposed rule changes would be realistic and not beyond the technical or economic capabilities of licensees.*

To conduct this demonstration, Mound entered into a contract with a commercial nuclear-fuel manufacturer to apply the CUA methodology to a high-throughput, low-enrichment uranium fuel fabrication plant. The scope of the project was limited to the evaluation of the process to determine the added safeguards potential that could be achieved from the current measurement system. In order to provide a minimal impact on the licensee's production operations, the methodology was carried only through the step of identification of dominant errors in the process, with suggestions for potential refinement.

However, in addition to the determination of dominant measurement uncertainties, this study was expected to provide valuable insight into process modeling procedures and to identify specific problems associated with retrofitting a near real-time accounting system to an existing process. Implementation of specific process and measurement refinements to upgrade the performance of the plant, as per the CUA methodology, was beyond the scope of the study.

*Now the Office of Research.

*These goals are as stated in the Mound Facility work proposal/budget documents for FY1978, FY1979, FY1980, and FY1981 submitted to NRC/OSD.

It should be stressed that the purpose of this project was to test the CUA concept and techniques under actual process conditions; the study was not intended to audit the material control system or to pressure the licensee into implementing specific refinements. The selection of a low-enrichment plant for this study does not imply that restrictions are under consideration for low-enrichment processes.

Process modeling and data collection

A process model is a mathematical representation of material flows and measurement uncertainties in the process. Mound personnel worked with the licensee's engineers to develop a model of the low-enrichment plant. This model included preparation of detailed flow diagrams of all portions of the process; identification of specific material quantities for major flows and side streams in each process step, all appropriate physical and chemical forms of uranium, and all operational modes; identification of all measurements in the plant and all random and systematic error components associated with each measurement; estimations of in-process quantities and hold-up for each of the operational modes; and plant physical inventory information.

This modeling information was used to divide the process into 37 control units, so that each control unit was bounded by quantitative material measurements in each side stream (measurement nodes). Material balance closure equations were determined for each of the control units. A block diagram of the entire process is given in Figure 1. This figure also shows the spans of 17 short-term closure equations and the six-month plant-wide closure equation. It is not necessary to show all 37 closure equations; several equations are identical in order to provide individual coverage of multiple parallel conversion and pelleting lines. The configuration of these control units and closure equations provided a basis for identification of the measurement nodes in the process for which operational data would be required for the CUA test. No new measurements were proposed; only those data that were normally taken by the licensee to operate the process were requested.

Data collection covered a six-month period which started and ended with formal plant-wide SNM inventories. During this period the licensee supplied Mound with raw data from approximately 170 measurement points throughout the process. The total volume of data transmitted to Mound during this period was about 1.7 million data points.

Calculations of the measurement system variability

With a CUA designed system, the sensitivity to loss of SNM is inversely related to the variability of the material balance determined for each control unit, as described by a closure equation. A large variability means that a loss of SNM will likely be more indistinguishable from the noise inherent in the measurement and from stochastic variations in resident material in process equipment. A reliable estimate of the measurement variability of each control unit is therefore required to determine the loss sensitivity for the process.

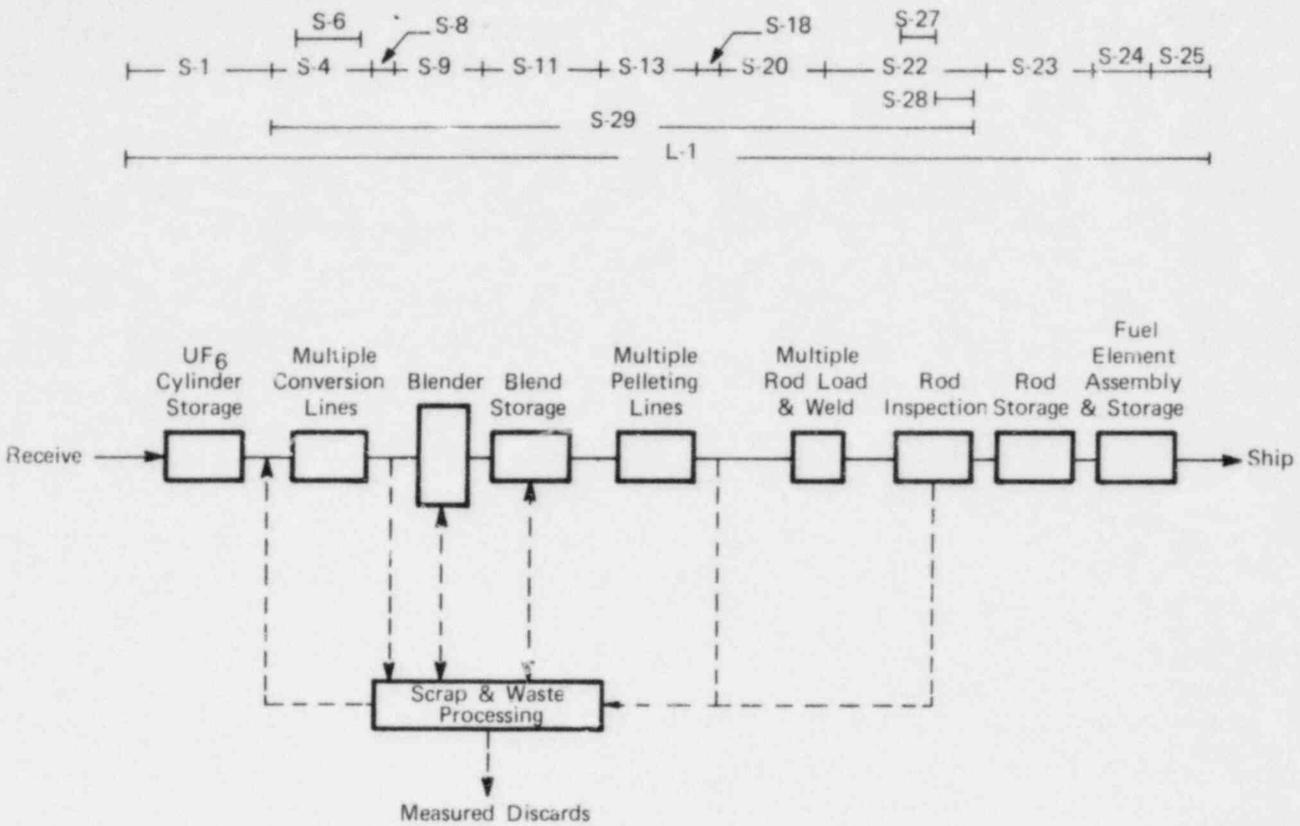

FIGURE 1 - Flow diagram of low-enrichment uranium fuel process showing spans of closure equations.

The variability of a closure equation is defined as twice the square root of the variance of closure imbalances ($2\sqrt{CEIV}$) [4]. Estimates of the closure equation variability are based on measurement control information and model-based material flows. Verification of the CUA model includes comparing the model-based variabilities with estimates based on actual data ($2\hat{\sigma}_{cei}$).*

There are five types of equation closures that can be employed in this plant. Closures may be obtained by identification number (ID#), item count, bulk weight, uranium weight, and/or uranium-235 weight.

*The term "cei" used throughout this report refers to "closure equation imbalance."

The type of closure employed for a given equation depends on the type of data available from the measurement nodes. Of the five types of closures, only the ID# closures are considered to have zero measurement variability; an item is either there or it is not.

In order to protect the proprietary position of the licensee and still be able to correlate CUA results with the current MC&A system, it was necessary to convert the material quantities noted in this report to a set of normalized units. For this purpose, the normalized unit, NU, is defined in this report as 1/1000th the plant LEID (Limit of Error of Inventory Difference) for the inventory period surveyed.

The variabilities of the modeled 17 "generic" short-term closure equations, expressed in terms of $2\sigma_{cei}$, are shown in the histogram in Figure 2. This figure shows that expected mass variabilities range from 0 to 45 NU in various areas of the plant; the one exception is the scrap processing area where the variability is estimated to be greater than 585 NU. Zero variabilities occur with ID# closures in the UF_6 cylinder area and with item count closures in the Fuel Element Assembly storage area. The larger variabilities occur in those areas where chemical and physical processing of the fuel material takes place rather than in storage areas. The increased localization of loss detection that could be obtained by partitioning the process into control units is evident in Figure 2.

The detailed tables that were used to calculate these variabilities identified dominant sources of measurement or predictor error for each control unit in the process. These dominant errors delineate where efforts would need to be concentrated if it were desired to upgrade the material control system.

Based on the model information, the most effective implementation of improvements would be in scrap processing.

The CUA modeling also indicated that improved timeliness of loss detection could be achieved for many areas of the process. However, with the data that became available from the process, it was not possible to obtain closures in all equations on a short-term, i.e., 24-hr, basis. In several storage areas the data would support closures only with formal inventory data, so that closures could not be performed in these areas more frequently than every six months. Figure 3 shows a comparison of the closure periods supportable by available data for the closure equations. Closure periods range from 8 hr to 6 months.

It is useful at this point to introduce the distinction between formal inventories and informal inventories. Formal inventories are defined as complete plant-wide SNM material balances taken for safeguards purposes on a regular basis, as required for license compliance. Informal inventories refer to any material accounting measurements of stored material, not necessarily plant-wide, which the licensee performs for his own benefit, usually for process control.

Model verification through closure analysis

Primary estimates of mass sensitivity and timeliness of loss detection were based on modeled information. In accordance with the next step of the CUA methodology these estimates were tested with actual data. In order to verify the model of the low-enrichment process, approximately 2200 closure equation imbalances (cei's) were calculated using plant data. The variances of these imbalances were calculated for each control unit where possible and compared with model predictions.

Results from the closure studies for specific operating areas are summarized in Table 1 along with specific parameters for alarm thresholds and material loss detectabilities that were derived from the cei standard deviations. With the

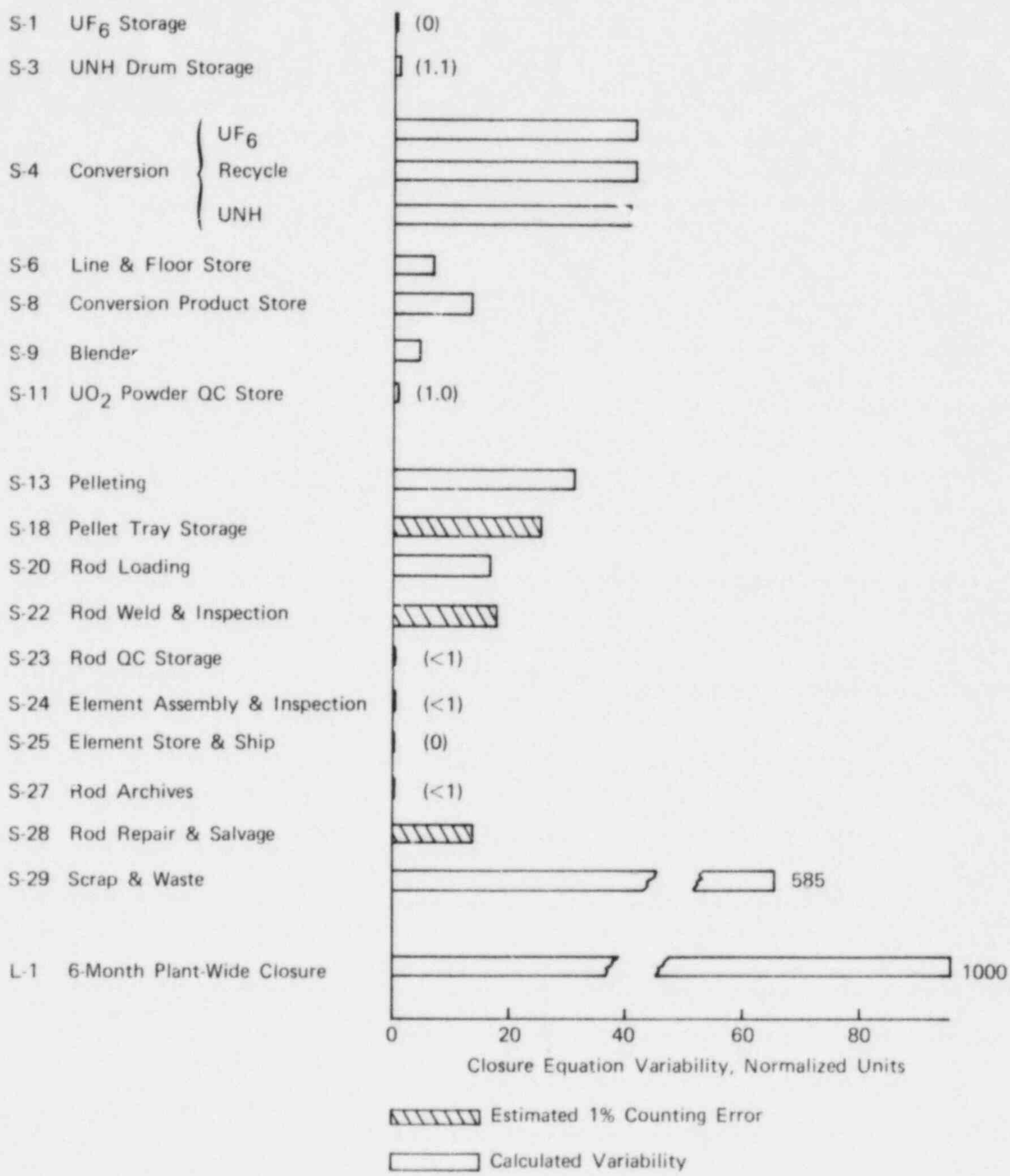

FIGURE 2 - Comparison of model-based closure equation variabilities (2σ normalized units).

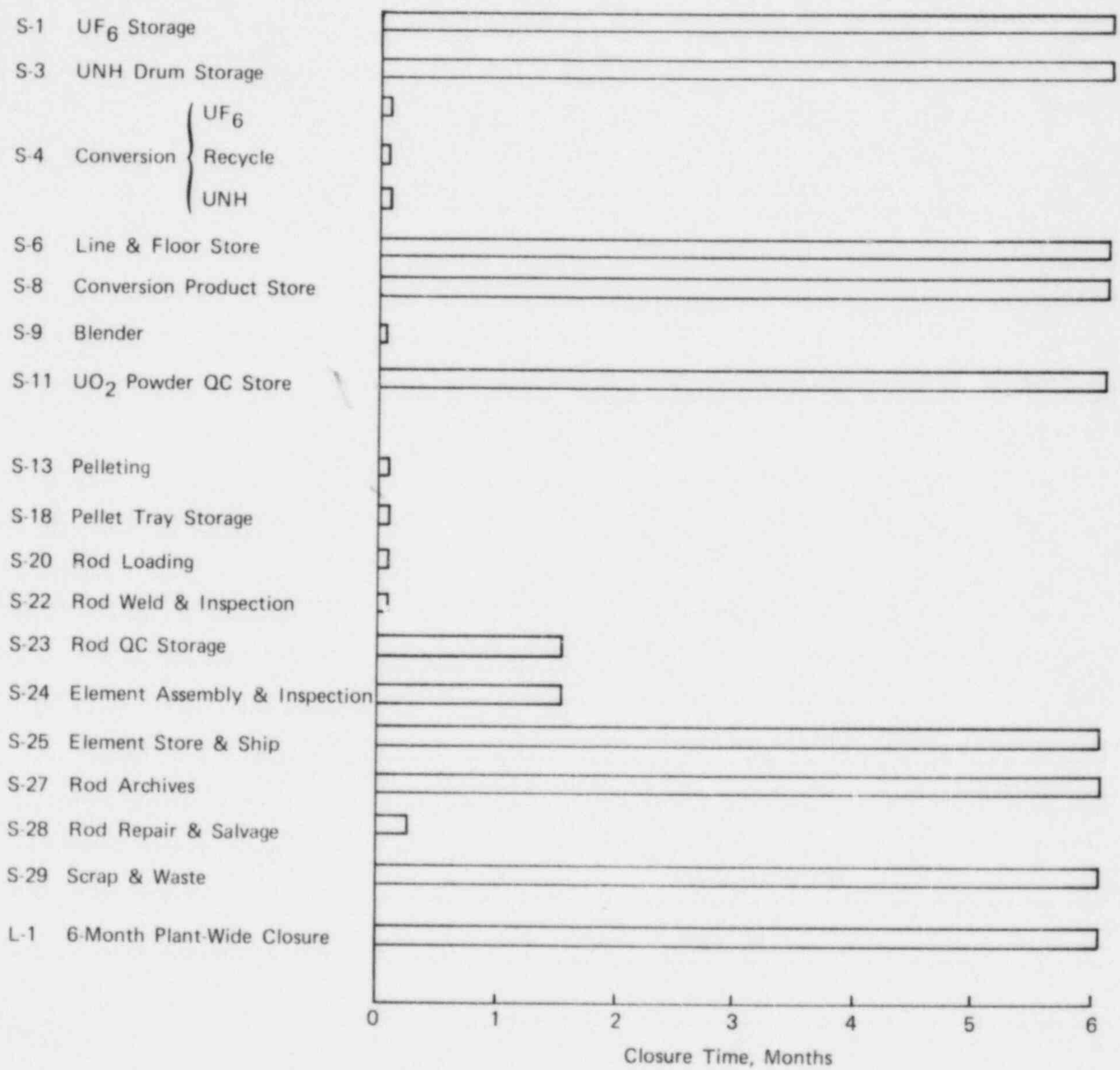

FIGURE 3 - Closure periods for closure equations as determined by informal and formal inventories.

Table 1 - SAFEGUARDS PARAMETERS FOR SPECIFIC CONTROL UNITS IN THE LOW-ENRICHMENT FUEL PLANT

Control Unit No.	Operation	No. of Closures per Inventory Period	Model-Based Stand. Dev. Norm. Units	Observed cei Stand. Dev. Norm. Units	Alarm Threshold[a] Norm. Units	Loss Detectable @ 90% Prob. Norm. Units
4	Conversion	> 200	22.8	49.9[b]	143[b]	207[b]
9	Blender	> 200	2.2	66.7	181	266
13	Pelleting	> 200	17.2	52.7	150	217
18	Tray Storage	> 200	3.2	12.6	36	52
22	Rod Inspection	> 25	< 1 rod	10 rods	19 rods	31 rods
29	Scrap and Waste	1	282	--	728[c]	1191[c]

[a]Based on an average of one false alarm in control unit in the six-month period.

[b]Based on 30 closures with refined data.

[c]Based on model standard deviation.

exception of the pellet tray storage area, which was inventoried daily, closures in the other storage areas of the plant could be performed only on a six-month basis; there were no interim informal inventory data available for these areas. Since reliable statistics cannot be obtained for single closures, results from these areas were not included in Table 1. Closures for the UF_6 Cylinder Storage (ID# closures) and the Fuel Element Assembly Storage area (item-count closures) exhibited cei's = 0; i.e., there was an exact accounting for items in these areas.

COMPARISON OF MODEL WITH DATA CLOSURES

Three observations were derived from comparison of actual data closures with the process model. First, the data verified the basic model parameters, such as material flows through the various portions of the process, schedules of closure times, estimates of resident material, and estimates of holdup. Secondly, comparison of closure statistics with the model revealed that the system was dominated by nonmeasurement errors. There were two sources of nonmeasurement error identified which dominated the uncertainties in some parts of the process. These are data errors and phasing errors. Data errors include missing data, transcription errors, encoding errors, and duplicated data. Phasing errors arise when the documentation describing material movements through the process does not correlate exactly with informal material inventories.

The third result obtained from the closure analysis was the indication that closure imbalances can be employed under dynamic line operations to verify predictors of in-process material and holdup. In the conversion lines, for example, the largest source of uncertainty was the limit-of-error of the predictors for in-process quantities during operation. Cei data, uncorrected for in-line quantities, were used to determine differences of integrated input flows and output flows for each control unit. These differences would be the in-line quantities at the closure times, within the precision of the measurement system.

An example of this application, as applied to one of the conversion lines for a portion of the operating period, is shown in Figure 4. In this figure, the solid line is the predicted in-line quantities of uranium; these predicted quantities are based on the experiences of the conversion process engineers at the licensee's plant and on a wealth of historical data. The dashed line connects data points calculated from equation closures. In general, the correlation of the measured and predicted values agree within the variability of the control unit except near the end of the period. The discrepancy in this time frame has subsequently been identified as resulting from missing data.

SPECIFIC OBSERVATIONS FROM THE CUA TESTING PHASE

The effects of data errors and phasing errors on the closure analysis of specific portions of the process are illustrated in the following sections. The blender, pellet-tray storage, and other storage areas are not included in the examples since error effects are well illustrated by the examples given.

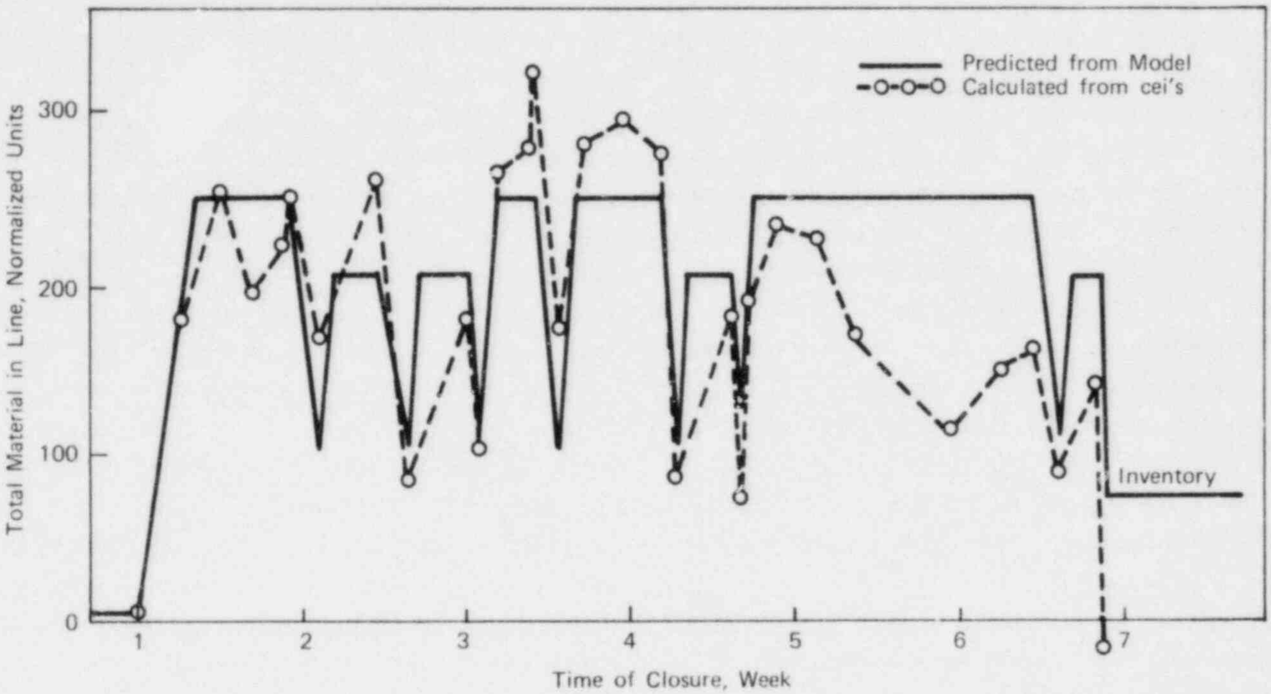

FIGURE 4 - Comparison of data-based conversion line in-process quantities with expected quantities based on the process model.

Conversion

There were three separate production modes in the conversion operation and four levels of runout and cleanout. Since only one production mode or cleanout mode was in effect at any one time, closures in this area were "event-controlled." The data received from the licensee better supported closures of the material balance equation at specific times, when the status of each conversion line was best defined, rather than periodically.

Preliminary closures in the conversion lines were dominated by data errors. These closures exhibited abnormally large imbalances (cei's) with standard deviations of the order of 230 NU. Computerized review of the encoded data identified significant quantities of missing information related to UO_2 powder packs in interim and product storage that contributed to this uncertainty. It was found that, in many cases, estimated weights and material movements for many of the affected powder packs could be reliably inferred from other available information. With corrections based on these inferences, the data-based standard deviation for the conversion operation, all modes, was reduced to approximately 50 NU. The residual uncertainty is believed to be a combination of unidentified missing data and phasing errors.

Pelleting

Preliminary closures in the pelleting area yielded cei's with standard deviations much higher than expected from the process model. Also, these cei's exhibited a definite bimodal distribution for each pelleting line. An inspection of the original data revealed that the materials in the pelleting area frequently resided for several hours or days in informal staging areas after being transferred to one of the pelleting lines, so that the recorded time of material transfer would not necessarily correlate with actual material movement. This is an excellent example of a source of phasing error. These informal staging areas were not included in the original model, so it was necessary to restructure the control units to provide better correlation of material movements and inventories. Since the raw data were already computerized, it was a relatively simple task to restructure the control units and their associated closure equations to generate a new set of cei's.

Although the results in Table 1 were corrected for the observed phasing error, there were still significant residual discrepancies between the data-based and model-based variabilities. The data used to determine these cei's appeared to be reasonably complete, so this difference could not be explained by missing information. The dominant error in the pelleting process was the uncertainty of in-process and holdup materials at each closure. Predictors used for uranium concentration of scrap materials awaiting processing could not be verified from the data available in the current study. Uncertainties associated with pellet trays in storage appeared to be the result of a combination of tray counting errors and uncertainties in predictors of average tray weights.

Rod Welding and Inspection

Closures in this area were based on rod item counts. Closure uncertainties were dominated by both missing information and phasing errors. Missing information was identified by scanning for gaps in sequential rod-lot numbers and by cross checking rod-lot totals with rod-loading information obtained from the Detail-of-Pelleting form (Form P-3, Table B-3). Preliminary closures were performed across all contracts in the rod inspection area with data corrected as well as possible for the identified missing information. These closures exhibited a standard deviation of approximately 160 rods. Since the calculated variability (Table D-3) indicates this standard deviation should be less than one rod, there was apparently a serious source of error in the closures. It was shown that most of this uncertainty was due to lack of correlation between rod lot documents and the aperiodic informal rod inventories taken for each contract. The closures were dominated by phasing errors.

Cei's were recalculated using differences between successive, informal, rod inventories to correlate flows and inventories. These cei's were found to have a standard deviation of 19 rods. This uncertainty appears to result from small counting errors that occurred during the informal inventories.

It is apparent that the combination of counting errors and phasing errors is a significant contributor to the variability in the measurement system for the rod area. From these data alone it is difficult to determine the maximum amount of material that can be controlled in this area. However, by properly accounting for phasing error, the cei standard deviation with rod-counting practices employed during the study period appears to be about 35 rods per contract (this number is based on an average of 3.4 in-line inventories per contract during the inventory period).

Scrap and Waste Processing

There is only one control unit associated with this area; this unit encompasses all scrap and waste processing operations in the plant (except for clean scrap operations specific to each pelleting line), the analytical laboratories, and the uranyl nitrate storage area. No data for informal inventories in this area were received, so closures were based on one six-month closure for each contract using data derived from the two plant-wide formal inventories. The largest variability in the model was the uncertainty of uranium concentration in materials in storage after preliminary processing and awaiting final processing.

In addition to the uncertainties associated with uranium concentration, there was ample evidence that significant amounts of information describing movements of material into and out of the scrap area and movements between contracts within the area were missing from the data set. Also, it was necessary to make a number of assumptions concerning fractional flows and holdup in this area during the CUA modeling phase, and these assumptions could not be verified with the data available. Since the scrap area was not a formal material balance area (MBA), the uranium concentration in the materials entering the area were estimated for individually weighed containers. However, uranium concentration measurements were performed on all materials exiting the scrap area, so the material accountability of the plant was not compromised.

Conclusions

If CUA (or any other process-data-based material accounting system) were to be implemented in a process of this type, it would be necessary to establish procedures that would guarantee that all pertinent data would be available to the MC&A system. This could be accomplished by formatting data recording forms to enable rapid key encoding of information and, where practical, the use of remote computer terminals to provide instant verification of input data. Implementation of timely data verification procedures would also aid significantly in resolution of unacceptable inventory differences from plant inventories.

Valid equation closures also depend on frequent informal inventories of the in-process material quantities in the control units. Unless reliable predictors can be employed to estimate resident material quantities at closure times, these informal inventories should be scheduled at intervals commensurate with timeliness requirements of the performance criterion. In order to minimize the effects of phasing errors, work rules standardizing the times and conditions of the interim inventories should be established to better correlate in-process inventories and material movements.

Several major conclusions could be reached from the results of this study:

- The Process was Modeled with Minimum Difficulty

  The CUA process-modeling technique provides a valid basis for evaluating the impact of measurement uncertainties on a measurement control system that utilizes available process data. The low-enrichment process was modeled with no major difficulties, and such problems that were encountered were easily identified and rectified. All material flows, in-process quantities, and measurement uncertainties were verified by operational data and measurement control data.

  The calculated variability for the six-month plant-wide closure agreed very well with the LEID and the inventory difference for the ending formal inventory. This confirms that the material throughputs and measurement error components that were selected for the process model were correct.

- PC/QC Data Can Be Used for Material Accounting

  The test demonstrated the integration of process control, quality control, historical data, and material accountability information into a control-unit-based safeguards system. A viable control unit network was established that spanned the entire process and depended only upon existing measurements to operate.

- Significant Improvements in Materials Safeguards are Achievable

  The study established data-based control parameters that revealed that significant improvements in loss detection, i.e., mass sensitivity, localization, and timeliness, could be achieved in the process by using operational data to enhance material accountability information.

  Except for the scrap and waste processing area, all operations in the plant could be controlled to less than 20% of the plant LEID; this could be accomplished with no changes to the measurement system or to the measurement schedules.

- Process Predictors were Verified

  The CUA system verified the use of historically based predictors for estimation of unmeasured flows and material holdup under dynamic operating conditions.

- CUA Analysis Identified Dominating Errors Requiring Refinement

  The study showed that the data set, as received, was dominated by two types of nonmeasurement errors, i.e., data errors and phasing errors. Data errors included improperly recorded data, transcription errors, missing data, and duplicate data. Phasing errors arose when the paper work describing material movements and locations was not properly correlated with actual material locations.

  The six-month plant-wide closure was dominated by uncertainties associated with large amounts of unused resident material. The amount of material in storage during the period was almost twice the material throughput for the period. Inventory uncertainties were, in many cases, dominated by sampling errors.

In addition to inventory uncertainties, there were significant uncertainties in the scrap and waste processing area because uranium concentration of incoming material was characterized only by predictors.

- Potential Problems in Retrofitting MC&A Systems were Identified

  The study identified two major problems related to retrofitting a near-real-time MC&A system to an existing process. These were the necessity of reconciling data inconsistencies as soon as possible and the need for frequent informal inventories or other material identification procedures in all formal and informal material storage areas.

- Potential Refinements were Suggested

  Nonmeasurement errors can be reduced in a cost-effective manner by implementing computer editing capabilities to recognize significant data errors with sufficient timeliness to permit correction. Introduction of specific work rules to better correlate material movements and inventories could be employed.

  Inventory errors could be reduced by proper securing of unused materials and by more comprehensive analytical sampling of materials in temporary storage. More frequent inventories would be needed to upgrade loss detection timeliness. A weekly schedule of informal inventory of material in storage is suggested.

  Inadequate predictors can be upgraded only through additional measurements. A method is suggested for using material imbalances to verify predictors.

  It is estimated that using the refinements suggested would reduce the uncertainty in each control unit to less than 5% of the plant LEID. Implementation of such refinements would require only moderate changes to the measurement system.

1.0 Introduction

The Controllable Unit Approach (CUA) to nuclear material control and accounting was developed by Mound Facility for the Nuclear Regulatory Commission, Office of Standards Development,* to demonstrate the feasibility of controlling any nuclear material process to a specified performance criterion. CUA is a systematic process for evaluation and design of real-time MC&A systems. The methodology, described in detail in other reports [1-4], makes extensive use of day-to-day process control, process monitoring, quality control, analytical, and other operational data, in addition to specific safeguards data, to determine the mass sensitivity and timeliness of loss detection afforded by the process measurement system.

For material accounting, these data are supplied to a contiguous network of material balance closure equations; each equation closes on a schedule compatible with the schedule of the measurements comprising the equation. This arrangement allows for monitoring all material movements within a process on a near-real-time basis, and thereby identifies significant material imbalances both by time and by in-plant location. An extensive evaluation of the error components of each of the in-process measurements in combination with these closure equations is used to define the

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maximum material flows that can be permitted within portions of the process or maximum inventory in any storage area and still retain control of the process within its performance criterion.

The term "performance criterion" refers to any set of performance control parameters imposed upon a process for MC&A. The current MC&A procedures, as contained in 10 CFR - Part 70, have a performance criterion of controlling the uncertainty associated with material balance to 0.5% of total SNM throughput in any one inventory period. The NRC is giving consideration to more stringent performance criteria [5]. These criteria would focus on detection of smaller amounts of material losses over shorter periods of time. An example of such a performance criterion that would pertain to a high enrichment plant might be:

> The process material control system must be able to detect the loss of 5.0 formula-kilograms (fkg) or more of special nuclear material during any two-month period. Furthermore, detection of the loss must occur within 24 hours from the time the loss reaches the 5.0 fkg magnitude, and the detection probability must be at least 90%.

Prior to the current study, CUA methodology was applied successfully to a proposed mixed-oxide fuel-fabrication process [2] where it was shown that a maximum-loss performance criterion of 2.0 kg of PuO_2 could be met with the measurement system proposed by the potential licensee. It was also demonstrated that a computer-controlled closure equation network, using simulated data which were based on this proposed measurement system, would provide rapid detection of PuO_2 loss from a wide variety of simple and complex diversion scenarios [3].

The true test of any system is in how well it behaves in actual practice. It was determined early in the development of CUA that a test with operational data from an actual plant would ultimately be required. Such a test would be expected to verify the CUA modeling process and identify the dominating areas of uncertainty in the process. Results of the study were also expected to provide a strong statistical and scientific authenticity to the information base that will be used to support Regulatory Guides and Rules and would provide greater assurance that proposed rule changes would be realistic and not beyond the technical or economic capabilities of licensees.*

To do this, Mound entered into a contract with a commercial nuclear fuel manufacturer to apply the CUA methodology to a high-throughput, low-enrichment-uranium fuel-fabrication plant. The scope of the project was limited to the evaluation of the process to determine the added safeguards potential that could be achieved from the current measurement system. In order to provide a minimal impact on the licensee's production operations, the methodology was carried only through the step of identification of dominant errors in the process, with suggestions for potential refinement.

In addition to the determination of dominant measurement uncertainties, however, this study was expected to provide valuable insight into process modeling procedures and to identify specific problems associated with retrofitting a real-time accounting system to an existing process. Implementation of specific process and measurement

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refinements to upgrade the performance of the plant, as per the CUA methodology, was beyond the scope of the study.

This report describes the modeling of the low-enrichment-fuel process; formulation of the closure equations; calculations of the expected variabilities of these equations; development of the historical data base; compilation of computer files of this data base at Mound; and analysis of equation closures in the conversion, pelleting, fuel rod fabrication, and scrap recovery areas in the plant [6].

The selection of a low-enrichment plant for this study does not imply that restrictions are under consideration for low-enrichment processes. This plant was chosen because its material control system regularly kept material imbalances within ID/LEID limits, and because the process was sufficiently complex to provide a convincing demonstration of the CUA versatility. The study was never intended either to audit the licensee's material control procedures or to pressure him into implementing specific refinements. The CUA methodology was used to determine how well a process of this type can be controlled by using all available process data to enhance the material control system.

In order to protect the proprietary position of the licensee and still be able to correlate results with the current MC&A system, it was necessary to convert the material quantities noted in this report to a set of normalized units. For this purpose, the normalized unit, NU, is defined as 1/1000 of the plant LEID for the inventory period surveyed.

2.0 CUA methodogy

The CUA methodology, diagrammed in Figure 2.1, provides a system for evaluating measurement uncertainties in all portions of a process. The methodology is described in detail in the "CUA Application Manual" [4]. By combining these uncertainties the overall degree of control provided by the measurement system can be evaluated. Material control and accounting is achieved by a network of material balance closure equations that span all facets of the process. This network uses quantitative data that are normally generated for process control, process monitoring, quality control, and safeguards.

In order to set up a closure equation system to monitor a process, the process must be modeled. A model is a mathematical representation of material flows and measurement uncertainties in a process. To prepare a model, it is necessary that the process be well defined, all measurements be identified, and the variability of the measurement system be evaluated to determine the overall measurement uncertainty. As is noted in Figure 2.1, the first step in the CUA methodology, "Processing Modeling," entails:

1. Construction of detailed process flow diagrams of all processes in the plant.

2. Identification of all material flows and side streams in all portions of the process.

3. Definition of all physical and chemical forms of material handled.

4. Determination of the magnitudes of all flows under all operating conditions.

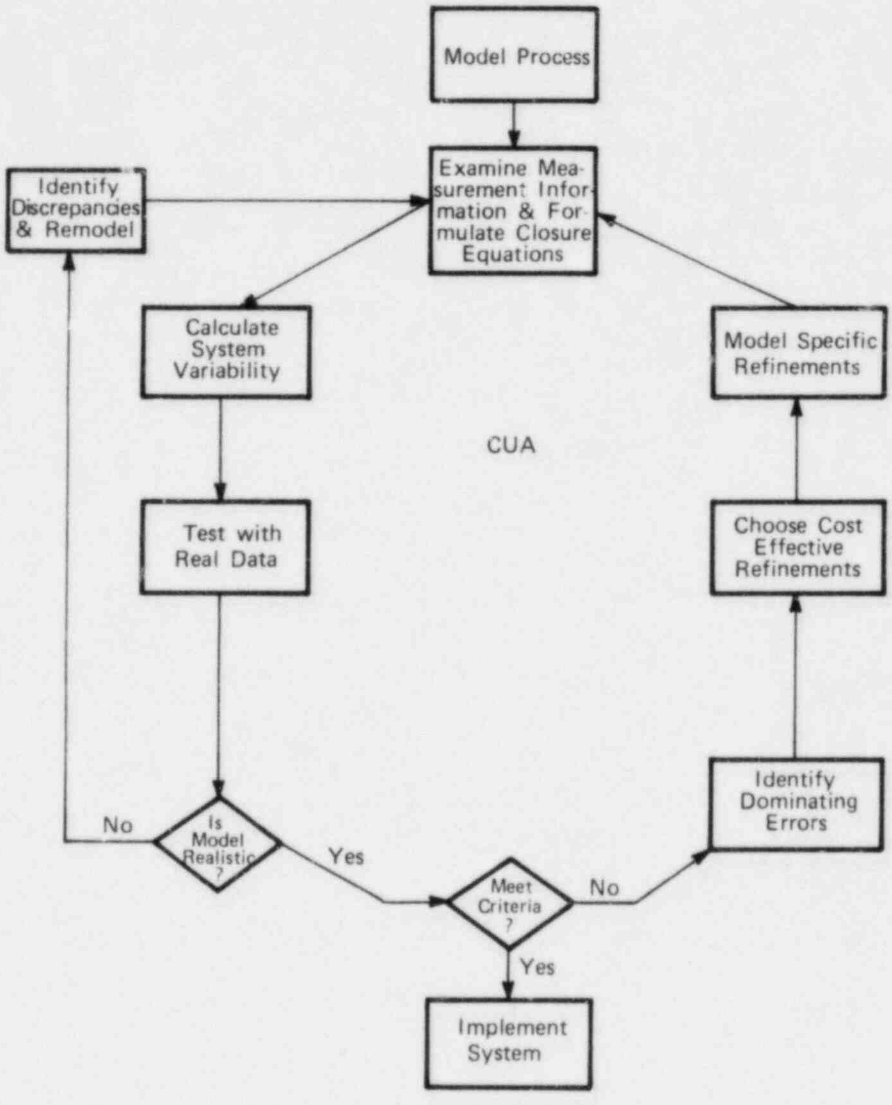

FIGURE 2-1 - The CUA methodology.

5. Determination of material quantities in storage, in process, and in holdup in all portions of the process.

6. Identification of all pertinent measurement points in the system.

7. Determination of all measurements and their schedules.

As a corollary to the modeling process, a determination of all random and systematic error components of each measurement in the system is required.

Once the process is modeled, the next step, as shown in Figure 2.1, is to examine the measurement system and formulate closure equations.

1. Each process module is divided into control units, such that each control unit is bounded by measurement nodes; i.e., there should be at least one quantitative material measurement in every input and output flow associated with the control unit. These should be normal process measurements that are taken at intervals commensurate with the desired controlling time frame.

2. Material balance closure equations are written to span each control unit. These equations are mathematical expressions of material balances within control units, and, as such, they relate the sum of all input and output flows with the change in resident material during each closure period. Any nonzero value for an equation closure is defined as the "closure equation imbalance" (cei).

3. In order to close the equation one must be able either to measure the amount of material within each control unit at closure time or to apply reliable predictors to the unmeasured materials in residence.

4. For effective control, each closure equation should close on a schedule commensurate with the time restrictions of performance criterion.

After the control units are delineated and the closure equations are formulated, the variability of each closure equation is calculated. If none of the errors are correlated, errors in the various measurements comprising a closure equation can be combined by root-sum-squaring (RSS) the absolute error components. If, however specific error components are correlated within a closure equation, they must be grouped in a manner dictated by the correlation (e.g., systematic errors in the tare weights of before and after weighings of the same container, on the same balance, in the same calibration period, would be correlated exactly and would cancel). After the correlated absolute components have been properly grouped, all grouped components are combined by root-sum-square. This grand combination of uncertainties in a closure equation is defined as the "variability of closure equation imbalances." It is useful to consider the variability as $2\sigma_{cei}$ since the relative error components are usually reported as 2σ.

The next step in the CUA methodology is to test the results of the variability calculations with real data to determine whether the process model is valid.

Once the validity of the model is assured, the operation of the plant is compared with its performance criterion to see if this criterion can be met. Normally, if the process does not meet its criterion, the error components are examined to identify the dominating errors. At this point specific refinements are examined for potential implementation. Refinements can be one or more of four types: 1) revision of the control units to bridge areas of large variability or to provide overlapping and redundancy of closure equations; 2) application of more sophisticated statistical techniques to increase the loss detection sensitivity; 3) modification of the measurement system, either by changing sampling schedules or by installing more precise equipment in key locations; and 4) modification of the process itself.

Specific refinements can be examined for their potential improvement of material control and cost effectiveness prior to actual implementation in the process by using the CUA evaluation methodology. Each potential refinement is woven into the process model, and the system variability is recalculated. The upgraded system is compared with the performance criterion for compliance. If compliance is not achieved, the system must be iterated through more refinements until criterion compliance is assured.

2.1 Application of CUA to the low-enrichment process

A model of the low-enrichment process was constructed from process flow sheets, engineering information, and measurement control data. The process was divided into control units, and material balance closure equations were written to span each control unit. Data acquired from the plant were applied to the various closure equations, and the variabilities of closure imbalances were compared to model-based values. Major sources of uncertainty were identified. The results are discussed in Chapter 6. This project was carried through the CUA loop only to the stage of identification of dominant errors. However, some recommendations for potential refinements are discussed. The project was not carried beyond this point in the current study since verification of the effects of any proposed refinements would require implementation in the plant and collection of another data set. Such additional verification was beyond the scope of the contract.

3.0 The fuel fabrication process

3.1 Synopsis of plant operations

The process, in brief, consisted of converting gaseous uranium hexafluoride (UF_6) to uranium dioxide (UO_2) powder, compacting and sintering the powder into small cylindrical pellets, grinding the pellets to specified precise diameters, loading the pellets into metal tubes and seal-welding the tubes to form fuel rods, and assembling the fuel rods into matrices to form fuel elements. Ancillary operations consisted of processing all scrap to recover material suitable for recycle, processing and disposing of all liquid and solid wastes, and operation of analytical laboratories. A summary flow diagram of the plant is shown in Figure 3.1.

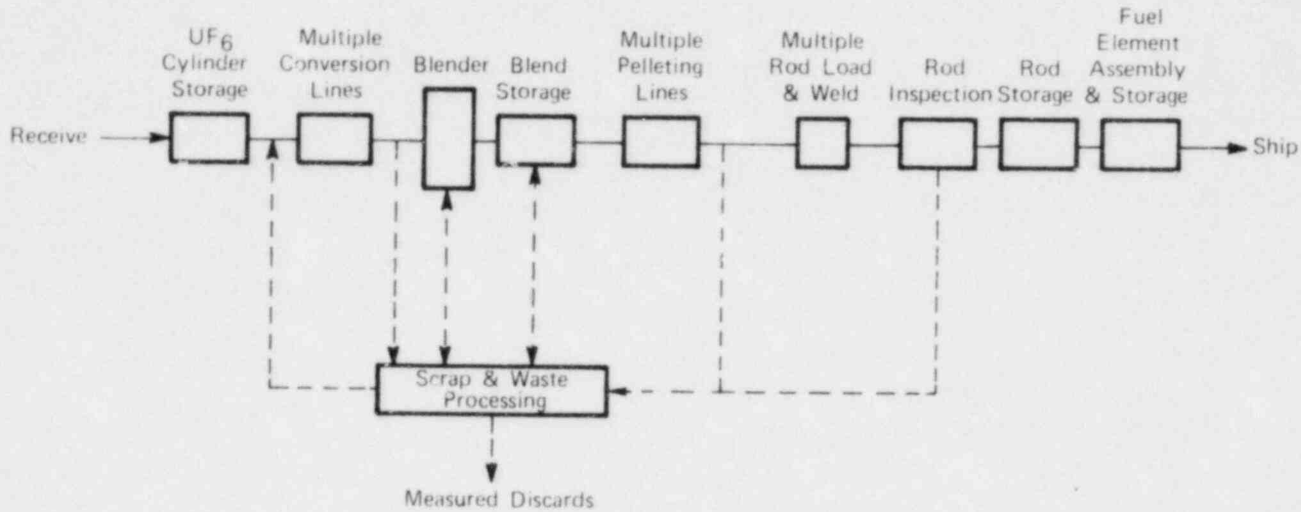

FIGURE 3-1 -low diagram of low-enrichment uranium fuel plant.

It was determined from the information received that the plant could conveniently be divided into four major operational modules. These modules are: 1) UF_6 to UO_2 conversion; 2) UO_2 pellet compaction, 3) fuel rod fabrication and fuel element assembly, and 4) scrap reprocessing and waste disposal. The analytical laboratory was included within the scrap reprocessing operations.

This high-throughput plant processes uranium with several different uranium-235 enrichments less than 5%. To demonstrate the feasibility of controlling this type of process, the CUA-based system would have to show a significant improvement in detecting loss of quantities that would be significantly less than the current LEID limit. It will be shown in Chapter 5 that, by application of CUA, such improvement is indeed possible.

In order to accommodate the processing of materials with varying uranium-235 enrichment without cross-contamination of the isotopes, the conversion, pelleting, and rod-loading operations were divided into parallel operating lines. Each line had essentially identical equipment and operating capacity, but different lines might be processing different enrichments at any one time. However, there were common operations between some of these multiple lines where it was necessary to allow for multiple inputs and outputs with varying enrichment.

The licensee maintained material accountability by assigning each material, including scrap, to one of a number of project accounts, called "contracts." Since the existing MC&A system was based on these contracts, proper delineation of the contracts was indispensible for collating all data received.

Detailed process descriptions and discussions of material flows in each of the six process modules are given in Appendix A.

4.0 Process modeling

The exact amount of material in a process and/or its location within the process can be estimated only through measurement or by using predictors based on measurement. Since all measurements and predictors are subject to error, the accuracy of the material holdings or flows depends on the precision and any biases associated with the measurements.

However, by defining specific material flows, inventories, holdup, etc., in a process model, one can compute, by evaluation of measurement error components, the uncertainty associated with the determination of material distribution within the model. If the assumed model approximates reality within the process, the computed uncertainty will be a valid measure of the limits of control of the process measurement system. The purpose of modeling, therefore, is to postulate exact material flows and distribution for a process under conditions of normal and maximum material throughput and, thereby, provide an absolute basis to evaluate the precision of the measurement system.

In order to apply the first step of CUA, "Process Modeling," it was necessary to develop an understanding of the process in sufficient detail to permit construction of adequate flow diagrams of the process. This required that the following information be well-defined:

All material chemical and physical forms handled in the plant; all main stream and side stream material flows; all specific operating modes; all major pieces of equipment and their operation; all material storage points; all analytical and in-line measurements, measurement points, measurement schedules, and the measurement control program; magnitudes of typical average and maximum flows in all portions of the plant; estimates or measurements of in-process and holdup materials in all portions of the plant; and all material inventories and their locations and schedules.

Detailed meetings were held with the licensee's process engineers and line supervisors for all production modules in the plant. Each engineer was given a detailed outline of the type of information required for his process. An abbreviated version of this outline is given in Appendix B, Table B-1. The authors worked with these engineers until satisfactory flow diagrams were developed for all process modules. These diagrams identified all main streams, side streams, material forms, storage areas, major pieces of equipment, all measurement points in the system, and the types of measurements taken. Simplified summaries of these flow diagrams are included with the process module descriptions in Appendix A.

The licensee supplied detailed information for each numbered block of the flow diagrams by utilizing "Process Operating Point" data sheets (POP sheets). An example of the POP sheet is given in Appendix B, Table B-2. The "Material Balance" section of the POP sheets involved obtaining an accurate and detailed material balance for each of the numbered stations within each module and correlating these balances between modules. Material quantities were based on a normal six-month operating period.

Mound constructed a plant-wide six-month material balance from the POP sheet data and thereby defined the absolute material flows and inventories for all portions of the plant. The flow diagrams were then divided into process control units so that each control unit was bounded by process measurement points. Identification of measurement points on the flow diagrams was required, therefore, to establish realistic control units and closure equations. Average and maximum material flows at each measurement point were determined, and preliminary closure equations were established.

There are two characteristics for valid closure equations; each material movement into and out of a closure equation control unit must pass through some sort of quantitative measurement node, and the resident material in the control unit itself must be capable of being measured or predicted at equation closure times. Since not all measurements and inventories normally occur simultaneously or even with the same frequency, it is necessary, in some cases, to resort to predictors to estimate in-process material and/or holdup at closure.

With many processes the only way to measure in-process material is to shut the line down and run the material out. However, by observing whether each piece of equipment in a module is in normal operation, has been run out, or has been cleaned out, the engineer can develop relatively reliable predictors for the amounts of in-process material and holdup in each piece of equipment, thereby providing an estimate of the amounts within an entire control unit. Thus, in the absence of a physical measurement, the reported status of an assemblage of equipment can provide a valid basis for estimating the amount of in-process material during running conditions.

Naturally, the degree of control within a control unit employing predictors depends on the variability of the predictors. To avoid complete loss of material control, each of these areas needs to be run out or cleaned out occasionally, and quantitative measurements need to be performed on the material removed. This type of information is frequently available from historical data in a plant.

The process was first divided into 98 control units with more than 400 measurement nodes. However, it was found that many of the measurements were taken for the benefit of line operation control only, and the data were rarely recorded. Thus, complete sets of these data would not be available.

With modifications to the control unit network to bridge areas of unavailable data, the process was restructured into 37 control units with 170 measurement nodes; this network was monitored by 37 short-term closure equations and one long-term equation. The closure equations will be discussed in detail in Chapter 5.

4.1 Data collection and transmission to Mound

The data collection phase of the project started with a formal, plant-wide, physical inventory and continued through the next inventory six months later. Data forms received from the licensee consisted of computer printouts and reproductions of a variety of forms including process data sheets, a number of different equipment operating logs, material traceability documents, computer data encoding sheets, and material movement tickets. A summary of the types of forms sent, the number of pages of each form, and the number of computer input records created is given in Appendix B, Table B-3. The volume of information encoded from the material received was about 1.7 million data points. Details on handling, encoding, verification, and computer configuration of these data are given in Appendix C.

Because of the mode of collecting, transmitting, and encoding such a large volume of data, there were a number of discrepancies that developed in the data set. Although many of these discrepancies were easily identified and resolved, others were not discovered until equation closures were performed. The specific impact of some of the unresolved discrepancies will be discussed in Chapter 6 on equation closure analysis.

It should be emphasized that many of the discrepancies encountered with the data set during this study are not inherent in the CUA system, but rather were artifacts created by the method of acquiring and transmitting the data. With a near real-time material-control system with computerized monitoring, any missing, erroneous, or duplicate data would be immediately apparent to the closure equation network, and the discrepancies could be identified and rectified promptly.

5.0 Calculation of the variability of closure equation imblances (2 $\sqrt{\text{CEIV}}$)

With the modifications to the closure equations noted in Chapter 4, the revised network consisted of 37 short-term equations and one long-term equation. These equations monitor 37 control units which are bounded by 170 measurement nodes. Several control units and their closure equations are identical in that they describe multiple, parallel, identical conversion and pelleting lines with identical hardware. The number of different, or "generic", control units and closure equations is 17.

A summary list of these equations is given in Table 5.1, and the plant-wide closure equation network is given in Figure 5.1. Block diagrams of each of the control units, closure equation spans, measurement node information, and calculated variabilities for each module in the plant are given in Appendix E.

Calculation of the variabilities is based on specific material quantities flowing through each control unit during each closure period. For short-term closures, typical values for these quantities were determined from POP sheets during the process modeling operation described above.

Table 5.1 - REVISED LIST OF CLOSURE EQUATIONS FOR LOW-ENRICHMENT PLANT

Conversion		# of Equations
S-1.	UF_6 Cylinder Storage	1
S-4a.	Conversion - UF_6 Mode	>1
S-4b.	Conversion - Recycle Mode	
S-4c.	Conversion - UNH Mode	
S-6.	Off-stream Line and Floor Storage	>1
S-8.	Product Storage	>1
S-9.	Blender	1
S-11.	Product Powder QC Storage	1
Pelleting		
S-13.	Pellet Preparation	>1
S-18.	Pellet Tray Storage	>1
Fuel Rod Fabrication		
S-20.	Rod Loading	1
S-22.	Rod Welding, QC Inspection, and Rerun and Rework	1
S-23.	Rod QC Storage	1
S-27.	Rod Archives	1
S-28.	Rod Repair and Salvage	1
Fuel Element Assembly and QC Inspection		
S-24.	Fuel Element Assembly and QC Inspection	1
S-25.	Fuel Element Storage and Shipment	1
Scrap and Waste Treatment		
S-29.	Scrap and Waste Processing, Analytical and Health Physics Labs, and UNH Receipt and Storage[a]	1
L-1.	Plant-Wide Six-Month Inventory Period	1

[a] Although variability tables were computed for UNH Receipt and Storage, data could not be found to support this area as a separate control unit.

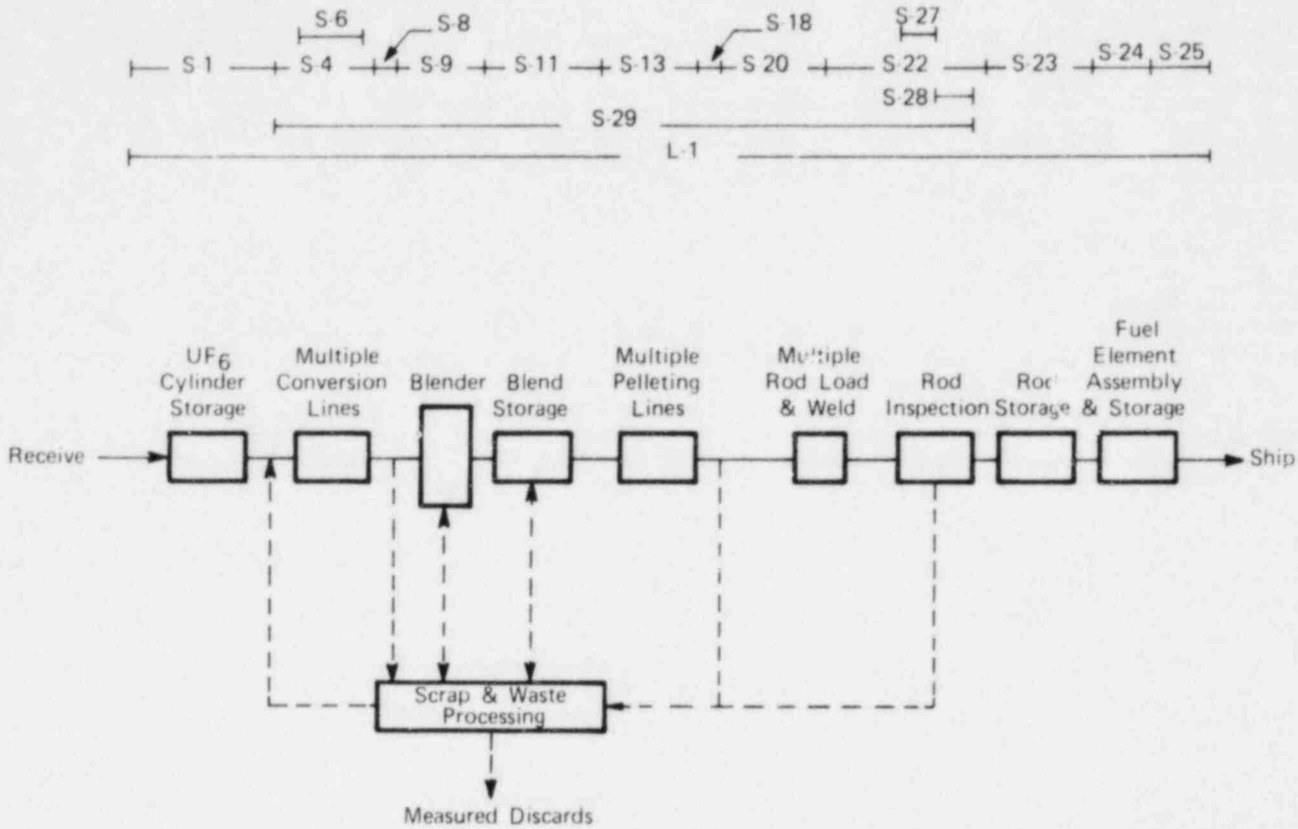

FIGURE 5.1 - Process flow diagram showing plant-wide closure equation network.

The degree of control attainable by any measurement system depends on the uncertainty associated with the measurements and the assurance that sample aliquots are representative of their parent materials. The errors associated with each measurement are generally divided into random and systematic components. For this discussion all sampling errors have been included with the random components of the pertinent measurements.

Information on relative error components for all measurement nodes in the process was received in response to the requests outlined in Appendix B. Also, the licensee supplied copies of the error matrices for both beginning and ending inventories. These matrices list 2σ random and systematic components of every measurement associated with the two formal physical inventories.

In order to estimate the overall error of a given closure equation, it is necessary that the errors associated with the various measurement nodes comprising the equation be properly combined. To do this it is useful to list the error components for each measurement node in the format shown in Table 5.2. This table lists relative random and systematic errors associated with each measurement node. The absolute error components are calculated from material quantities in the process model. Effects of multiple sampling and replicate measurements must be considered in calculating the absolute error. These components were included in the working tables used to calculate the variabilities, but to avoid clutter, these

Table 5.2 - GENERAL FORMAT FOR CALCULATION OF VARIABILITY FOR EACH CLOSURE EQUATION

Node No.	Process Model (wt. U)	Relative Error		Absolute Error (wt. U)	
		Random	Systematic	Random	Systematic
1	u_1	σ_{r1}	σ_{s1}	$u_1(\sigma_{r1})$	$u_1(\sigma_{s1})$
2	u_2	σ_{r2}	σ_{s2}	$u_2(\sigma_{r2})$	$u_2(\sigma_{s2})$
3	u_3	σ_{r3}	σ_{s3}	$u_3(\sigma_{r3})$	$u_3(\sigma_{s3})$
4	u_4	σ_{r4}	σ_{s4}	$u_4(\sigma_{r4})$	$u_4(\sigma_{s4})$
.	.	.	.	.	.
.	.	.	.	.	.
.	.	.	.	.	.
b	u_n	σ_{rn}	σ_{sn}	$u_n(\sigma_{rn})$	$u_n(\sigma_{s4})$
		Total Errors (RSS)		(Ran)	(Sys)
		Variability = $2\sqrt{(Ran)^2 + (Sys)^2}$			

components were omitted from Table 5.2. Both random and systematic components must be examined for correlation before combining. All correlated error components in a column, either additive or self-cancelling, are grouped by algebraic addition before the composite error is calculated by root-sum-square (RSS). Once the correlated components are grouped, the composite systematic error is calculated by root-sum-square combination of all the group totals (uncorrelated components are classed as groups with one member each). The composite random and systematic errors for the equation are then RSS combined to obtain the composite variability of the closure equation.

One major advantage for displaying the error components in the Table 5.2 format is that dominant errors in a given equation can be readily identified by inspection. This provides a concise diagnostic tool for use during testing phases of closures. Likewise, the effects of changing one or more measurements within a closure equation can be evaluated very rapidly.

Summary variability tables, based on the process model, are given in Appendix D for each of the closure equations listed in Table 5.1.

The calculated 2σ variability, obtained from these tables, is shown in Figure 5.2 for each generic closure equation; these values represent the relative mass sensitivity for loss detection of each equation at each closure. There are two points immediately apparent upon inspection of this diagram. First, the mass sensitivity of each portion of the plant is at least a factor of 10 smaller than the plant LEID except for the scrap and waste processing area. Thus, upgrading the measurement system of the conversion area or pelleting area without a major improvement in the

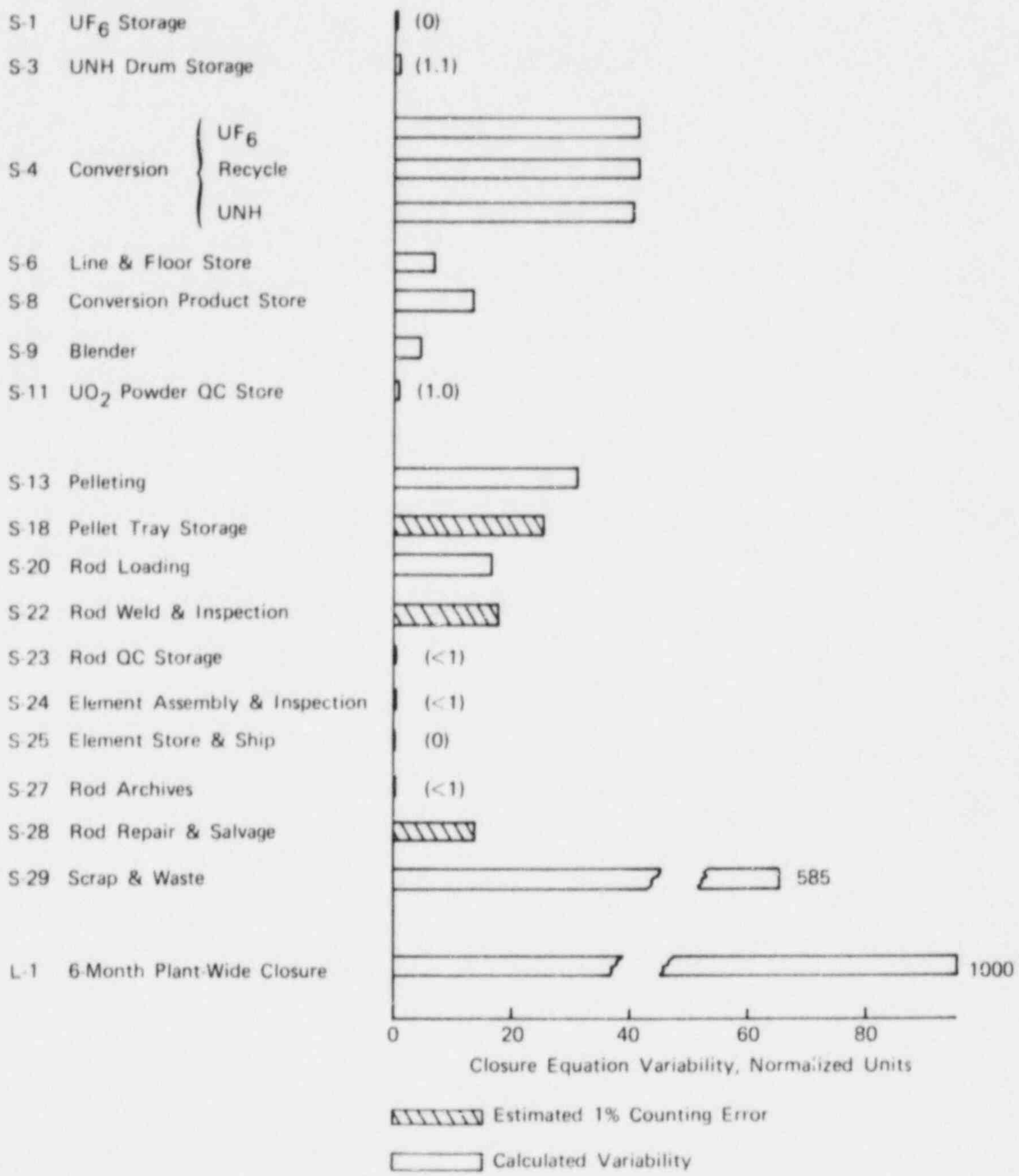

FIGURE 5.2 - Comparison of model-based closure equation variability (2σ normalized units).

scrap area, for example, would not contribute significantly to reduction of the overall plant uncertainty. Secondly, the largest variability in the CUA network, i.e., 585 NU in the scrap processing control unit, is still substantially less than the current LEID of 1000 NU. Thus, a significant improvement in mass sensitivity for abrupt loss, in addition to loss localization, could be achieved with no changes in current measurements, just by partitioning the process into control units.

The closure schedule for each of these generic equations is shown in Figure 5.3. This figure illustrates the areas in which the measurement system would need to be upgraded to improve timeliness of loss detection.

It should be emphasized that the values represented by the bar graphs in Figures 5.2 and 5.3 were calculated from the process model and from the licensee's measurement control information and are not based on the specific operational data

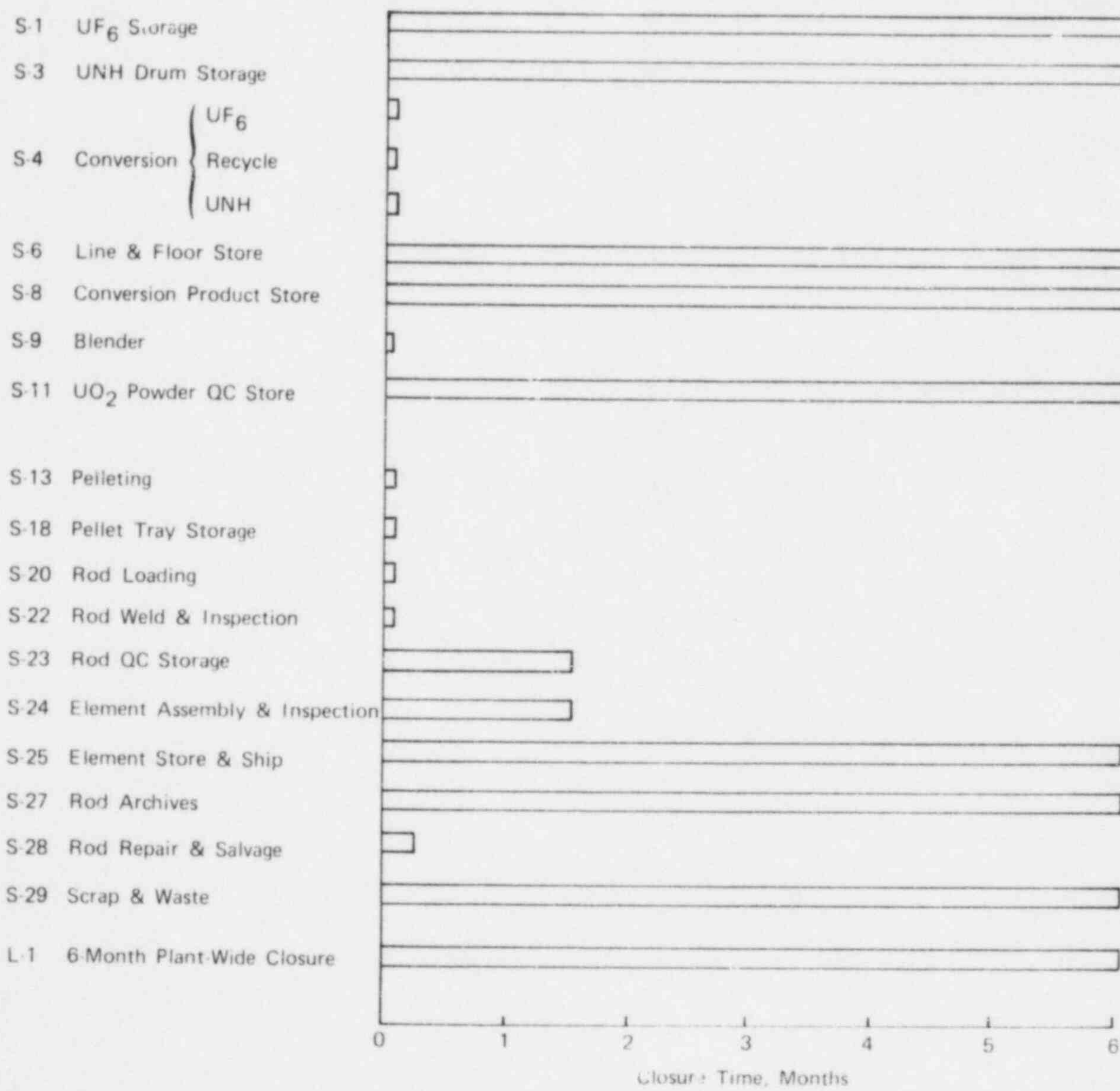

FIGURE 5.3 - Closure periods for closure equations as determined by informal and formal inventories.

collected for this study. The purpose of the equation closure analysis, to be described in Chapter 6, was to test validity of these control values against the actual operation of the plant.

6.0 Closure equation tests

This chapter describes in detail the closure equation verification tests that were performed with the data collected from the low-enrichment plant. If the process model is correct, measurement variabilities calculated from the data set should agree with the variabilities calculated from the model for each control unit. However, if significant differences are found between the process and the model variabilities, this is an indication that there are dominating errors in the process that were not accounted for in the model.

As will be shown in this chapter, there were significant differences in many portions of the process, but the dominating uncertainties in these areas were the result of nonmeasurement errors in the data set. In those areas where nonmeasurement errors were minimal, the agreement with the model was satisfactory.

6.1 Types of closures

There are five types of equation closures that are possible in a uranium process: namely, identification number (ID#), item count, bulk weight, uranium quantity, and uranium-235 quantity. Each of these types of closures has potential application in this process. In general, the type of process involved with each closure equation and the degree of control required to achieve the performance criterion would dictate the type of closure to be utilized for each equation, although some equations may be limited by lack of available data. Variances for each of these types of closure may be significantly different for the same areas of control.

6.1.1 ID# CLOSURES

Closures by identification number are considered to be exact; i.e., the variability = 0. This is the simplest type of closure since a specific item is either there or it is not. As long as the integrity of the contents of each item is maintained, incoming and outgoing errors are exactly correlated. ID# closures may or may not be applicable at inventory time, depending on whether the item contents were remeasured. If analyses are required to detect changes in material within an item, simple ID# closures can no longer be used.

Closures by ID# only make no allowances for material removal from any of the items or for substitution within any of the items, but will detect any missing specific items.

6.1.2 ITEM COUNT CLOSURES

Large numbers of identical or nearly identical items can be controlled by item count, particularly if ID# control is not practical. If items are sealed or otherwise protected, incoming and outgoing errors would be correlated, and the only type of error contributing to the variability would be counting error. With any large assemblage of identical items, there may be an error of some small magnitude associated with the counting process. This type of error is difficult to quantify since its magnitude can vary with individuals doing the counting and also with any one individual under different conditions. If the counting errors become the dominant contributor to variability in a process, they can be reduced or practically eliminated by replicate counting or with machine counters. Implementation of improved item counting techniques would be a cost/benefit trade-off for the licensee.

As with ID# closures, item count closures make no allowance for detecting removal of material from individual items or substitution of material within items, but this type of closure can detect how many items may be missing.

6.1.3 BULK WEIGHT CLOSURES

This type of closure requires a predictor for uranium concentration, but can generally be used on most processes where there are no major changes in chemical composition of the material. It can also be used in chemical processes if reliable predictors are available. The variability associated with bulk weight closures includes weighing errors, weight calibration errors (including tares and uncertainties in standards), and errors associated with predictors. Bulk weight closures are not adequate for processes with unknown or unpredictable chemical changes of material.

Bulk weight closures can detect simple material removal, but cannot detect material substitution.

6.1.4 URANIUM WEIGHT CLOSURES

This type of closure includes uranium analysis information and must be used for material control where chemical, physical, or uranium concentration changes occur. This type of closure should be employed in processes where material substitution (either deliberate or accidental) is possible. The variabilities for these equations include weighing errors, weight calibration errors, analytical and sampling errors, analytical calibration errors, and errors associated with predictors.

Closures by uranium weight are not adequate to detect process errors involving materials of differing isotopic enrichments or to detect isotopic substitution.

6.1.5 ^{235}U WEIGHT CLOSURES

The variabilities associated with equation closures based on uranium-235 content must include weighing errors, weight calibration errors, analytical and sampling errors, analytical calibration errors, isotopic analytical errors, isotopic analytical calibration errors, and errors associated with predictors. The data received for this study would not support this type of closure in the low-enrichment plant except for the six-month plant-wide inventory equation.

Isotopic closures would be necessary for many high-enrichment processes, however, to detect possible isotopic substitution, particularly, if credible substitute materials were available.

6.1.6 STUDY OF CLOSURE EQUATION I' LANCES

Closures for the CUA application to the low-enrichment plant are discussed next in Sections 6.2 through 6.6 in the following order: UF_6 to UO_2 conversion, blending, pelleting, fuel rod fabrication and element assembly, and scrap recovery.

6.2 Closures in the UF_6 to UO_2 conversion area

This operation encompassed conversion of UF_6 to UO_2 and blending of the UO_2 powder to achieve homogeneity. A detailed discussion of the conversion operation and the factors that must be considered in modeling this portion of the process is given in Appendix A. The control units that were established for the conversion operation and the closure equation spans are shown in Figure 6.2.1; details of the closure equations are given in Appendix E.

The conversion process consisted of several parallel lines that permitted simultaneous conversion of materials of different enrichment and/or different production contracts. The UF_6 storage area, the UNH storage area, and the blender were common to all conversion lines, so there was only one control unit associated with each of these operations. The data received supported separate closures for each conversion line, however, so a control unit was established for each line. All lines were essentially identical, so the control unit configuration in Figure 6.2.1 was generic in that it applied equally to any one of the conversion lines. Equation S-4, in Figure 6.2.1, is shown as threefold; this configuration reflects the three production modes for this portion of the process.

There were several types of closures in the conversion area that were supported by the data set. In the UF_6 Cylinder Storage Area (CU-1), closures were by identification number (ID#), so the propagated measurement error should be zero.

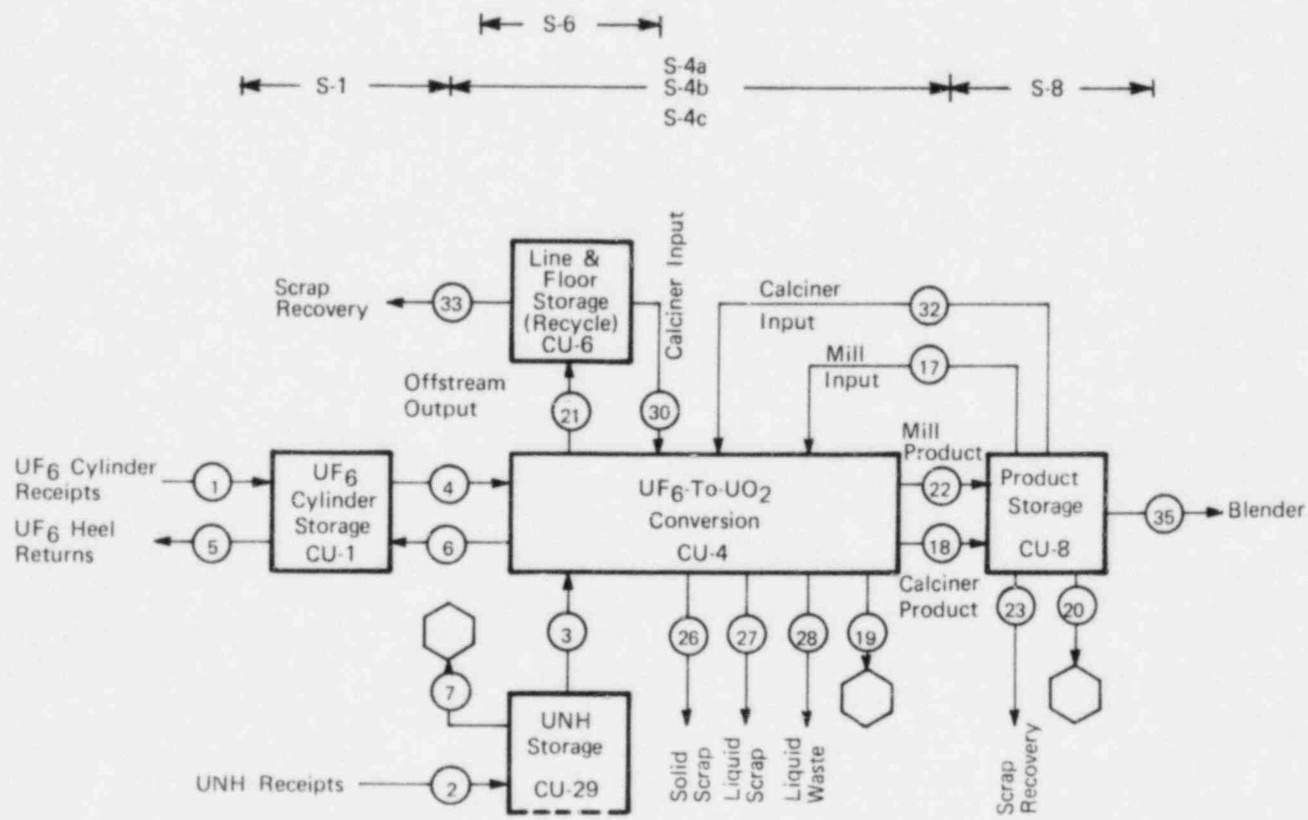

FIGURE 6.2.1 - Control units and closure equations for each conversion line.

In each of the conversion lines themselves (CU-4's), it was necessary to close by uranium content since several different chemical forms of uranium flow through the various measurement nodes. Since there were no measurements of in-process or holdup material quantities in the conversion equipment at any time between the two formal inventories, it was necessary to resort to predictors of the in-process quantities to permit closures on a short-term basis. Consultation with the process engineers provided estimates of typical in-process material quantities for 15 different operational conditions.

These conditions reflect most of the conceivable configurations encountered in the conversion operations. These conditions are noted in Table 6.2.1 along with estimated 2σ variabilities.

Since the quantities of in-process material and holdup of each line can be estimated reliably only at these specific points in the operational cycles, it is evident that closures in the conversion operation should be "event-controlled." Thus, an equation should be opened at line start-up from a known cleanout mode and then be closed at times when the integrated material inputs are well defined.

Utilization of event-controlled closures in this manner can aid in the actual measurement of in-process material and holdup. If, for example, a closure is performed between the end of a normal operation and the end of the following cleanout, the material that was removed from the line during runout and cleanout is, in effect, the removable holdup.

For the UF_6 mode there were only a few occasions when partially emptied cylinders were weighed; as a rule only full weights and heel weights were taken on each cylinder. Measurements of UF_6 into and out of the lines were therefore performed only when cylinders were introduced to the line and when they were removed with their heels. The optimum closure times for a UF_6 campaign, then, were at initial cylinder start-up, changes of cylinders, termination of flow from the final cylinder in the campaign, and termination of the subsequent runout (or cleanout) operation. This time period was variable because of interim line shutdowns. A bar chart showing the distribution of closure times observed for the UF_6 mode is shown in Figure 6.2.2.

Recycle and UNH campaigns were rarely run for more than a few days without a major runout or cleanout. For these modes the

Table 6.2.1 - OPERATION CONDITIONS AND MODEL HOLDUP QUANTITIES[a] PER CONVERSION LINE

Mode	Normal Operation[b]	Runout[b]	Flush Cleanout[b]	Intermode Cleanout[b]	Enrichment Cleanout[b]
UF_6	255 ± 32	131 ± 29	29 ± 8	105 ± 29	6 ± 1
Recycle	208 ± 31	119 ± 29	29 ± 8	105 ± 29	6 ± 1
UNH	209 ± 31	122 ± 29	29 ± 8	105 ± 29	6 ± 1

[a]Normalized units.

[b]Estimated uncertainties are 2σ.

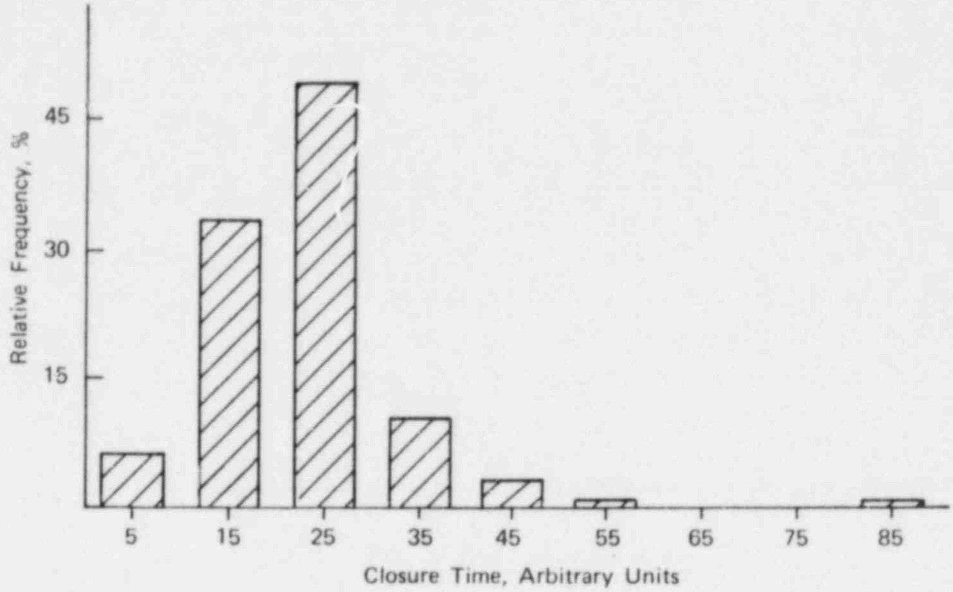

FIGURE 6.2.2 - Closure times for the UF_6 mode.

closure periods were determined by complete campaigns; i.e., closures were performed at mode start-up, at mode termination, and at runout or cleanout termination.

Since only one mode could operate on a given line at any one time, closure schedules were established for each line so that maximum advantage could be taken of predictor information in Table 6.2.1; closures occurred chronologically throughout the operating schedule at whatever times the line passed through one of these relatively well-defined states. Thus, the entire operation of one conversion line was handled by a single computer algorithm in which the closures were triggered by specific events. However, closures on different lines were independent and generally occurred at different times.

To aid in establishing the closure schedule, detailed operational profiles were prepared for each of the conversion lines for the 23-week data-collection period. These profiles defined all significant operations and operational changes in each line during the period. The use of these profiles will be discussed in paragraph 6.2.1.2.

Closures in the conversion off-stream product storage areas (CU-6) and the unblended product powder storage areas (CU-8) associated with each line were based on uranium content, even though much of the material was stored as individual items with identification numbers. There are two reasons that ID# closures could not be used for these areas. Primarily, there were no weight data available for packs of material that were in storage at the beginning inventory; these packs were not identified by number on the inventory. During their subsequent use, it was necessary to assign average weight values (predictors) to each pack to obtain quantitative input information for closure. Secondly, materials being sent out to scrap recovery from these areas were not always identified by pack serial number, but uranium weights always appeared on the material move tickets. No informal interim inventory data were available to permit closure of equations in these storage areas more frequently than on a six-month basis.

A summary of the control units, closure equations, closure schedules, and calculated progated measurement errors for the conversion area and the blender area is given in Table 6.2.2. Summary variance charts for the eight generic closure equations comprising coverage for these areas are given in Appendix D, Table D-1, and a detailed list of the closure equation components is given in Appendix E, Tables E-2 and E-3.

6.2.1.1 Analysis of Closures in the Cylinder Storage Area

ID# closures were used in the cylinder storage pad (CU-1). The closures were based on material transfer receipts for full cylinders, material transfer shipments for cylinder heels, full cylinder status reports, cylinder heel status reports, and cylinder use records.

As expected, the six-month closure of S-1 exhibited zero cei; i.e., there was an exact accounting of all UF_6 cylinders in the area. However, intermediate closures based on cylinder status reports frequently indicated imbalances of several cylinders.

Table 6.2.2 - SUMMARY OF CLOSURE EQUATIONS IN THE CONVERSION AREA

Control Unit	Description	EQ	Span	Closure Period	Propagated Meas. Error ($2\sqrt{CEIV}$) Normalized Units
CU-1[a]	UF_6 Cylinder Storage	S-1	Pad and Bay	6 months	-0-
CU-4	Conversion UF_6 Mode	S-4a	Per Line	Per Cylinder	45.6
CU-4	Conversion Recycle Mode	S-4b	Per Line	Per Campaign	45.8
CU-4	Conversion UNH Mode	S-4c	Per Line	Per 100 Drum Campaign	44.9
CU-6	Line and Floor Storage	S-6	Per Line	6 months	14.9
CU-8	Conversion Prod. Storage	S-8	Per Line	6 months	5.2
CU-9	Blender	S-9	Blender	Per Blend	4.4
CU-11	QC Powder Storage	S-11	Powder Stor.	6 months	1.0

[a]The fact that there is zero error in this control unit means only that any weighing error would be found in another control unit. Only cylinder discrepancies can be detected by ID# type closures in this control unit.

This discrepancy was shown to be exclusively the result of phasing errors. The date when a cylinder was moved into a line, or an empty cylinder (with heel), was moved to the pad, would not necessarily appear on the next chronological cylinder status report; occasionally several days were required to update the status report after a cylinder was moved.

6.2.1.2 Analysis of Closures in the Conversion Operations

Data used to determine material movements into, through, and out of the conversion lines; the line and floor storage areas; conversion product storage areas; and the blender were taken primarily from computer summaries of conversion daily operations, daily operational logs, and cylinder use records. These data were backed up by data from material move orders (i.e., production control tickets).

Closure schedules for the UF_6 operational modes were "event-determined" around each UF_6 cylinder emptied into the line. The equation was opened when the cylinder emptying operation was started, and the equation was closed when the cylinder was empty (before heel eduction) or whenever the next full cylinder was brought onto the line.

These times were determined from cylinder-use records and daily operational logs. Closures for the Recycle and UNH modes were performed on a per-campaign basis. The type of operating mode, downtime periods, various cleanout modes, and their chronology were identified from detailed operational profiles prepared for each conversion line. A portion of one of these profiles is shown in Figure 6.2.3.

In the verification phase of the CUA methodology, a preliminary set of closure equations was calculated in order to test for missing data or model discrepancies. Figure 6.2.4 shows a plot of cei's as a function of time-of-closure for one of the conversion lines; a histogram of the plot is also given on the graph. This plot is typical of the hundreds of cei's generated in the conversion operations in the course of this study. Data were analyzed for three major production modes and four runout/cleanout modes. The production modes were UF_6, UNH, and recycle; the nonproduction modes were enrichment

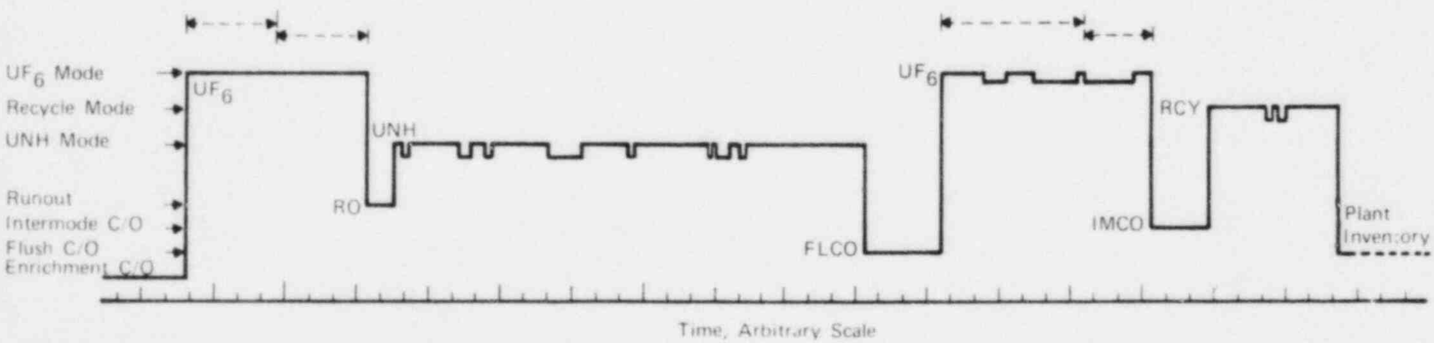

FIGURE 6.2.3 - Conversion line operational profile. (Small indentations in profile indicate temporary line shutdown; dashed lines indicate times individual UF_6 cylinders are on-line.)

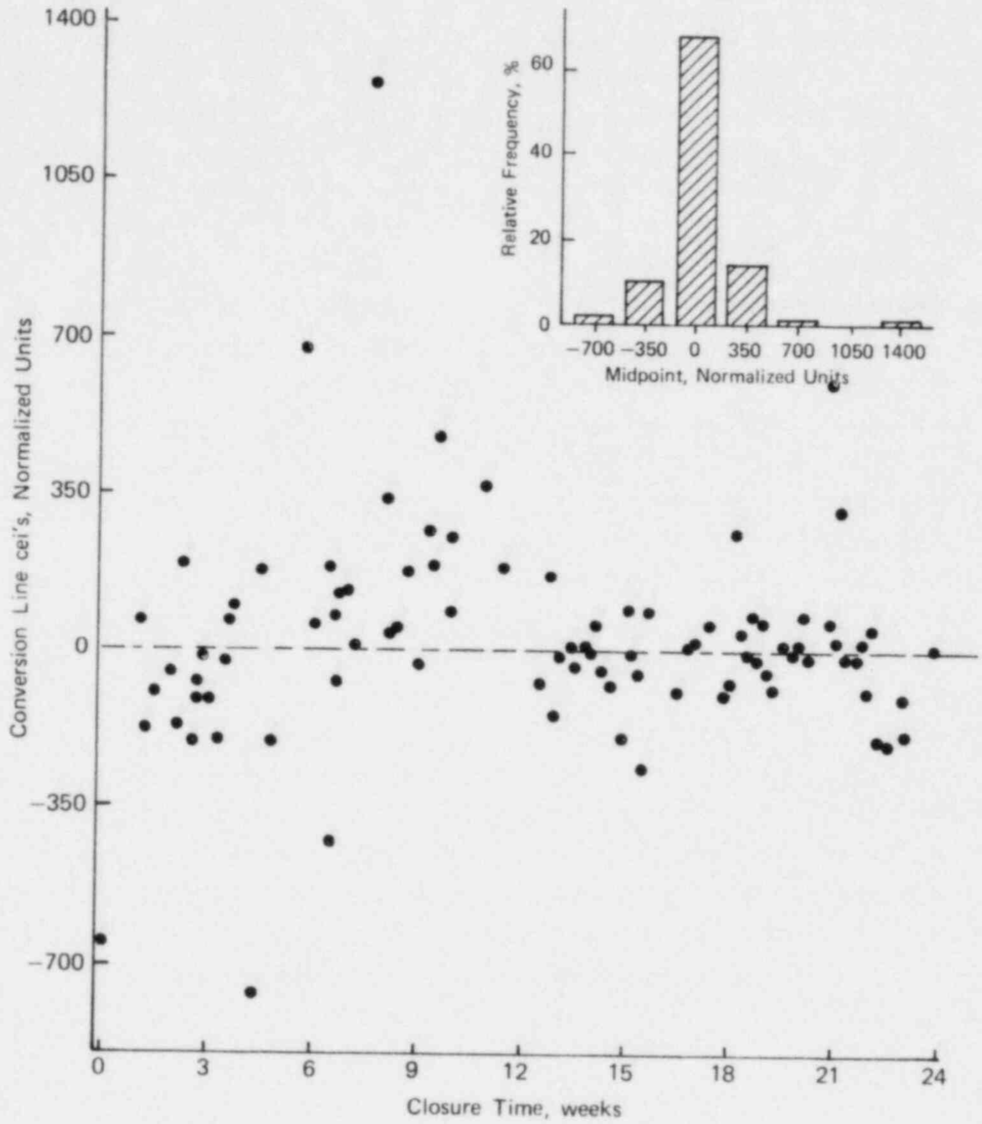

FIGURE 6.2.4 - Typical cei's for uncorrected conversion line closures.

cleanout (ENCO), flush cleanout (FLCO), intermode cleanout (IMCO), and runout (RO). The four nonproduction modes represented only a small part of the material throughput; most material uncertainties arose during the production modes. The predicted cei variability is a different value for each of these modes, due in part to different holdup uncertainties. A quantitative description of the mean values and standard deviations of these cei's may be seen in Table 6.2.3. Standard deviations of cei's for the conversion lines were considerably larger than the model-based standard deviation of approximately 23 NU, thereby indicating the effects of large nonmeasurement errors. These discrepancies were tentatively identified as resulting from a combination of phasing error and missing data.

Phasing errors arose in these closures from two sources. Not all cylinder-use records were available, so a number of the opening and closing times had to be estimated. Secondly, conversion-product powder packs were not necessarily weighed promptly when the material exited the line, so the amount of unweighed conversion product was part of an unpredictable holdup.

The fact that significant quantities of information were missing became apparent when ID# closures were performed on conversion powder packs. After allowances were made for packs in storage at the two formal inventories, computer sortings by contract and pack ID# revealed discrepancies in creation and use dates of a number of powder packs. Many packs were created for which there were no use dates, and conversely, use dates were listed for many packs for which there were no creation dates.

The computer sorting also revealed a number of gaps of varying length in sequential pack numbers. These gaps are also suspected as representing missing information, but verification as such was much more difficult.

In many cases the use date or the creation date of a powder pack and its movement through a specific measurement node could

Table 6.2.3 - CONVERSION LINE CEI STATISTICS[a]

Operation Node	Number of Closures	Mean cei (NU)	Std. Dev. cei (NU)	Model-Based $\sqrt{CEIV}$ (NU)
UF_6	>100	46	230	22.8
UNH	> 10	31	92	22.9
Recycle	> 10	-146	250	22.4
Enrichment Cleanout	> 10	63	188	~ 1
Flush Cleanout	> 10	124	74	4.0
Intermode Cleanout	> 10	36	176	14.4
Runout	> 10	28	90	14.4

[a]Composite of all conversion lines.

NU = Normalized Unit.

be inferred quite accurately from data on packs with adjacent serial numbers. It was possible, by applying historically based predictors to material quantities and uranium concentrations, to correct almost completely for missing pack information for several of the production contracts.

Figure 6.2.5 shows a set of cei's corrected for missing data in this manner which covers a partical operating period of one of the production contracts in the conversion area; the distribution histogram for these corrected cei's is included on the graph.

These data exhibit a mean value of +0.52 NU and a standard deviation of 49.9 NU. Although this standard deviation represents a major improvement over the raw data in the measured variability of the conversion process, it is still significantly larger than the model-based standard deviation of 22.8 NU. The residual uncertainty is believed to be a combination of unidentified missing data and a phasing error.

It should be noted that in spite of careful data screening that was performed during the data collection and transmission phase of this project, some of the missing data were not identified until equation closures were obtained. In a real-time application of CUA, such missing information would be identified promptly by improper closure of the controlling equation, and the discrepancy could be corrected while data were still available.

Another result obtained from the closure analysis in the conversion operation was the indication that closure imbalances

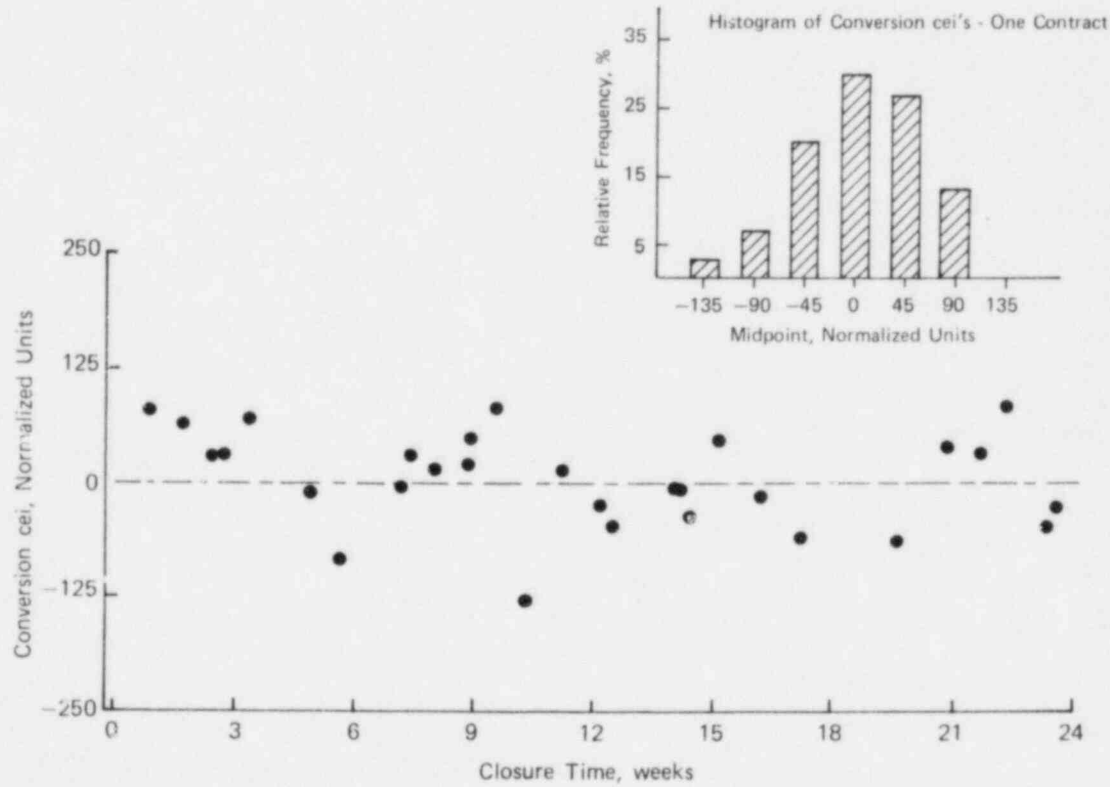

FIGURE 6.2.5 - Corrected cei's for one conversion contract.

could be employed under dynamic line operations to verify predictors of in-process material and holdup. The largest source of measurement error in the conversion operation was the uncertainty of the predictors of in-process quantities during operation. When cei data are used without correcting for in-line quantities, the differences of integrated input flows and output flows for the control unit would determine the quantity of resident material in the line at closure time. If there were no data errors or phasing errors, this determination should fall within the precision of the measurement system.

The cei's corrected for missing data for the one contract described in Figure 6.2.5 were used to calculate the total amount of resident material at each closure in the operating period. These amounts of in-line material were then compared to in-line quantities predicted from the process model. This comparison is shown in Figure 6.2.6. In this figure the solid line represents the predicted in-line quantities of uranium; these predicted quantities are based on the experiences of the conversion process engineers and on a wealth of historical data. The dashed line connects the data points calculated from equation closures. In general, the correlation of the measured and predicted values agree within the variability of the control unit except near the end of the period. The discrepancy in this time frame has subsequently been identified as resulting from missing powder pack information.

This technique appears to be very promising for determination of in-process holdup quantities during dynamic operations.

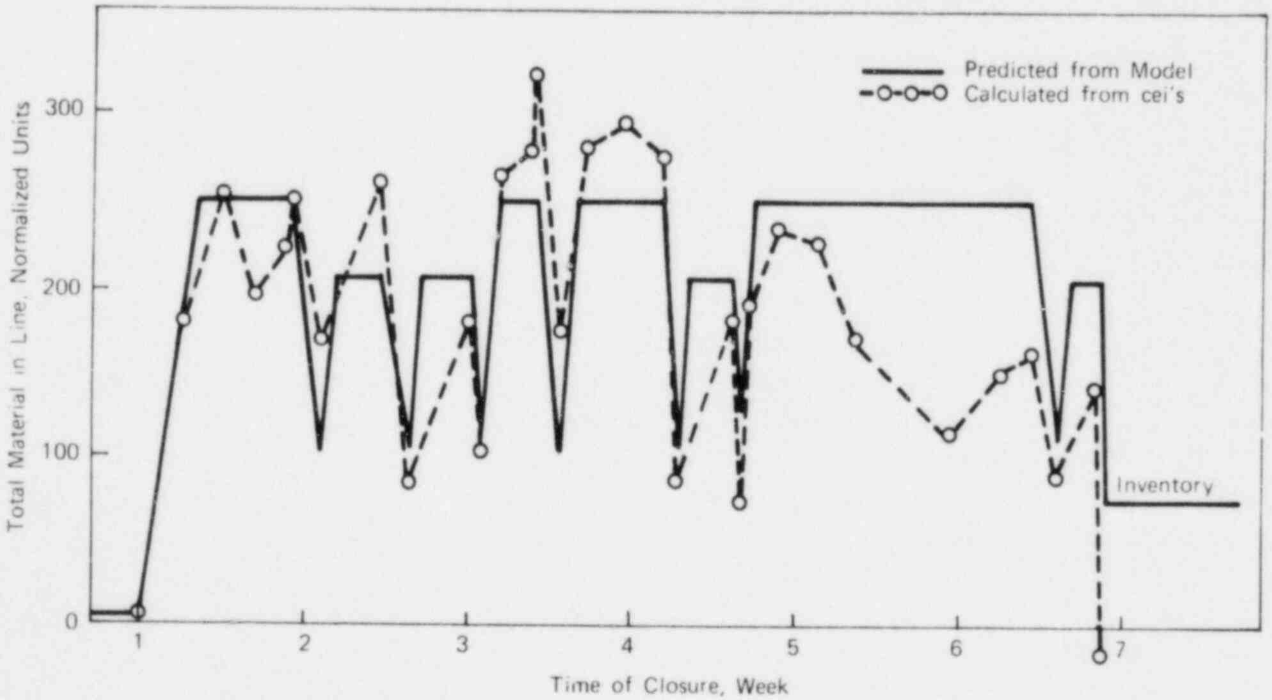

FIGURE 6.2.6 - Comparison of data-based conversion line in-process quantities with expected quantities based on the process model.

6.2.1.3 Analysis of Closures in Line and Floor Storage Areas

In order to analyze closures in these storage areas, three combinations of data were used: 1) closures per conversion line for the six-month period; 2) closures per contract; and 3) closures of combined conversion lines for the six-month period. All these combinations of closures indicated positive cei's for various contracts ranging from 10 times to 500 times larger than the expected propagated error. Since only well-characterized and identified materials were handled in these areas, it was concluded that uncertainties of this magnitude could arise only from nonmeasurement error, probably missing data. Because of the errors of this magnitude, no conclusion concerning the validity of the model of the conversion interim storage areas could be reached.

6.2.1.4 Analysis of Closures in the Conversion Product Storage Areas

These areas likewise exhibited very large positive cei's of about the same magnitude as those of the line and floor storage areas. Again, the discrepancies are believed to be the result of missing data, and no conclusions concerning the validity of the model relative to this area were reached.

In an effort to determine types of data missing in addition to powder pack information, a six-month closure was performed for each entire conversion line, i.e., combined CU-4, CU-6, and CU-8 areas for each line. Each line exhibited unacceptably large positive cei's of about the same magnitude as for its respective CU-6 and CU-8 areas. This result indicates a significant contribution to uncertainty from missing material move tickets describing transfers of material out of the conversion area, probably into the scrap area. Although move tickets were monitored for completeness during the data collection phase of the project, the fact that many such tickets were missing could not be verified until after closures were performed with the data.

6.3 Closure equations in the blender area

Powder packs from each of the conversion line storage areas were formed into batches and were blended in a common blender. Control units and closure equation spans in the blender area are shown in Figure 6.3.1. Closures in the blender, CU-9, were controlled by uranium weights of input packs and output packs. Since the residual holdup in this area was nominally very low and since the blender was cleaned out after each batch blending operation, the optimum equation closure period was for each blend batch. Details of the blender closure equation are given in Appendix E, Table E-3.

The blender input consisted solely of weighed packs dumped into the blender input hopper. The blender output flows were the weighed packs of blended powder and scrap consisting of spilled powder recovered from the blender upon cleanout. The data obtained for this operation indicated that cleanout material was transferred to scrap recovery only occasionally rather than after each blending operation, thus contributing to the holdup uncertainty.

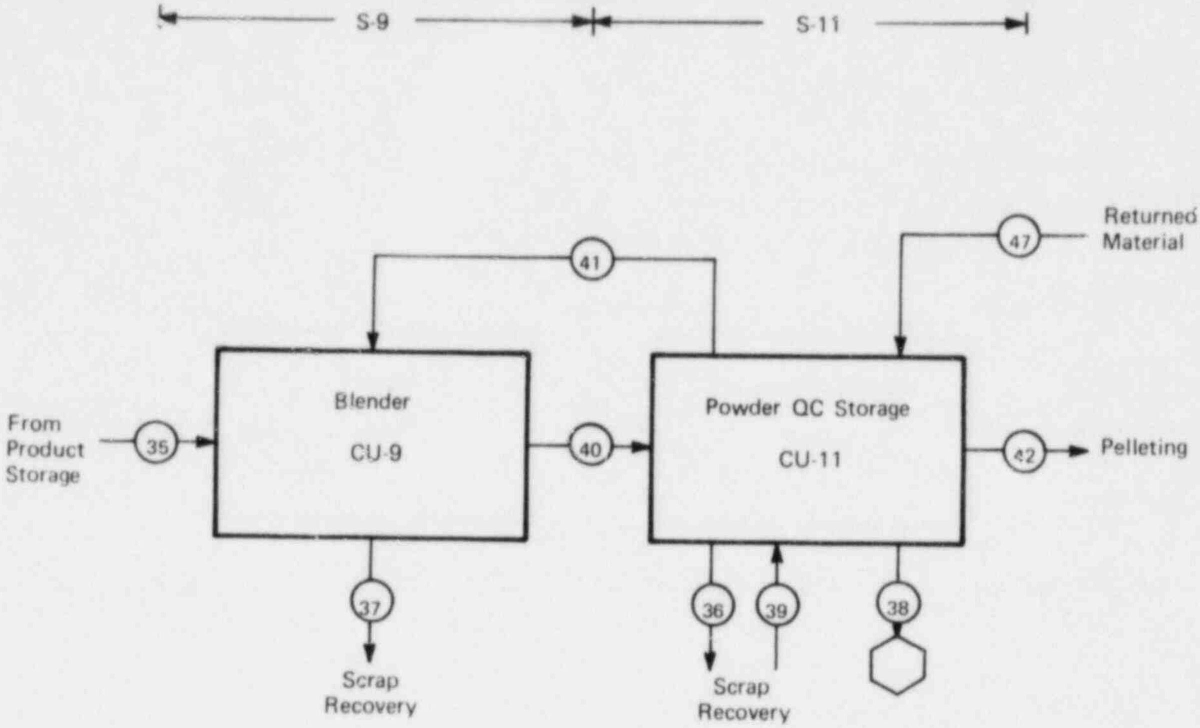

FIGURE 6.3.1 - Control units and closure equations for blender and powder QC storage.

Figure 6.3.2 is a plot of the blender cei's from the six-month operational period; a histogram of the observed cei's is included on the graph. Many large cei's (both positive and negative) are apparent in this figure. Examination of data for the blend represented by each of these large cei's revealed that data were missing for significant numbers of both input and output powder packs. Information from material transfer forms, which recorded powder blend movements between the blender and the storage areas, was used to correlate some of the larger uranium cei's with blends identified as missing a significant number of powder packs. This correlation was then used to delete approximately 25 blends affected by discrepant pack numbers from the statistical analysis. The remaining data exhibited a mean value of -24 NU per blend and a standard deviation of 67 NU. These corrected cei's are shown in Figure 6.3.3.

The predicted variability for the blender, as obtained from Appendix D, Table D-1, was 4.4 NU.

The large closure imbalances that were observed in the blender arose from three sources. There were inherent errors in weight measurements for input and output packs. Secondly, the scrap material from a given blend was not normally recovered after each blending operation, so the scrap became an unmeasured holdup. Under normal operation, scrap generation was relatively low, and the variances of weight measurements and uranium concentration measurements were well-defined. The most serious source of uncertainty in the blending operation was missing powder pack data.

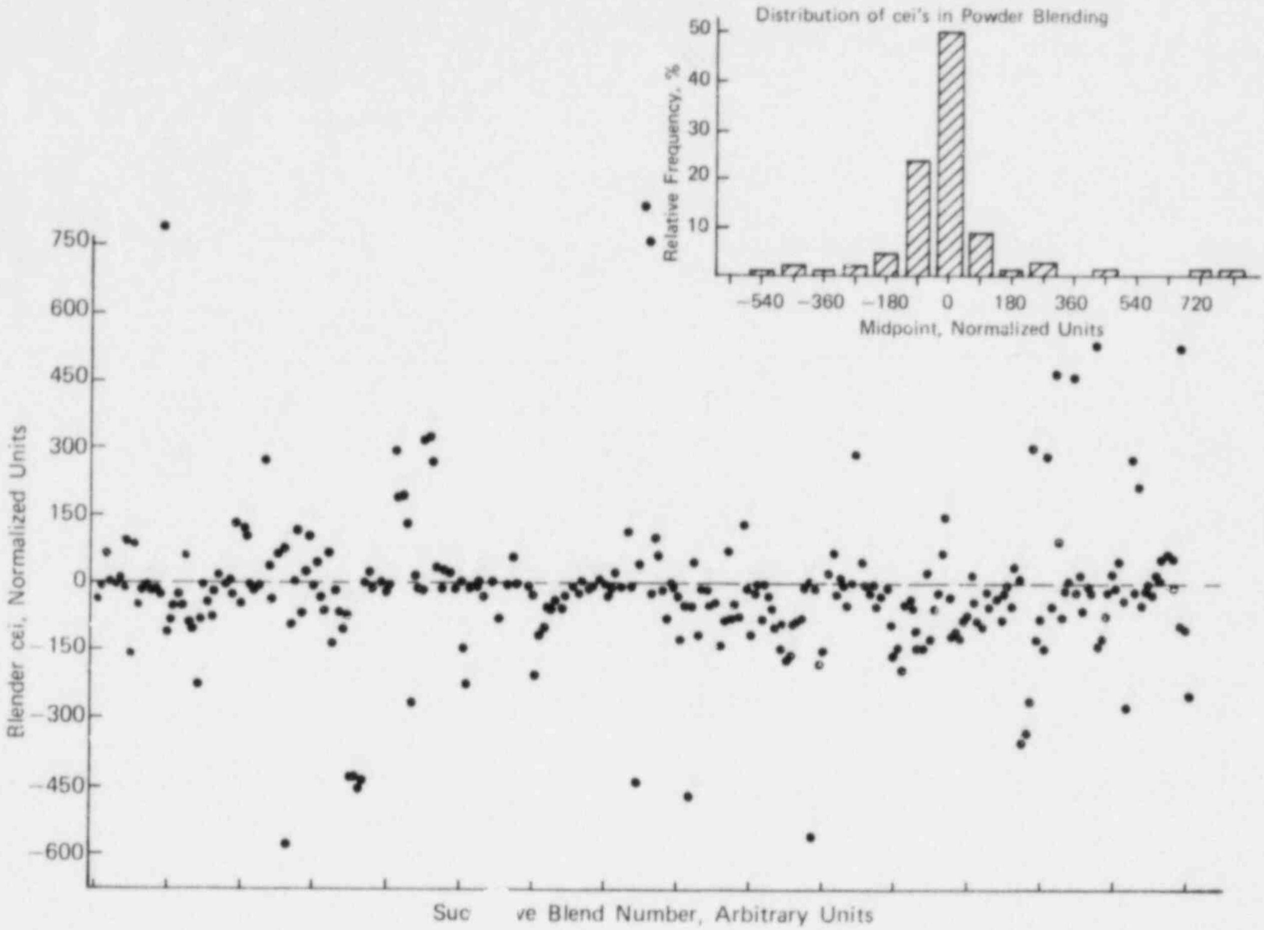

FIGURE 6.3.2 - Uncorrected cei's for the powder blending operation.

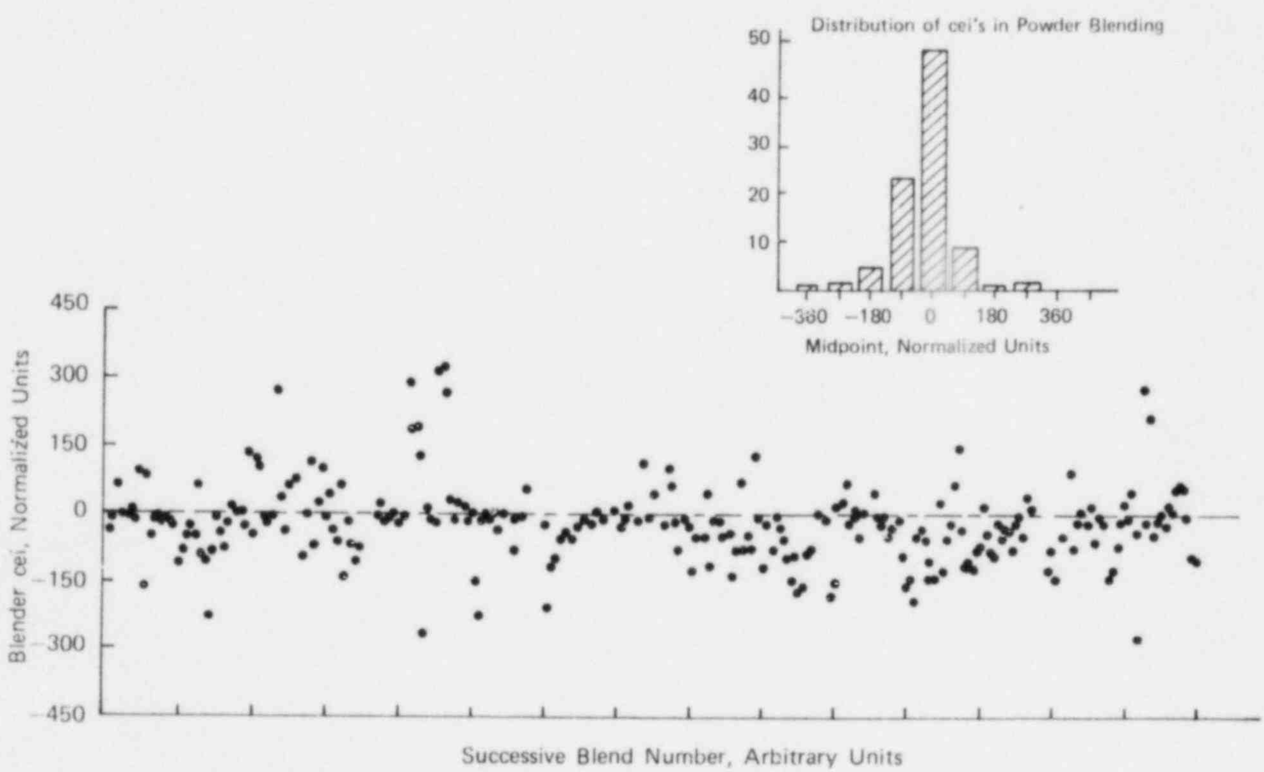

FIGURE 6.3.3 - Corrected cei's for the powder blending operation.

6.3.2 ANALYSIS OF CLOSURES IN QC POWDER STORAGE

Closures in the QC powder storage utilized the daily computer printouts from the conversion area and production control tickets, which monitored the traffic between the storage pelleting and the scrap recovery areas. Closures were based on uranium content. This area was not normally inventoried other than at the times of the formal plant inventories, so the data would not support closures more frequently than every six months. Also, there was no attempt to account for every powder pack by identification number, since transfers to and from the pelleting operations were by blend number only. ID# closures in this area could be a potential refinement if tighter control would be needed.

The six-month cei for the QC powder storage area was approximately 5ε5 NU. Since the variability for this control unit from Appendix D is 1.0 NU, it is apparent that this closure is significantly affected by nonmeasurement error, presumably missing transfer data. Either an extensive survey to compensate for missing data or another data set would be required to resolve the discrepancy.

6.4 Closures in the UO_2 pelleting operation

This operation encompassed compaction of UO_2 into cylindrical pellets, sintering and grinding these pellets, pellet-tray loading and storage, and clean scrap recycling. A detailed discussion of the operations in this portion of the process is given in Appendix A.

There were multiple, parallel, pelleting lines in this plant which provided capacity for simultaneous fabrication of pellets for different production contracts and/or different uranium-235 enrichments. The process operating modes, material flow patterns, equipment, and measurement nodes were essentially identical for all lines.

Data acquired from the licensee were found capable of supporting at least two control units for each pelleting line. One unit was comprised of powder preparation, pellet compaction, sintering, grinding, and in-line scrap-reprocessing operations. The other control unit was the pellet-tray-storage area. The generic control units and spans of the associated closure equations (as applicable to each of the parallel lines) are shown in Figure 6.4.1. The measurement nodes comprising each closure equation and the closure equations are given in Appendix E. The modeled variability information for the two equations is given in Appendix D. As was with the case of the modeled conversion lines, the dominant error in this portion of the process model was the uncertainty associated with the amount of in-process material and holdup.

Data that were used to determine material flows through the various measurement nodes and in-process material quantities were obtained from daily pelleting status reports (Form P-3, Table B-3) for each line and from production-control tickets which described the material traffic between the powder QC storage area and each line. The production-control tickets also described material movements between lines and transfers of nonusable material from each line to the scrap-reprocessing facility. Data from rod-loading documents

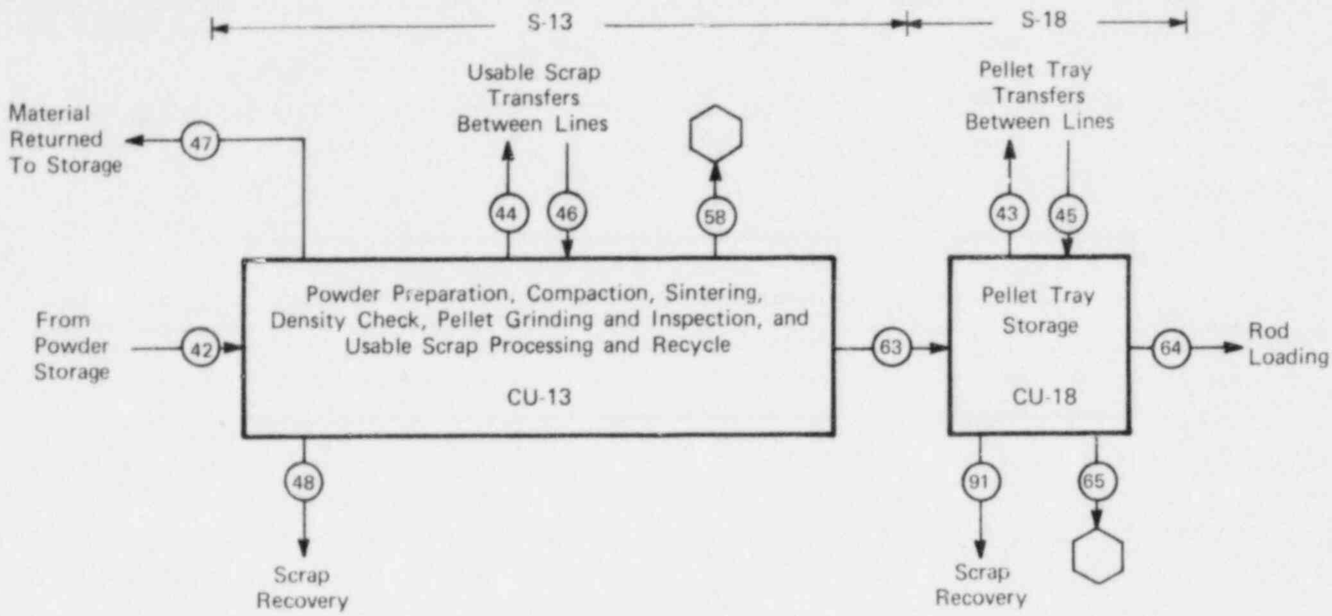

FIGURE 6.4.1 - Control units and closure equations for pelleting lines.

were used to describe material flow from the tray storage area to rod loading (Node #64). The data from these three forms were sufficiently detailed to permit daily closures for each line.

Clean scrap was reprocessed within each pelleting line. Although this operation was separate from the pelleting operation, the available data did not support this function as a separate control unit; therefore, in-line scrap reprocessing was included within the pelleting control unit. Occasionally, usable scrap was transferred between pelleting lines; the closure equations described in Appendix E contain proper nodes to allow for this type of transfer. This material movement was relatively rare, and for modeling purposes, typical flow magnitudes were assumed to be very small.

6.4.1 ANALYSIS OF CLOSURES IN THE PELLETING OPERATIONS (CU-13)

Equation closures were based on daily pelleting status reports and were performed on a 24-hr schedule for each pelleting line over the six-month period. Daily pelleting status reports were available for every operational date in the period except four. Cei data points specifically associated with these four days were eliminated from consideration. Calculated standard deviations of cei's for each pelleting line were of the order of 300 to 400 NU (normalized units). The model-based variability for these control units, from Appendix D, Table D-2, is approximately 34 NU, so there was a significant disagreement between the actual data and the model.

Figure 6.4.2 show a cei time-series plot for one of the pelleting lines for the six-month period; the distribution histogram for these data is also given in the figure. A bimodal distribution is evident, which is indicative of a dominating unaccounted-for error. Examination of similar closure histograms for each of the pelleting lines showed that the cei distributions for most of the lines were also bimodal. These bimodal peaks appeared to be approximately 500 to 600 NU apart in the affected lines. Likewise, individual closures for these lines revealed many positive-negative data pairs in sequential closures where each member of the pair was a cei of the order of 250 to 300 NU.

It was concluded from this evidence that the uncertainty of closure imbalances in the pelleting area was dominated by phasing errors. It was also found that this phasing error could be substantially reduced by restructuring the pelleting area control units. This refinement will be discussed in Section 6.4.3.

6.4.2 ANALYSIS OF CLOSURES IN THE PELLET TRAY STORAGE AREAS (CU-18)

Closures in this area were also based on the daily pelleting status reports. Closures were performed each day for each contract in storage; data that were affected by the four missing days were eliminated. With preliminary closures

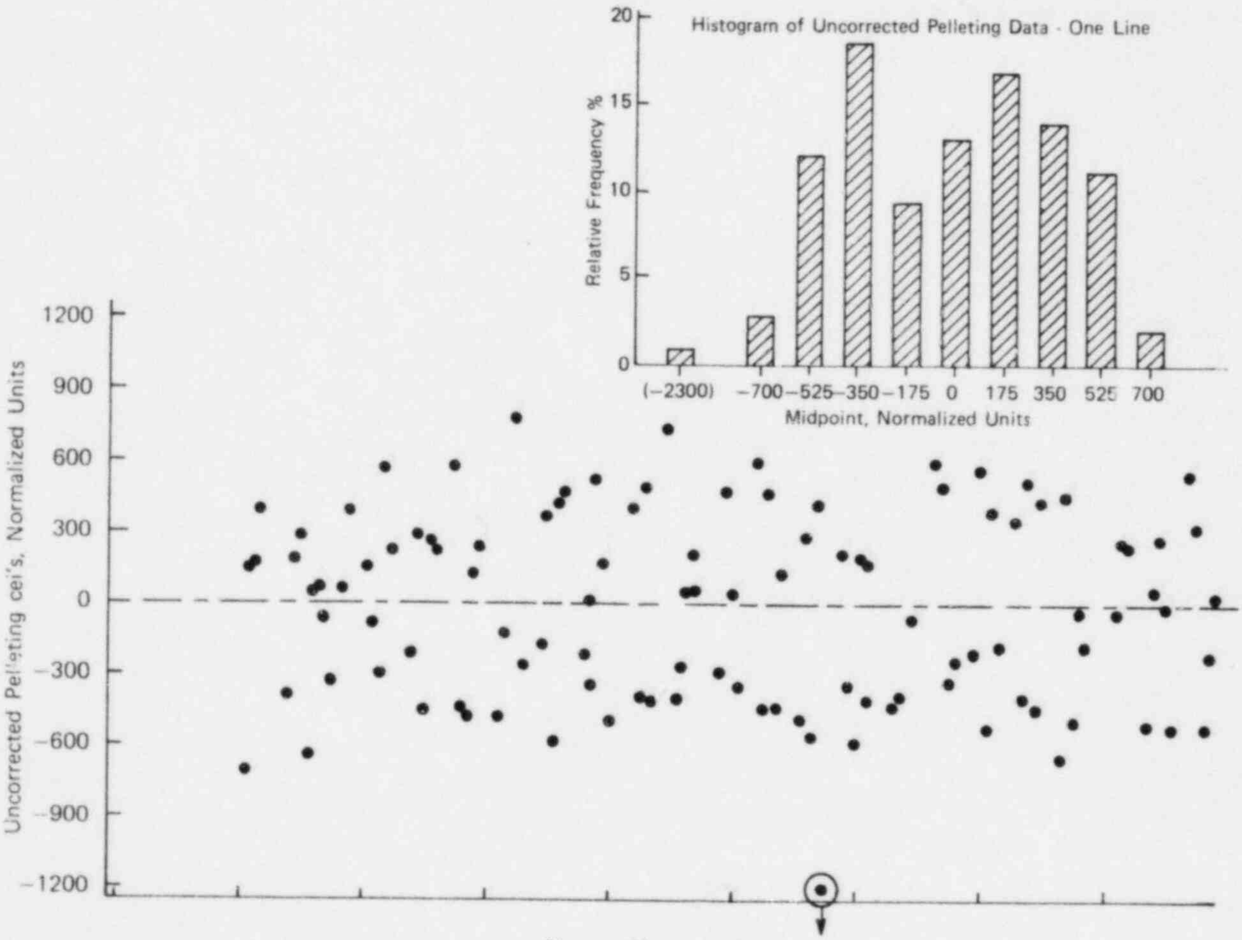

FIGURE 6.4.2 - Preliminary cei's for one pelleting line.

in this area, standard deviations for cei's ranged from 17 to 34 NU per line. The expected variability of this control unit, from Appendix D, Table D-2, is 6.5 NU. However, the changes in control unit configuration, described in Section 6.4.3, resulted in significant improvement in the variability of the pellet-tray-storage areas in addition to the pelleting lines.

6.4.3 SPECIFIC REFINEMENTS IN PELLETING

While an attempt was being made to ascertain the source of the bimodal distributions of closure imbalances in the pelleting lines, it was observed that materials moving into or out of an area would not necessarily appear on matching data forms for several hours or several days. Upon reexamination of the work practices in the area, it was found that the licensee frequently held materials in informal staging areas near the pelleting lines, and these staging areas had not been included in the process model.

In accordance with the CUA methodology, the model was revised to make allowances for these informal staging areas. The control units and measurement nodes were restructured to better use correlated material movements from a single type of data form. The revised control unit configuration is given in Figure 6.4.3.

A new set of closure data was generated for each pelleting line using the restructured control units. A typical cei time series plot for the same pelleting line shown in Figure 6.4.2 is given in Figure 6.4.4; the distribution histogram of these data is included in the figure. Comparison of the cei plots before and after the control unit revision showed improvements of at least a factor of four in the data scatter. Pooled means and standard deviations for the revised

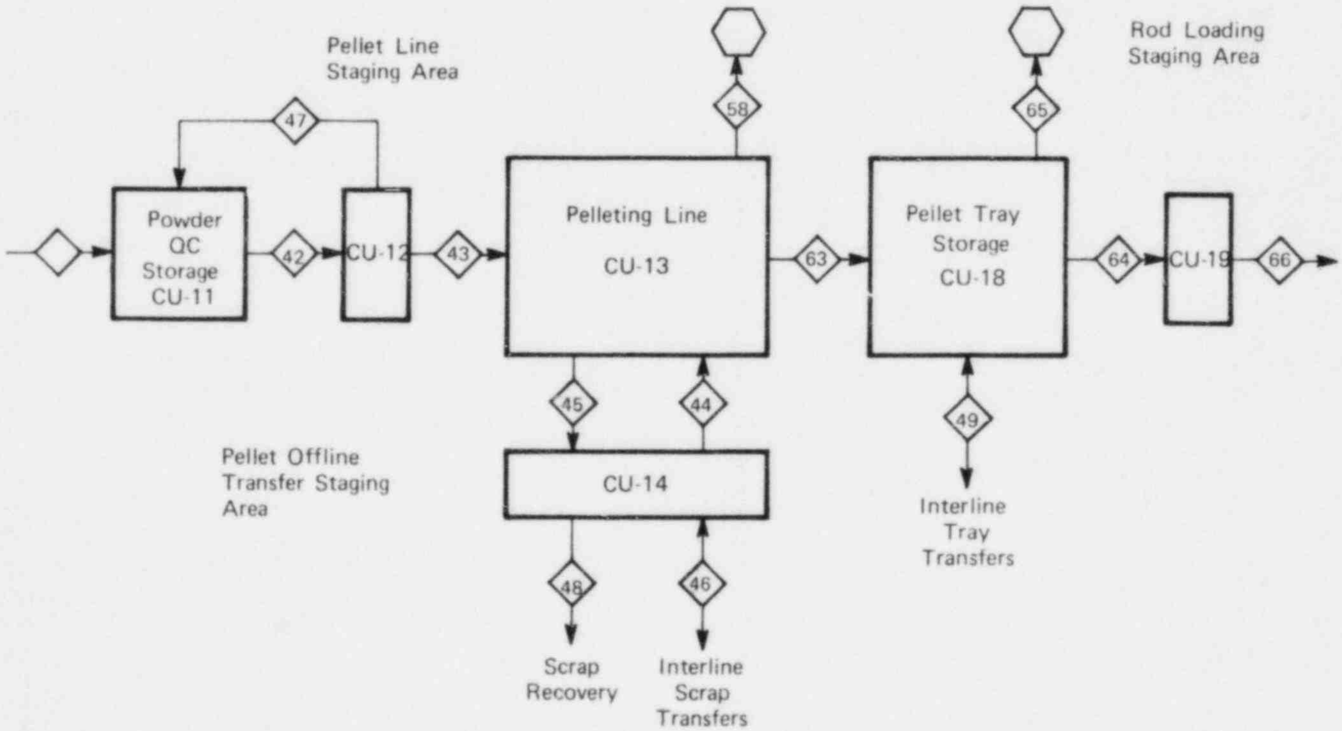

FIGURE 6.4.3 - Revised control units for pelleting lines.

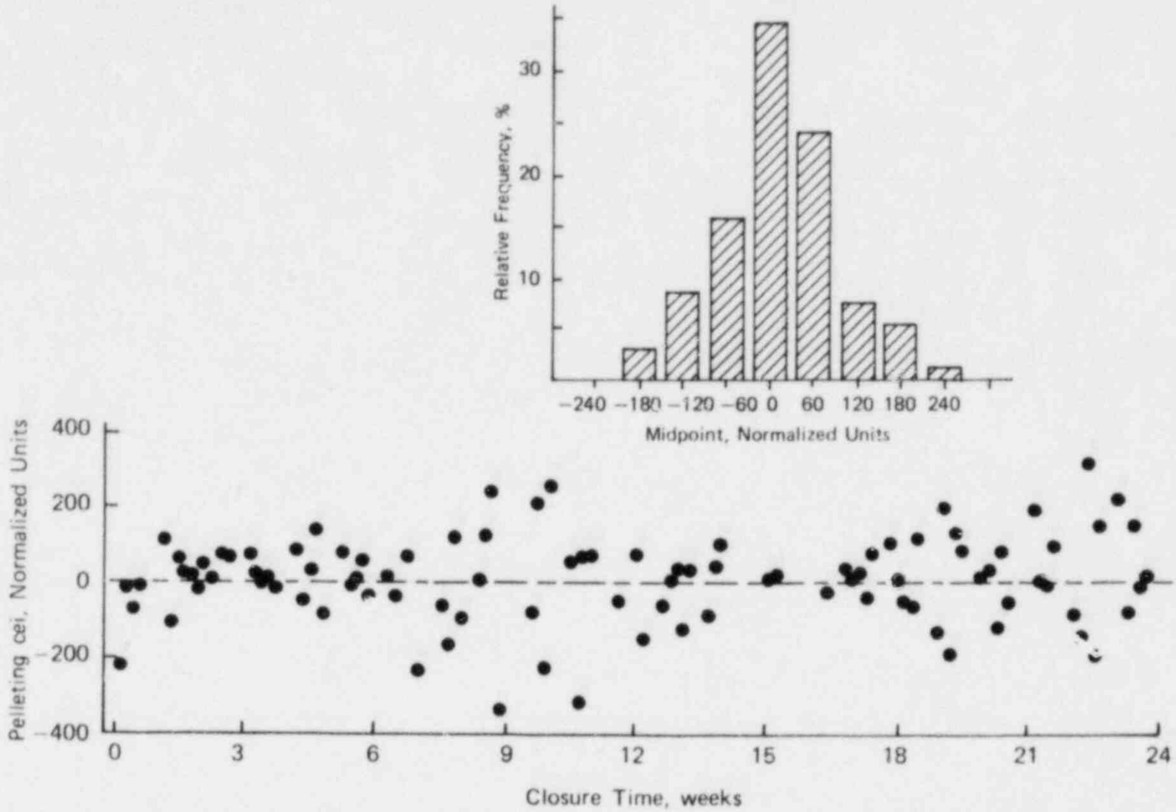

FIGURE 6.4.4 - Revised cei's for pelleting line.

cei's are listed in Table 6.4.1. Although the revision did result in a significant improvement in data scatter, there were apparently some residual phasing and data errors within the data set. The closure data indicate that σ_{cei} for the pelleting operation can be reduced to the order of 50 NU with the control unit revisions. Further refinements that would reduce the variability to the level of measurement uncertainty will be discussed in Chapter 7.

Closures in the newly created staging areas, CU-12, CU-14, and CU-19, shown in Figure 6.4.3, could not be performed since no inventory data were available for these areas.

A typical time series plot of cei's in one of the pellet-tray-storage areas, using the restructured control units, is given in Figure 6.4.5. These data points exhibit a mean value of -3.5 NU and a standard deviation of 12.6 NU. The other

Table 6.4.1 - POOLED MEANS AND STANDARD DEVIATIONS FOR PELLETING CONTROL UNITS

cei's, All Lines	Pellet Lines (CU-13) (Normalized Units)	Pellet Tray Storage (CU-18) (Normalized Units)
Pooled Mean	6.1	-3.8
Pooled Std. Dev.	73.5	16.9
cei's, Best Line		
Mean	4.0	-0.9
Std. Dev.	52.7	12.7

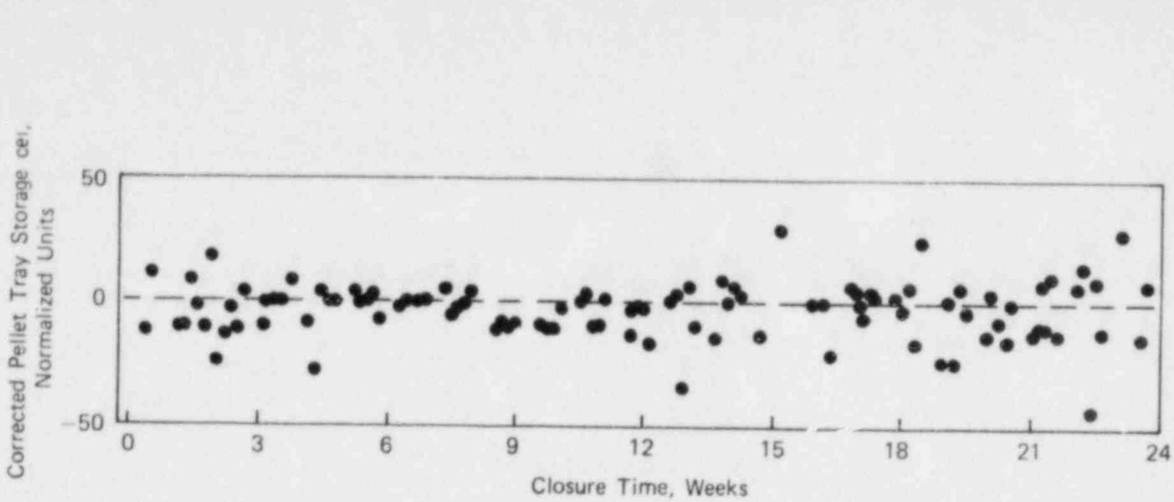

FIGURE 6.4.5 - Revised cei's for one pellet-tray-storage area.

pellet-tray-storage areas exhibit comparable mean cei's and standard deviations.

6.5 Closures in the rod fabrication and fuel element assembly operations

These operations included the loading of UO_2 pellets into fuel rods, seal-welding the rods, QC inspection of sealed rods, rod QC storage, assembly of rods into fuel elements, fuel element QC storage, and two ancillary operations, i.e., rod archive storage and rod repair and salvage. For purposes of this report, a fuel element is defined as a matrix assembly of fuel rods; each fuel element is a unique sealed item with a serial number.

A detailed discussion of the above operations is given in Appendix A. Control units and closure equations for this area of the process are shown in Figure 6.5.1. The measurement nodes comprising each of these equations and the closure equations themselves are given in Appendix E. The modeled variability information for the seven control units in this portion of the process is given in Appendix D, Tables D-3 and D-4.

There were two dominant sources of uncertainty identified by the model in this area. These were in the rod-loading operation and in the element QC storage area. The uncertainty in the rod-loading operation arose from partial-tray inventories; tray counts were rounded off to the nearest whole number for the informal inventories that were taken for production control purposes, and sometimes there were four or five partial trays in the loading area at one time. The largest uncertainty in the modeled fuel element storage area was a systematic error in the uranium content of each fuel element. Uranium totals in each fuel element were frequently based on estimated average uranium weights per rod. When a fuel element was shipped, however, it was weighed and lot averages for the hardware were subtracted from the gross weight to obtain a more precise uranium weight. Because only sealed items were handled in this storage area, this systematic error would be completely correlated between inputs and outputs to the control unit, and the errors would cancel. However, the magnitude of this uncertainty is important since the fuel elements in storage represent a sizeable fraction of the plant-wide material balance.

There were multiple, parallel, loading and welding lines in the rod fabrication area. After welding, the rod lots from

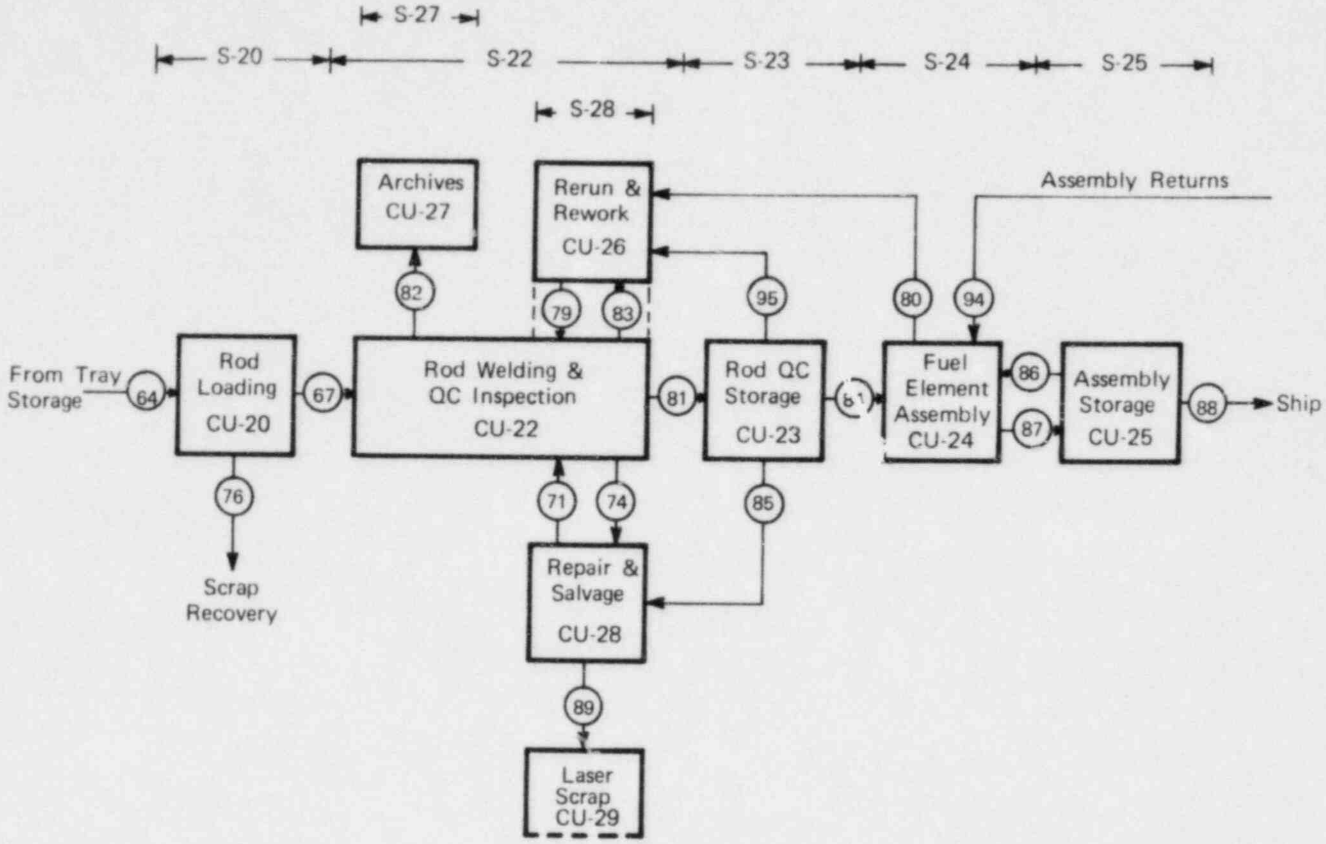

FIGURE 6.5.1 - Control units and closure equations for fuel rod fabrication and fuel element assembly.

all welding lines were channeled into a single inspection line. Material accounting throughout the entire operation was controlled and reported by contract number. From the standpoint of loss localization it would have been advantageous to employ a closure equation across each welding line. However, not all in-line inventories related the in-process rod lots with their respective fabrication lines; the data that were received would not support any contiguous closures other than for each production contract.

The only quantitative material measurement in this part of the process, other than tray and rod counts, were individual tray weights at physical inventory time and scrap weights at time of infrequent scrap removals. Interim inventories in this area listed only the pellet tray count and rod count for each contract. These measurements employed predictors for average weight of uranium per tray and uranium per rod.

Except for scrap weighing, the only uncorrelated measurement errors for material flows through the various nodes were counting errors. Therefore, equations in this area were closed by item count. Since each production contract was subject to one or more informal inventories during its fabrication period, these inventories appeared to provide the optimum closure times. Closures at any other times would require estimates of the number of process rods at various locations throughout the area.

Data for all closures in the rod fabrication portion of this area were derived from rod-lot documents and informal contract inventories. These documents are listed in Table 6.5.1.

The R2 and R3 documents provided material flow information, and the R4 documents provided the necessary in-process rod-counting information in the fabrication and inspection lines at various times during the inventory period. Closure times for each contract in this area were determined by the R4 inventories for that contract.

There were two types of closure periods considered for each contract in this area, i.e., incremental closures and six-month closures. The incremental closures were made by calculating the closure imbalances (cei's) for each control unit between successive closure dates for each contract, as defined by R4 inventory dates. This type of closure represented individual estimates of gains and losses of each contract during each closure period. For a few of the contracts there were no data available for in-line inventories during the data collection period. Closures on these few contracts were, therefore, restricted to the two formal plant inventories.

6.5.1 CLOSURES IN THE ROD-LOADING AREA (CU-20)

This closure equation covers the loading of pellets from trays into fuel rods; closure data were derived from the R2 documents. Pellet-tray input data and rod output data were completely correlated for each rod lot since the data points were obtained from the same R2 data sheet. It was found that this equation could be conveniently closed once per day. The scrap-recovery flow, Node #76, was generally very small and was covered by entries from material move tickets. Closure imbalances in the rod-loading control unit exhibited a 2 $\hat{\sigma}_{cei}$ tray and rod counting error equivalent to 12.0 NU (normalized units) per contract. This value compares very favorably to the model based variability of 10.3 NU from Appendix D, Table D-3.

6.5.2 CLOSURES IN THE ROD WELDING AND QC INSPECTION AREA (CU-22 AND CU-26)

In the original closure equation network (See Figure 6.5.1) this area was served by two equations, one spanning CU-22, the other spanning CU-26. However, the data received would not support these two control units separately, so the rod QC inspection area was combined with the rerun and rework area into one control unit, CU-22. Separation of these two control units could be considered as a potential refinement, but additional measurements would be required.

Preliminary attempts to close each rod equation on an individual contract basis

Table 6.5.1 - TYPES OF DATA DOCUMENTS EMPLOYED FOR CLOSURES IN FUEL ROD FABRICATION

Mound Designation	Description	Frequency
R2	Initial Rod Loading Document	Each Rod Lot
R3	Rerun Rod Lots, From Rework and Repair Areas	Each Rod Lot
R4	Production Control Informal Inventories	3 or 5 Times per Contract

were unsatisfactory. The results were too variable, and there were too few closures in each contract to afford any reasonable interpretation. Data for all contracts were then included in the closures, and the results were compared for incremental closures for combinations of R2, R3, and R4 documents and for successive differences in R4 documents.

A histogram for cumulative closures in this equation is given in Figure 6.5.2. In this histogram, 47 cei's were generated from 14 different contracts. The histogram is unimodal with a mean of approximately 4.6 rods. However, because of a number of extreme values, both positive and negative, the calculated standard deviation was about 160 rods. The expected variability in this area, from Table D-3, was <1 rod.

In an effort to explain this unexpectedly large variation, it was noted that flow data transactions on the R2 and R3 documents did not necessarily correlate with the R4 inventory changes; sometimes a period of two or three days might elapse before moves indicated on one type of document showed up on the other. This is an excellent example of a phasing error since all these documents spanned the same time frames. These documents performed different functions for the licensee; the R2 and R3 documents were used for product quality control, and the R4 informal inventories were chiefly planning documents for the line supervisors. There were no production-related reasons for the licensee to attempt to correlate exactly the information on these two document types.

In order to gain some insight into the magnitude of this phasing error, the same closures were performed using differences of successive R4 rod counts to determine material flows. Again, cumulative closures were performed over all contracts. The results of these closures are shown in the histogram in Figure 6.5.3.

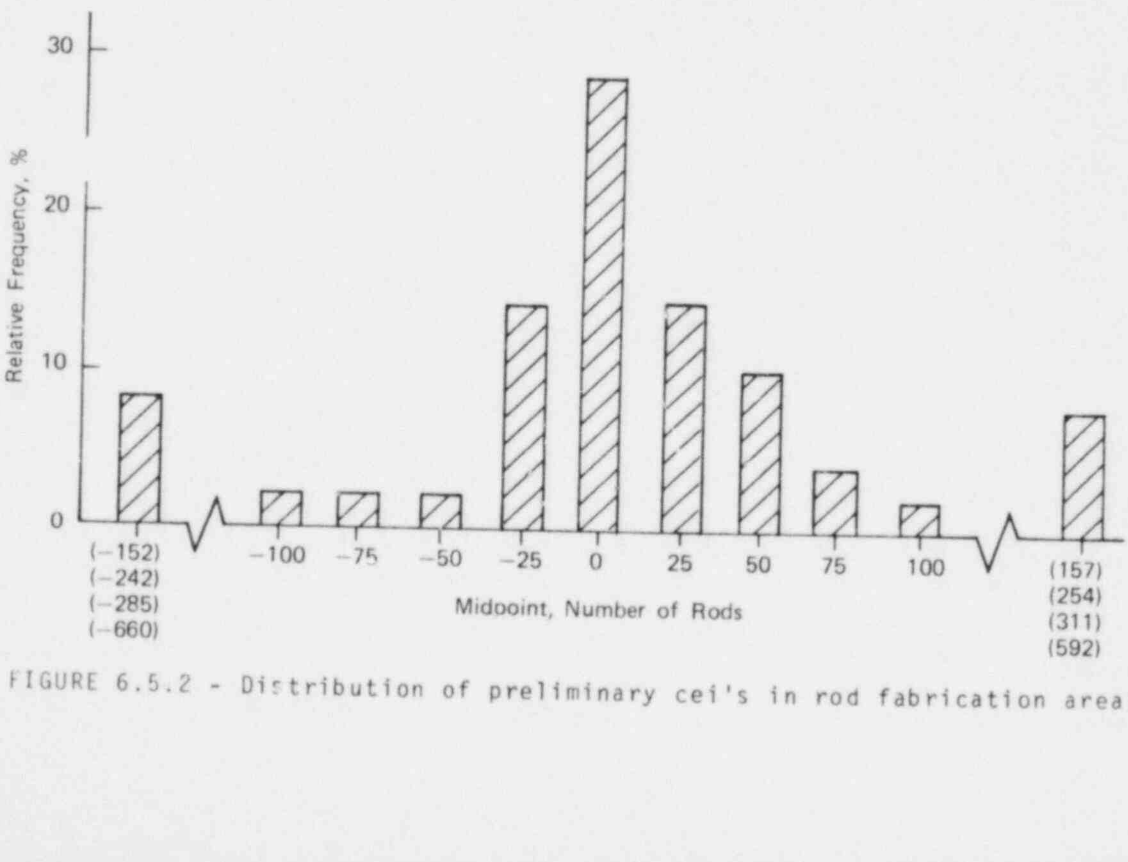

FIGURE 6.5.2 - Distribution of preliminary cei's in rod fabrication area.

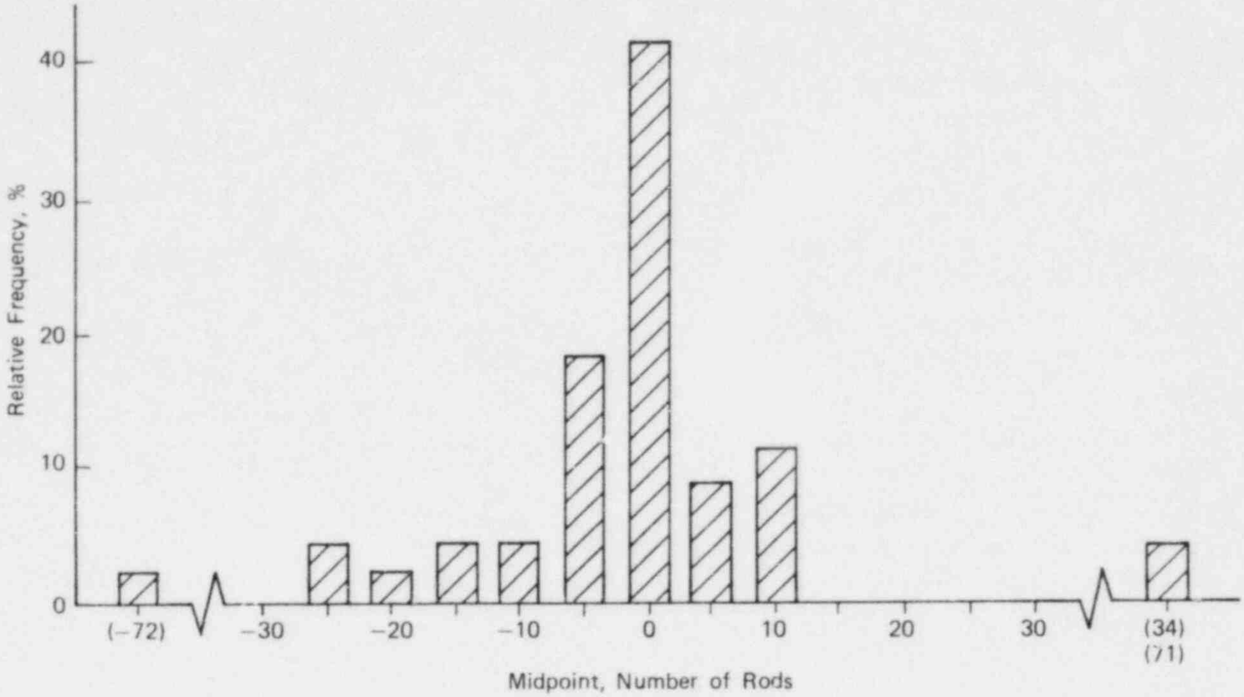

FIGURE 6.5.3 - Distribution of cei's in rod fabrication area (based on differences in informal inventories).

This histogram is also unimodal with a mean of approximately zero, but the noticeable difference from the previous set of cei's is the reduction in number of extreme values. The calculated standard deviation for these cei's is about 19 rods, most of which is probably counting error. The model-based variability in Table D-3 does not include a factor for counting error.

A summary of the means and standard deviations of all types of closures generated in the rod fabrication and inspection area is given in Table 6.5.2.

6.5.3 CLOSURES IN ROD QC STORAGE (CU-23) AND ROD ARCHIVES (CU-27)

Single six-month closures in these two areas resulted in imbalances of the order of several hundred rods in each area. This discrepancy is much larger than would be expected in areas where discrete numbers of sealed items are stored. Although counting errors can be expected in informal inventories, it was assumed that counting errors for the six-month inventory should be negligible. Since the overall plant-wide rod imbalance at the ending inventory was 100 rods, it was concluded that the imbalances in these two areas were due to missing rod-transfer data.

6.5.4 CLOSURES IN ROD REPAIR AND SALVAGE (CU-28)

Since this area handled both fuel rods and bulk UO_2, closures were based on uranium weight. This type of closure then required the use of predictors for the average uranium weight per rod. Data were derived from periodic rod repair status reports, R2 reject-rod information, R3 reconstituted-rod lots, and rod-scrap reports. Closures by contract for the several contracts

Table 6.5.2 - SUMMARY OF EQUATION CLOSURES IN ROD FABRICATION AND FUEL ELEMENT ASSEMBLY AREAS

Incremental Closures

CU #	Description	File Types	Mean cei	cei Std. Dev.
CU-20	Rod Load and Weld	R2	<1 NU	12.0 NU
CU-22	Rod QC Insp.	R2, R3, R3	4.6 Rods	154 Rods
CU-22	Rod QC Insp.	R4 only	-0.2 Rod	19 Rods
CU-28	Rod Repair	R2, R3, R4	18.4 NU	42.0 NU

Six-Month Closures

CU #	Description	File Types	Mean cei	cei Std. Dev.
CU-22	Rod QC Insp.	Inventory	55.6 Rods	584 Rods[b]
CU-24	Element Ass'y	Inventory	34 Rods	-0-[a]
CU-25	Element QC Storage	Inventory	-0-[a]	-0-[a]
CU-28	Rod Repair and Salvage	Inventory	-1.6 NU	44.4 NU[b]

[a]Exact accounting for all fuel element assemblies.

[b]Std. Dev. in normalized units is based on closures across 14 contracts.

handled in this area during the six-month period indicated a mean cei of +18.4 NU per contract. The six-month closure, also by contract, has a mean cei of -1.6 NU with a standard deviation of 44.4 NU. These closure results are also included in Table 6.5.2.

6.5.5 CLOSURES IN FUEL ELEMENT ASSEMBLY (CU-24) AND ELEMENT STORAGE (CU-25)

These equations were closed on a six-month basis by item count of the number of assemblies in each contract; documentation for more frequent closures was not available. Errors in this area were expected to be zero, since all closures would be by item count. However, preliminary closures in this area did generate significant cei's. Since there is considerable incentive for the licensee to avoid fuel element counting errors (the loss of an entire assembly would not be a trivial matter), these imbalances have been identified as resulting exclusively from missing data. The assembly build schedules exactly balanced, but there were missing rod transfers in Node #84, and several shipping documents controlling Node #88 were never received. However, the missing information was inferred from the assembly build schedules, and the area cei was zero for the six-month period.

6.5.6 SUMMARY AND CONCLUSIONS OF CLOSURES IN ROD FABRICATION AND ELEMENT ASSEMBLY AREA

The results of the closures in these areas are summarized in Table 6.5.2. It is apparent from this table and from the discussion that the combination of counting and phasing errors was a significant contributor to variability in the area measurement system. In this respect, it is difficult to determine from these data alone the maximum amount of material that could be controlled in this area. However, if the phasing error can be properly accounted for, with current rod counting practices, the 2 $\hat{\sigma}_{cei}$ for this area appears to be of the order of 20 rods per contract.

Some potential improvements in data collection procedures which would aid in the structuring of a more representative data set are discussed in Chapter 7.

6.6 Closures in the scrap-recovery and waste-processing area

This operation included the reprocessing of all scrap and waste materials generated throughout the entire low-enrichment plant that were not specifically treated within one of the in-line scrap operations. The control unit and closure equation for the scrap recovery and waste processing facility are shown in Figure 6.6.1. The measurement nodes comprising this closure equation and the closure equation itself are given in Appendix E.

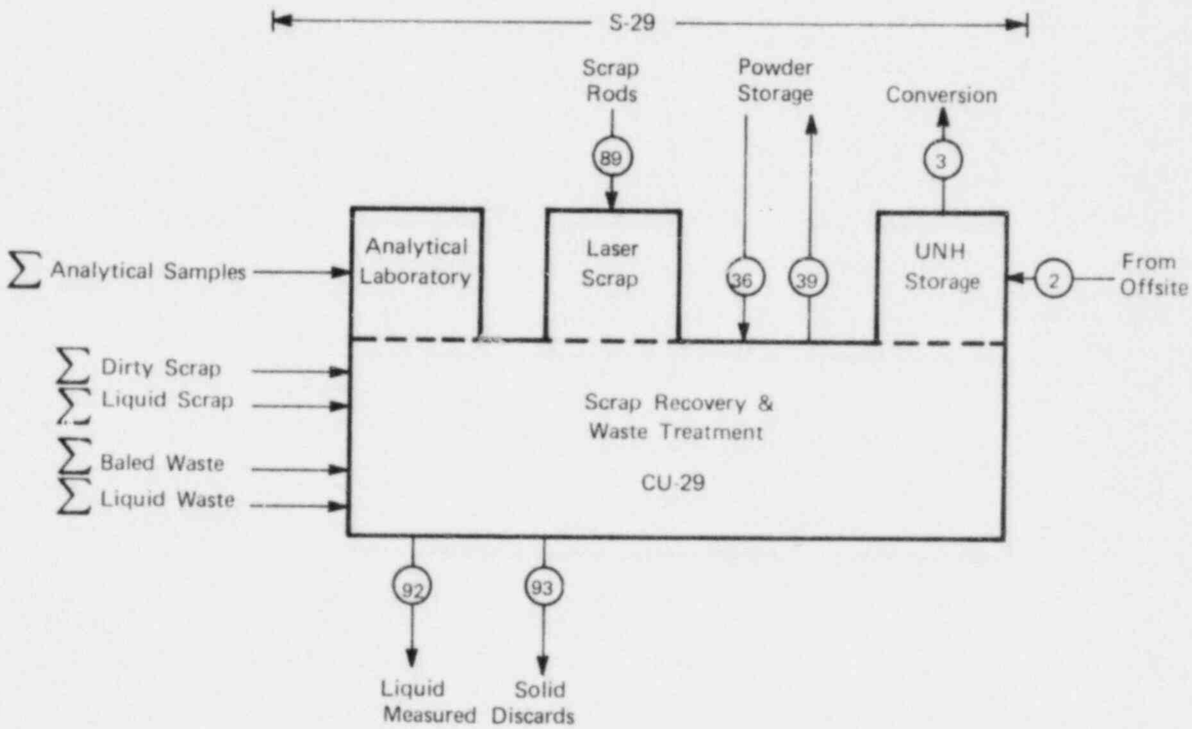

FIGURE 6.6.1 - Control unit and closure equation for scrap recovery and waste processing facility.

Although all materials transferred to scrap recovery were weighed prior to transfer, analytical data adequate to characterize the uranium concentration in these materials could not be obtained until after preliminary processing. Hence, the uranium concentrations of incoming materials awaiting processing were determined by predictors. These predictors were based on historical information for several scrap categories derived from previous formal inventories. Only the receipts of UNH from offsite were sufficiently characterized to provide measured uranium input to this area. All materials leaving the scrap area, either as measured plant discards or materials returned to process, were assayed.

The scrap side-streams in the plant-wide material balance that were used to compile the variability tables for production areas of the plant provided material input information to calculate the expected variability of the closure equation in the scrap and waste processing area. The summary of results of this calculation is given in Appendix D, Table D-5.

6.6.1 CLOSURE ANALYSIS FOR THE SCRAP AND WASTE PROCESSING AREA (CU-29)

The single six-month closure in this area was based on measured or estimated uranium content of the materials handled. There were no inventory data available for the area other than the two formal inventories that bracketed the data set. Data forms used for material-flow determination included production-control tickets, which described the material traffic between the scrap area and the processing and storage areas in the plant, and nuclear material transfer documents, which described measured discards and scrap shipments for offsite recovery, incoming material receipts, and uranyl nitrate drum usage records.

The six-month closure imbalance (cei) for this area was -400 normalized units (NU). This value falls within the $2\sigma_{cei}$ variability of $\pm$565 NU, calculated for the control unit from the process model. Other than representing a very large material discrepancy, there were no indications from this closure that there might be any serious data problems related to this control unit.

It should be emphasized that the calculated variability in the scrap area is the largest single closure uncertainty in this process. One source of known error associated with the scrap operation is the uncertainty in the estimated uranium content of scrap material in interim storage awaiting recovery operations. These concentrations were estimated from predictors which were historically based on the type of scrap. Only after the materials were sorted and preprocessed, and analytical samples were obtained, could the uranium contents be assayed.

However, it was found that the error associated with these predictions was not adequate to describe the expected uncertainty in the scrap process. The summary in Appendix D, Table D-5 shows that the measurement error associated with the uranium concentration of material in storage after preliminary processing is significantly larger than the predictor and measurement uncertainties related to the uranium concentration in input materials.

An examination of the analytical procedures in this area indicated that only about 4 out of 100 containers of contaminated scrap were sampled for analysis. The relative error related to intersample variation was, in some cases, as high as 60%, so the sampling plan that was utilized was probably not adequate to characterize materials within this wide a concentration variation. Potential refinements to reduce this error component are discussed in Chapter 7.

Attempts were made to estimate the variability of the closure equation for the scrap area by forming six-month closures across individual production contracts. Although the material balance across the combined contracts in the control unit was consistent with model predictions, there were not enough data describing transfers of materials between contracts within the scrap area to afford any valid conclusions concerning the variability of the closure equation. No further refinements with the data set were considered for this control unit.

7.0 Potential refinements

7.1 Discussion

As was noted in the introduction, the purpose of this project was to evaluate the effectiveness of the CUA methodology by applying the technique to an operating plant. It was not the specific intent to detect actual losses in the plant, but rather to identify dominating sources of measurement uncertainties and thereby determine the limit of control afforded by the process measurement system. These dominating uncertainties provided a basis for suggestions for effective potential refinements.

There are two major observations from the study that help identify effective potential refinements to the process. Primarily, the data set, as collected, was dominated by data errors and phasing errors. Secondly, the process was inventory-dominated; i.e., the total amount of material in storage during the inventory period studied was almost twice the total material throughput for the period, so the plant uncertainty was determined primarily by uncertainties of materials in storage.

7.2 Potential refinements process-wide

Data errors included transcription errors, encoding errors, missing data, and duplicate data. Phasing errors arose when material was inventoried in one location, while the paperwork describing its movements indicated the same material was elsewhere at the time of the inventory. Although computer verification techniques were used to reduce the number of data errors and to make allowances for phasing errors in this study, the calculated uncertainties contained residual errors of both types.

It should be noted that the problems with data errors that were encountered in this study are not inherent in the CUA methodology, but rather were artifacts introduced by the method of collecting, transmitting, and encoding the process-generated data. To use process data for MC&A purposes, it is necessary to utilize computerized monitoring of the data as they are collected so that unreasonable or missing data would be identified promptly, thereby enabling operators to take rapid remedial action.

Phasing errors can be reduced by application of appropriate work rules to correlate material movements and inventories more carefully. Because most storage areas in this plant were not inventoried except at plant-wide formal inventories, closures in these areas were restricted to one six-month period each. To achieve more stringent requirements for timeliness of loss detection, it would be necessary to implement more frequent informal inventories in the affected areas, as identified in Figure 5.3.

An additional refinement that would reduce the uncertainty in this process would be to restrict the amount of material in any one of the process storage areas to the active material only. Material that would not be expected to be used for any length of time should be tamper-safed and placed in an easily inventoried dead storage area.

If it were necessary to upgrade the measurement performance of this process to achieve a more stringent plant-wide mass sensitivity criterion, the initial efforts would need to be directed toward improvements in the scrap and waste processing area. Any measurement improvements elsewhere in the plant would have a negligible effect on the overall plant performance.

7.2.1 REFINEMENTS IN THE SCRAP AND WASTE PROCESSING AREA

Other than problems with data discrepancies, which were peculiar to this study, there were two dominating uncertainties in the scrap area. One was the estimation of the uranium content of materials awaiting preliminary processing and analysis. The other was the uncertainty of the intersample variation of preprocessed contaminated scrap awaiting final processing.

Although some NDA equipment was employed by the licensee to estimate uranium concentrations in unmeasured incoming materials, additional, rapid, reliable, NDA scanning techniques would need to be developed if additional control were necessary.

The second uncertainty could be reduced by a more comprehensive sampling plan to better characterize the intersample variation of preprocessed scrap materials in temporary storage.

7.2.2 REFINEMENTS IN CONVERSION

Except for the data errors and phasing errors described above, the dominant uncertainty in the conversion area was the amount of in-process material and holdup at any given time in the conversion line. One refinement that could narrow this uncertainty would be to list the status of each piece of equipment in the line at each closure time. A piece of equipment could be listed as "full", "drained", or "cleaned out" at any one time. Historical data from the process could determine reliable average quantities of material for each of these conditions with ranges of uncertainty for each piece of equipment (including connecting lines). The amount of in-process material and holdup in this line at any one time would be the summation of these conditions. The potential use of closure information to verify in-process and holdup predictors was discussed in Chapter 6.

7.2.3 REFINEMENTS IN PELLETING

The dominant error in this portion of the process was the uncertainty in material in-process and holdup at each closure. The holdup material was mostly recyclable scrap for which predictors for uranium concentration were used. The data forms that were used to identify these materials listed these values in relatively imprecise numbers.

A potential refinement that could improve both localization and mass sensitivity of the loss detection capability in the pelleting area would be the utilization of recycle scrap logs. Such logs were maintained routinely by the licensee for each pelleting line but were not available for the current study. This type of log would reduce the uncertainty of in-process material quantities and would permit partitioning each pellet line and its tray storage area into three additional control units.

7.2.4 REFINEMENTS IN FUEL ROD FABRICATION AND ELEMENT ASSEMBLY

The largest source of uncertainty in the rod area appeared to be the result of phasing errors. Changes in work rules for better correlation of rod inventories and rod lot movements could reduce this effect.

Most of the in-line rod inventories appeared to have been taken on an as-needed basis for production planning. One improvement in control would be to take these inventories on a regular basis, e.g., weekly for each contract in line. This procedure would permit more regular closures within each contract to achieve improvements in timeliness of loss detection.

It is not believed that using ID# closures in the rod area to account for every fuel rod would be a cost effective refinement. In view of other uncertainties, noted in the process, added mass sensitivity to be gained from tracing individual fuel rods would not be significant. The data received also would not support ID# closures in the element assembly and storage areas, so this type of closure could not be used in this study. However, the item counting procedures employed by the licensee in these areas appeared to provide excellent control.

8.0 Summary

8.1 System development - preparation of the process model

The process model of the low-enrichment plant was developed by preparing detailed process flow diagrams for all operations in the plant. All main-stream and side-stream material flows were quantified for each process step and for all types of operational modes. Estimates of in-process material quantities, in-storage quantities, and holdup were made for each portion of the process. All measurement points related to uranium content and flows were identified, and random and systematic error components were obtained from the licensee's measurement control information for each of the measurement techniques employed.

Modeling of the process proceeded with minimal difficulties. The process was conveniently divided into four major production modules: UF_6 to UO_2 conversion, UO_2 pelleting, fuel-rod fabrication and fuel-element assembly, and scrap and waste processing. These modules were separated by buffer storage areas in the plant, so that each module operated more or less independently of the others.

The process was ultimately divided into 37 control units, so that each control unit represented a process operation or collection of operations bounded by quantitative measurement nodes. The control unit network that was prepared completely spanned the process so that each operation in the plant was included in at least one control unit. Estimates of material flows and storage quantities for all portions of the process were determined from typical quantities observed during a previous six-month operating period. These flows were then used to calculate the absolute uncertainties associated with the measurements in each control unit and to compute a plant-wide material balance.

8.2 System application - safeguards development

Material-balance closure equations were written to span each control unit in process. Information obtained from the process model was used to estimate the variance of closure imbalances for each closure equation. Closure times were dictated by normal process and accountability measurement schedules. The mass sensitivity for detection of material loss from a control unit (i.e., a potential diversion) is directly proportional to the square root of the variance of closure imbalances from the appropriate closure equation. Also, the timeliness of loss detection is determined by the closure times. Specific control unit parameters were determined primarily by production requirements and production documentation.

Absolute error components for each measurement employed in the plant were determined from random and systematic relative error components and absolute mat rial flows during the expected closure period. Appropriate summation of the absolute error components for the measurements comprising each control unit yielded the total uncertainty for its closure equation ble 8.1 lists the model-based uncertainties and closure periods that were developed for each control unit in the low-enrichment plant.

Based on these model predictions, the largest variability, i.e., the poorest mass sensitivity, was in the scrap and waste processing control unit ($2\sqrt{\text{variance}}$ = 585 NU). Predicted variabilities for the other control units ranged from <1 NU to 46 NU per closure, and timelinesses ranged from less than one day to six months. Most of the six-month closures were related to storage areas where intermediate informal inventories were rarely taken; generally the only information available for storage areas were the two formal inventories. In some of the production line operations, closure periods were "event-controlled" rather than periodic; the data were available on a batch basis rather than a shift or daily basis.

Areas where measurement upgrading would be required for improved mass sensitivity and timeliness, which were based on model predictions, are evident in Table 8.1. As an example, a performance criterion requiring the detection of diversion of 100 NU of uranium with high probability would require refinements in the scrap and waste area, but refinements in other areas of the process would be of marginal or negligible value.

Table 8.1 - MODEL-BASED UNCERTAINTIES FOR CLOSURE EQUATIONS IN THE LOW-ENRICHMENT PLANT

Eq #	Description	Closure Period	Variability 2σ Normalized Units[a]
S-1	UF_6 Cylinder Storage	6 mo	-0-
S-4a	Conversion, UF_6 Mode	1-4 days	45.59
S-4b	Conversion, Recycle Mode	1-4 days	45.82
S-4c	Conversion, UNH Mode	1-4 days	44.94
S-6	Line and Floor Storage	6 mo	-0-
S-8	Conv. Product Storage	6 mo	5.23
S-9	Blender	Per blend	4.42
S-11	Powder QC Storage	6 mo	1.01
S-13	Pellet Preparation	24 hr	34.44
S-18	Pellet Tray Storage	24 hr	6.47
S-20	Fuel Rod Loading	24 hr	10.30
S-22	Rod QC Inspection	1-8 weeks	<1 rod
S-23	Rod QC Storage	1-8 weeks	<1 rod
S-27	Rod Archives	6 mo	<1 rod
S-28	Rod Repair and Salvage	6 mo	15.86
S-24	Element Assy. and Insp.	1-8 weeks	<1 rod
S-25	Element Stor. and Ship	6 mo	<10 rods
S-29	Scrap and Waste Process	6 mo	585.6
	Off-Site UNH Storage	6 mo	1.22
L-1	Plant-Wide Closure	6 mo	1048

[a]Based on plant LEID normalized to 1000 NU.

In this application of CUA, no refinements involving extra measurements or upgraded precision were imposed on the licensee. Only those measurements that were taken and recorded as part of the normal operation of the process were used.

8.3 Comparison of actual data and the model

When CUA is tested with actual process data, very useful information is obtained by comparing model-based and data-based variances for each control unit. If the process model is correct, these variances should agree. However, if significant differences are found, there are dominating errors in the process that were not accounted for in the process model. In such a case, an examination of the model and the data base would be required to determine the cause of the discrepancy.

Daily production and operational data covering a six-month operation period in the low-enrichment plant were used to test the CUA model and the performance predictions derived from it. These data, collected mainly for process operations rather than for safeguards, were applied to the closure equation network to obtain closure imbalance information for each control unit.

In general, application of the data from the low-enrichment plant verified that the process model was indeed valid. Mainstream and side-stream material flows and inventories of materials in storage agreed acceptably with the model. With one exception, all significant operations had been included in the model. The one exception was in the pelleting operation where the licenseee employed informal staging areas which were not discovered until after the data collection phase of the project had been completed. Modeling of these areas could not be verified since no informal inventory data were available for the new control units.

The variability associated with the plantwide six-month closure, as given in Table 8.1, agreed very well with the LEID for the formal closing inventory in the plant (1048 NU = 1.048 x LEID). This agreement confirms that the material throughputs and measurement error components that were selected for the process model were correct.

There were, however, major discrepancies between the model and the data-based calculations for several control units. It was found that these discrepancies were not the result of modeling inaccuracies but were due to two major sources of nonmeasurement error. These were identified as data errors and phasing errors. Data errors included improperly recorded data, transcription errors, missing data, and duplicate data. Phasing errors arose when data describing material movements in and out of control units did not correlate in time with material inventories within the control units.

Both of these souces of error led to data-based uncertainties ranging from 4 to 100 times as great as the model predictions would indicate. However, close examination of the data in some areas of the process enabled identification of specific time periods where these nonmeasurement errors were relatively small. The data related to these specific time periods were then selected to provide estimates of the limit of control attainable for each production type control unit. Mass sensitivity for abrupt loss, in normalized units, derived from the best available data, are given for the process operating areas in Table 8.2. Results for most of the material storage areas are not given in this table since there were no statistics available; the equations could be closed only once during the six-month period. Table 8.2 also lists specific-material-loss alarm thresholds which are based on an expected average of one false alarm per six-month period in each control unit. The right-hand column in this table represents, for the alarm threshold given, the material loss which would be detectable at 90% probability for each control unit.

One point is immediately apparent upon examination of this table. In all areas of the plant the effective material-loss alarm threshold for any six-month period may be set to a value significantly less than the plant LEID (normalized to a value of 1000 NU). Thus, by dividing the process into control units, it would be possible to achieve major improvements in mass sensitivity, timeliness of detection, and localization of loss, without requiring any additional measurements. The same systematic pattern of mass sensitivities is seen in this table as was seen for the model-based predictions in Table 8.1. The area with the largest measurement variance and hence poorest mass sensitivity is the scrap and waste processing control unit.

Table 8.2 - SAFEGUARDS PARAMETERS FOR SPECIFIC CONTROL UNITS IN THE LOW-ENRICHMENT FUEL PLANT

CU #	Operation	No. of Closures Per Inv. Period	Std. Dev. ($\hat{\sigma}_{cei}$) (NU)	Alarm Threshold[a] (NU)	Loss Detectable @ 90% Probability (NU)
4	Conversion	>200	49.9[b]	143	207
9	Blender	>200	66.7	181	266
13	Pelleting	>200	52.7	150	217
18	Pellet Tray Storage	>200	12.6	36	52
22	Rod Weld and Inspection	> 25	<10 rods	19 rods	31 rods
29	Scrap and Waste	1	282[c]	728[c]	1191[c]

[a]Based on an expected average of one false alarm in control unit in six-month period.

[b]Based on 30 closures with refined data.

[c]Model-based standard deviation.

8.4 Potential refinements

The CUA methodology identified two types of nonmeasurement error that dominated the data set received from the licensee. These were data errors and phasing errors. It should be noted that many of these errors were artifacts peculiar to this study and were created by the method of collection and transmission of data. However, their presence in this data set reveals how such errors can strongly influence data sets. Any MC&A system depending on process data for operation must be set up to minimize the effects of both of these types of error. One method of achieving this is to provide computerized scanning of incoming information to identify obvious discrepancies early enough to permit correction.

The largest measurement-based contributors to closure-equation-imbalance variances for the control unit network in this process were the uncertainties associated with materials in storage. During the period studied, the total amount of material resident in various storage areas was about twice the total plant throughput for the six-month period. Uranium uncertainties in stored materials, particularly in the scrap and waste processing area, were major contributors to the plant overall uncertainty. Restricting material in storage to active material only and tamper-safing the inactive materials could reduce the overall plant uncertainty significantly. Also, a more comprehensive plan for sampling and analysis of active materials would help reduce the uncertainty arising from intersample variations, one of the major errors in the scrap area.

The poor timeliness prevalent in storage areas was due to the lack of periodic material inventories between the formal plant inventories. Most storage areas could not be closed more frequently than the six-month period because of this limitation. More frequent informal inventories would be required to upgrade the timeliness of loss detection.

In addition to these general observations, there were dominating errors specific to the various modules in the process. In the scrap and waste area, a significant uncertainty arose from the use of predictors to estimate the uranium content of contaminated scrap awaiting preprocessing and analytical sampling. This uncertainty could be reduced significantly by more sophisticated NDA scanning techniques if such reduction were required. In the conversion area, the largest contributor to material balance uncertainty was the estimate of the amount of material in residence in each conversion line at closure time. This error could be reduced by maintaining a status log whereby each piece of equipment involved could be listed as "full", "drained", or "cleaned out" at each closure time. A similar behavior was observed in the pelleting area. The uncertainties of in-process and holdup in the line at each closure could be reduced by more formal use of existing pellet-scrap logs currently maintained for each line. Most uncertainties in the fuel-rod-fabrication and element-assembly area appeared to be phasing errors with some contribution from counting error. These errors could be reduced by implementation of wc rules that would better correlate material movements and informal inventories.

If it were necessary to upgrade the performance of this low-enrichment process to meet more stringent mass sensitivity requirements, initial efforts should be directed toward the dominating errors in the scrap and waste processing area. Any measurement improvements elsewhere in the plant would have a negligible effect on the overall performance.

8.5 Predictor development

One of the results of this study was the development of a technique to verify predictors for in-process materials and holdup quantities under dynamic conditions. The predictors used by the licensee to describe the status of conversion lines based on historical measurements of runout and cleaned-out material after the conversion line was shut down. With the CUA-based technique, if one started with data from a cleaned-out line and considered only material input and output flows (including side streams), then the total amount of material in the line at equation closure times would be the closure imbalances (within the uncertainty of the flow measurements). Since the estimation of resident quantities and holdup represents a greater uncertainty than the flow measurements, these closures should provide significantly better estimates of in-line quantities than the predictors.

Comparison of in-line quantities calculated from equation closures with quantities determined from the licensee's predictors showed good agreement between the two methods, thereby verifying the validity of the predictors used by the licensee. Although this technique was applied to only one conversion line with a thoroughly verified data set, this type of analysis could be more generally applied to any continuous or semicontinuous process.

8.6 Conclusions

Several major conclusions could be reached from the results of this study:

- <u>The Process Was Modeled With Minimum Difficulty</u>

The CUA process-modeling technique provides a valid basis for evaluating the impact of measurement uncertainties on a measurement control system that uses available process data. This process was modeled with no major difficulties, and any problems were easily identified and rectified. All material flows, in-process quantities, and measurement uncertainties were verified by operational data and measurement control data.

The calculated variability for the six-month plant-wide closure agreed very well with the LEID and the ID for the ending formal inventory. This confirms that the material throughputs and measurement error components selected for the process model were correct.

- <u>PC/QC Data Can Be Used For Material Accountability</u>

The test demonstrated the integration of process control, quality control, historical data, and material accountability information into a control-unit-based safeguards system. A viable control unit network was established that spanned the entire process and depended only upon existing measurements to operate.

- <u>Significant Improvements In Materials Safeguards Are Achievable</u>

The study established data-based control parameters that revealed that significant improvements in loss detection, i.e., mass sensitivity, localization, and timeliness, could be achieved in the process by using operational data to enhance the accountability information.

Except for the scrap and waste processing area, all operations in the plant could be controlled to less than 20% of the plant LEID with no changes to the measurement system or the measurement schedules.

- <u>Process Predictors Were Verified</u>

The CUA system verified the use of historically based predictors for estimation of unmeasured flows and material holdup under dynamic conditions.

- <u>CUA Analysis Identified Dominating Errors Requiring Refinement</u>

The study showed that the data set that was received was dominated by two types of nonmeasurement errors, i.e., data errors and phasing errors. Data errors included improperly recorded data, transcription errors, missing data, and duplicate data. Phasing errors arose when the paperwork describing material movements and locations was not properly correlated with actual material locations.

The six-month plant-wide closure was dominated by uncertainties associated with large amounts of unused resident material. The amount of material in storage during the period was almost twice the material throughput for the period. Inventory uncertainties were, in many cases, controlled by sampling errors.

There were significant uncertainties in the scrap and waste processing area because predictors were required to characterize incoming material flows.

- The Study Identified Problems In Retrofitting MC&A Systems

The study identified two major problems related to retrofitting a near-real-time MC&A system to an existing process, i.e., 1) the necessity of reconciling data inconsistencies as soon as possible and 2) the need for frequent informal inventories or other material identification procedures in all formal and informal material storage areas.

- Potential Refinements Were Suggested

Nonmeasurement errors could be reduced in a cost-effective manner by implementing computer editing capabilities to recognize significant data errors with sufficient timeliness to permit correction. Introduction of specific work rules to better correlate material movements and inventories could be employed.

Inventory errors could be reduced by proper securing of unused materials and by more comprehensive analytical sampling of materials in temporary storage. More frequent inventories would be needed to upgrade loss detection timeliness. A weekly informal inventory of material in storage is suggested.

Inadequate predictors can be upgraded only through implementation of additional measurements. A method for using material imbalances to verify predictors was suggested.

It is estimated that, by using refinements suggested above, which would involve implementation of only moderate changes to the measurement system, the uncertainty in each control unit could be reduced to less than 5% of the plant LEID.

Acknowledgements

The authors acknowledge the efforts of the following people at Mound who were directly involved in the program. The project was under the direction of D. R. Hill and W. H. Smith. Major contributions were made by F. C. Fushimi who handled all computer interfacing activities, provided basic programming for data verification, and participated in closure equation programming; Ms. E. K. Bachmann who arranged for all data encoding and file verification; R. Caldwell who assisted with computer graphics; and A. F. Ciramella who developed an interactive computer program for variance calculations. All data encoding was performed under the direction of Ms. Dorothy Whitney.

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4. C. R. Rudy, D. B. Armstrong, K. W. Foster, D. R. Rogers, and D. R. Hill, "Controllable Unit Approach: An Application Manual," MLM-2881, NUREG/CR-2538, June 1982.

5. NRC/NMSS, "Report of the Material Control and Material Accounting Task Force," NUREG-0452, April 1978.

6. K. W. Foster, D. R. Rogers, D. B. Armstrong, and J. C. Miles, "Application of the Controllable Unit Approach (CUA) To a Low-Enrichment Uranium Fuel Facility," J. Inst. Nuclear Mater. Manage. X, (Proceedings, 1981).

Glossary

Closure Equation - A mathematical expression that describes material flows into and out of a control unit over a closure period, accounting also for changes in holdup material and inventories.

Closure Equation Imbalance - The difference between the sum of the positive and the sum of the negative terms in a closure equation. CEI is assumed to be normally distributed with a mean of zero. Observed values of CEI are denoted as "cei".

Closure Equation Imbalance Variance - The actual variance of the closure equation imbalance. The estimate of this variance is the result of combining all the variance components of each term in the closure equation.

Contract - A licensee designation in this study to differentiate between individual customer orders.

Control Unit - Segments of a process or groups of process steps bounded by measurements sufficient to permit closure (material balance) equations to be formulated.

Criteria, Performance - A set of parameters against which the MC&A system is to be evaluated, such as may be defined by the NRC or facility management.

Diversion of Nuclear Material - The unauthorized removal of nuclear material from uses permited by law or treaty. Diversion may occur through actions by persons in authority or by theft, robbery, etc.

Error, Random - The chance variation encountered in all measurement work, characterized by the random occurrence of both positive and negative deviations from a mean value, the algebraic average of which approaches zero in a series of measurements.

Error, Systematic - A value from the population of possible measurement biases assigned to a measurement due to calibration. Since the biases are often considered normally distributed over time, this effect becomes the observed value of a random variable for a given period of calibration.

False Alarm - An alarm in the material control system that is not caused by loss of nuclear material but by statistical fluctuations in the measurement systems.

False Alarm Probability - The probability of occurrance of an alarm when no material loss has occurred.

Formula Kilograms - A quantity in kilograms of the isotope uranium-235 (contained in uranium enriched to 20% or more in the uranium-235 isotope), uranium-233, or plutonium alone or in any combination, computed by the formula, grams = (grams contained uranium-235) + 2.5 (grams uranium-233 + grams plutonium).

Holdup - The amount of material remaining in process equipment and facilities after the in-process material, stored materials, and product have been removed.

Inventory, Formal - A complete plant-wide material balance taken for safeguards purposes on a regular basis, as required for license compliance.

Inventory, Informal - Any material accounting measurement of stored material, not necessarily plant-wide, which the licensee performs for his own benefit, usually for process control.

Nodes, Measurement - Any point in a process where one or more measurements are taken.

Normalized Unit (NU) - That quantity of low-enrichment uranium equivalent to 1/1000th the plant uranium LEID for the formal inventory period studied.

Predictor - An algorithm used to predict the current value of an unmeasured quantity from historical data.

Process Model - A mathematical representation of material flows and measurement uncertainties in a process.

Standard Deviation - The square root of the variance, usually represented by the symbol, σ.

Variability - A measure of the precision of measurements comprising a closure equation. The variability is defined as twice the square root of the variance of closure equation imbalances, and is equivalent to $2\sqrt{CEIV}$.

cei - Closure Equation Imbalance (as defined).

CEIV - Closure Equation Imbalance Variance (as defined).

fkg - Formula Kilograms (as defined)

ID - Inventory Difference; a value calculated for each formal inventory as required for license compliance.

ID# - Identification Number, usually a serial number of a discrete item.

LEID - Limit of Error of Inventory Difference; a value calculated for each formal inventory, as required for license compliance.

MBA - Material Balance Area. A subdivision of a licensee's plant where complete material accounting is required.

MC&A - Material Control and Accounting.

NDA - Nondestructive Analysis.

PC/QC - Process Control and Quality Control information.

POP Sheets - Process Operating Point data sheets. These forms were used by the licensee in this study to describe detailed material flows through each piece of equipment in the process.

RSS - Root Sum Square. The square root of the sum of the squares of individual components.

σ_{cei} - The square root of the variance of a population of closure imbalances for a given closure equation.

$\hat{\sigma}_{cei}$ - The square root of the estimated variance of a population of closure imbalances for a given closure equation. This is equivalent to the standard deviation of a sample of closure imbalances.

Appendix A

Details of process module operation

A.1 Conversion

A flow diagram of the conversion area is given in Figure A-1. Uranium was received at the plant as uranium hexafluoride (UF_6) in large metal cylinders; each cylinder contained uranium of a specified uranium-235 enrichment. To drive the UF_6 from the cylinder into the conversion line it was necessary to heat the entire cylinder in a steam chest to vaporize the contents. Cylinders were weighed before and after emptying to determine the amount of UF_6 removed. As a rule there was a residual of several normalized units of material that could not be easily removed from a cylinder, and it was necessary to maintain a "heel" account for empty cylinders.

In the conversion operation, the vaporized UF_6 was reacted with deionized water to produce uranyl fluoride in solution. Ammonium hydroxide was added to this solution to adjust the pH to a desired value and to precipitate the uranium as ammonium diuranate (ADU). The solid precipitate was separated by centrifugation, and the wet ADU was dried in a special drier furnace. The dried ADU was then reduced to UO_2 in a continuous feed calciner. Product UO_2 was then passed through a grinding mill for comminution of the powder to a particle size suitable for blending and compaction. Product UO_2 powders were collected in polyurethane-coated cardboard containers. The material was stored in these powder packs until it was analyzed and selected for blending.

The amount of potential product material that is carried out of a process in side streams must be considered in the

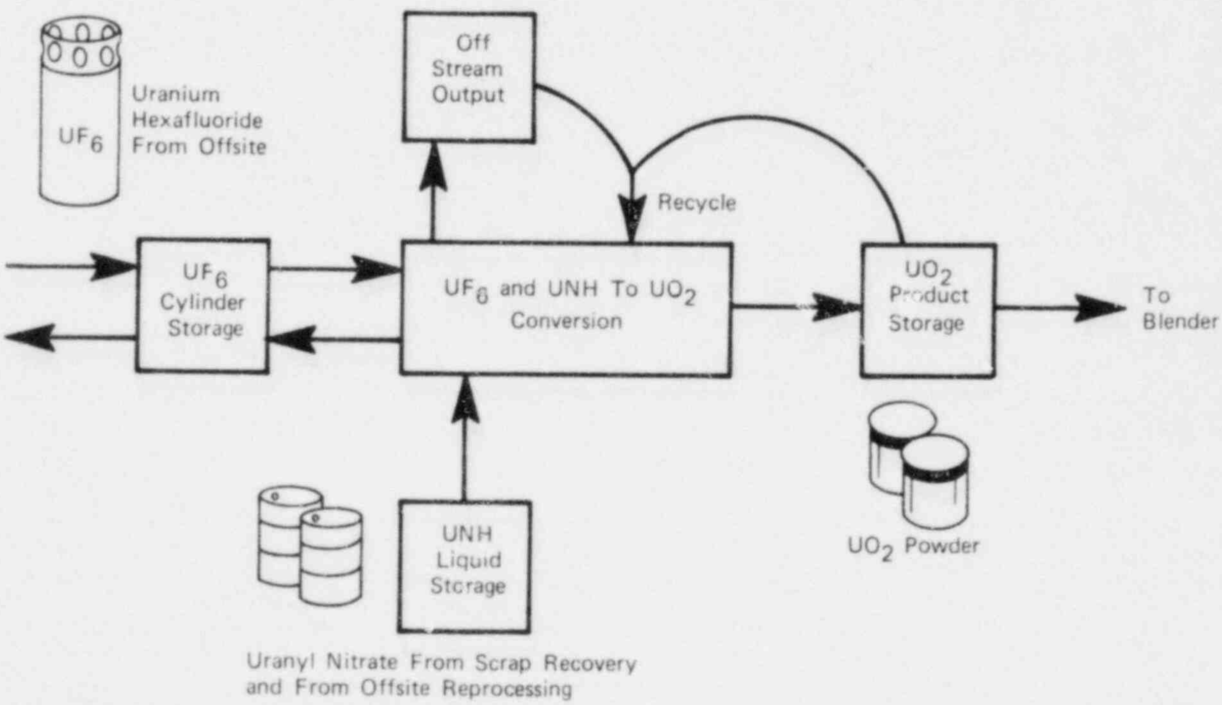

FIGURE A-1 - Flow diagram of conversion operations.

determination of the material balances. In this process uranium was collected from conversion side streams by "polishing" centrifuges, filters, liquid scrubbers, and various acid washing and cleanout operations. A sizeable fraction of these "off-stream" materials was of high enough purity to be directly reusable, so this material was placed in line and floor storage in the conversion area to await reprocessing. Liquid scrap and waste, and contaminated scrap, on the other hand, were transferred to the scrap processing facility for recovery or disposal.

In addition to the main UF_6 operational mode, two additional operational modes were employed in the conversion lines to process off-stream materials, i.e., Recycle and Uranyl Nitrate (UNH) modes. The Recycle mode was employed to process wet and dry, solid, off-stream materials that had accrued into line and floor storage. The UNH mode was set up to process uranyl nitrate solution, which was the product of the scrap recovery operations. With this mode, the UNH solution was inserted in the line at the pH adjustment step, and the uranium was precipitated as ADU. During both of these alternate modes of operation, the UF_6 vaporization was stopped.

In order to properly evaluate the effects of holdup in the conversion lines, it is necessary to consider the quantities of in-process material to be expected in each conversion line under the various operating conditions; these conditions include full-line operation, runout, and cleanout. There were three levels of cleanout employed at this plant. These were flush cleanout, intermode cleanout, and enrichment cleanout. Flush cleanouts were employed routinely to remove deposited material in various portions of the process; intermode cleanouts were used specifically when changing from one operational mode to another (e.g., UF_6 to Recycle), and enrichment cleanouts were employed to completely scour the line to avoid isotopic cross-contamination when enrichment changes were planned.

Modeling of the conversion process therefore must consider each of the three operational modes (UF_6, Recycle, and UNH) as well as the holdup associated with runout and the three levels of cleanout associated with each of the operating modes.

A.2 POWDER BLENDING

A flow diagram of the powder blending operation is given in Figure A-2. Packs of product UO_2 were collected, blended for homogeneity, and sampled and analyzed for purity and uranium-235 enrichment. Powder aliquots were routinely sent to a pilot press line to establish optimum powder compaction parameters. Acceptable blends were QC released, while unacceptable blends were either sent to scrap or were mixed with new material to form another blend.

A.3 PELLETING

A schematic diagram of the pelleting process is shown in Figure A-3. QC released production blends of UO_2 were transferred to one of the pelleting compaction lines. Incoming virgin powder was frequently blended with usable scrap recovered from downstream in the same pelleting line. The prepared powder was precompacted and reground to establish optimum granule size. The reground

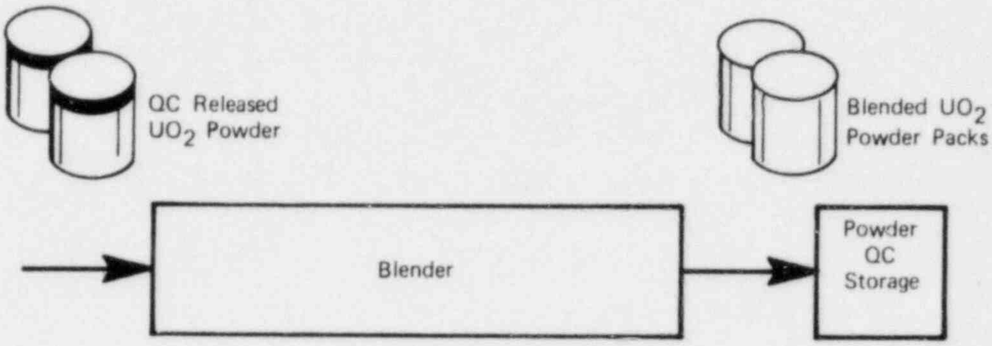

FIGURE A-2 - UO_2 powder blending operation.

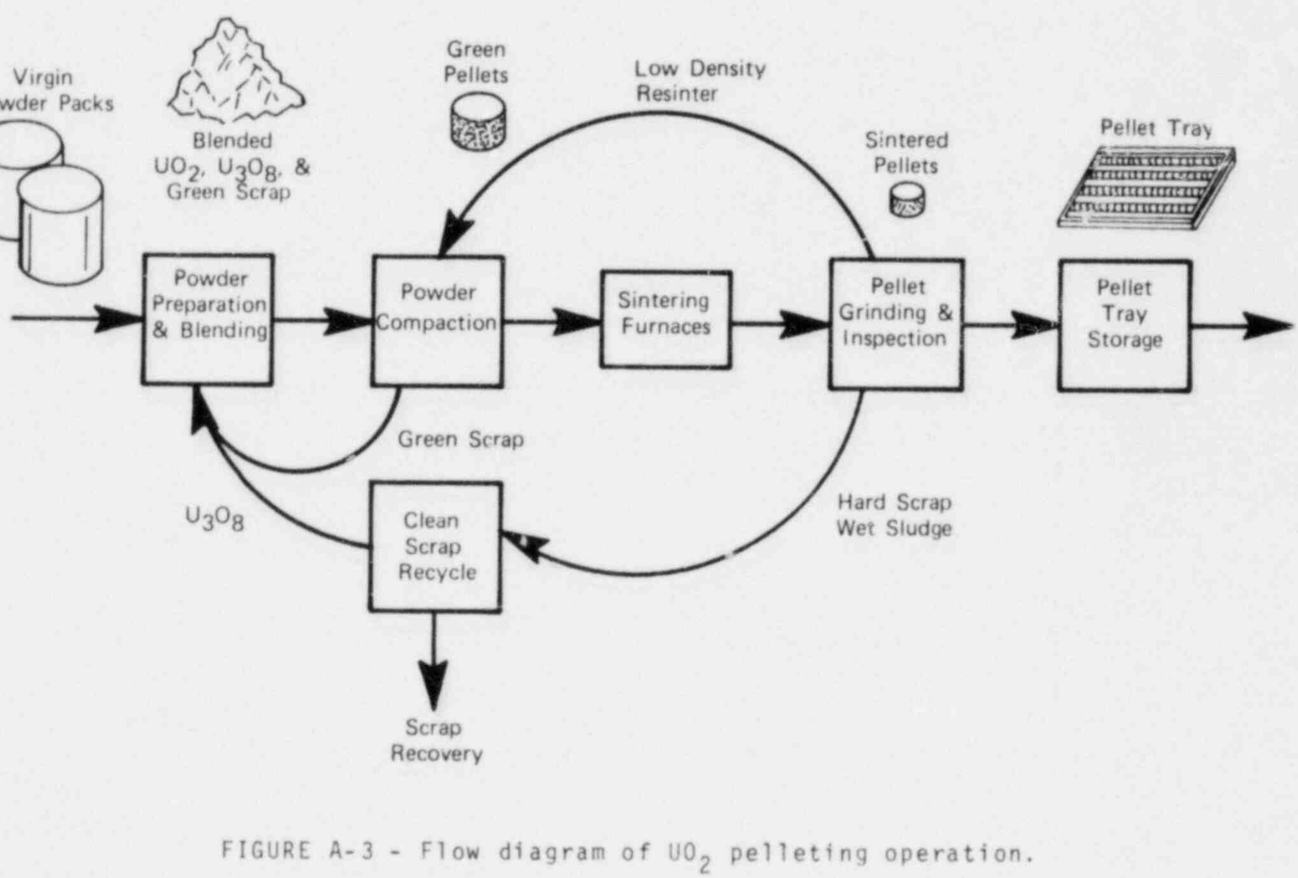

FIGURE A-3 - Flow diagram of UO_2 pelleting operation.

material was then fed to a large automatic rotary press and compacted into small cylindrical pellets. These green pellets were loaded into molybdenum boats and passed into one of the sintering furnaces. In order to accommodate the capacity of the press and to avoid line shutdown in case of furnace malfunction, there were several sintering furnaces associated with each pelleting line. The time and temperature of sintering directly affected the density of the sintered pellets, so pellets were randomly selected for density measurement from the boats as they left the furnace. Boats with low density pellets were returned for resintering, and high density pellets were scrapped. Pellets with acceptable density were fed through a centerless grinder, and each pellet was ground to a precise diameter determined by the inside diameter of the fuel rod tubes to be loaded. Ground pellets were loaded onto special trays which were used directly in the fuel-rod-loading operations. Broken, chipped, undersize, or otherwise unacceptable ground pellets were scrapped. Acceptable pellets were stored on the trays in the pellet storage area until they were transferred to rod-loading operations.

Pelleting operations resulted in significant quantities of reusable scrap, namely green scrap from unacceptable pressings, reject sintered pellets (hard scrap), and sludge from the grinding operations. Green scrap was directly reusable and needed only to be reground to the proper particle size range. However, both hard scrap and wet sludge had to be treated by an in-line processing facility to oxidize the material to U_3O_8 powder. Both green scrap and U_3O_8 could be blended with virgin UO_2 in the powder preparation area, as noted, to obtain recycle material acceptable for pellet compaction.

Clinkers from the hard scrap oxidation step and contaminated scrap from the pelleting operations were not immediately reusable and were transferred out of the pelleting area to the scrap recovery operations.

A.4 FUEL-ROD FABRICATION

A flow diagram of the fuel-rod fabrication and inspection operation is given in Figure A-4. Pellets were loaded from the special trays into prepared metal tubes. Each rod was uniquely identified by serial number and enrichment. Rods were generally loaded and handled as lots on individual trays; rod lots were usually a standard size. Although odd-sized lots were encountered occasionally, as a rule the error in estimating the number of rods for an informal inventory by counting lot trays was small. After initial filling, the stack length of the pellets in each rod was adjusted to within tolerances by hand addition of one or more half-pellets specifically prepared for this purpose. Loaded rods were then plugged, welded, and sent to rod inspection. Each rod was examined for visual and dimensional defects. NDA techniques were used for verification of enrichment of all internal pellets, and fluoroscopic and X-ray techniques were used to examine the pellet stack for gaps or hang-ups and to examine weld integrities. Rods were then leak tested in a helium leak detector. Rods that passed all tests were placed in large metal channels for storage; each channel contained the exact number of rods to be loaded into a fuel assembly.

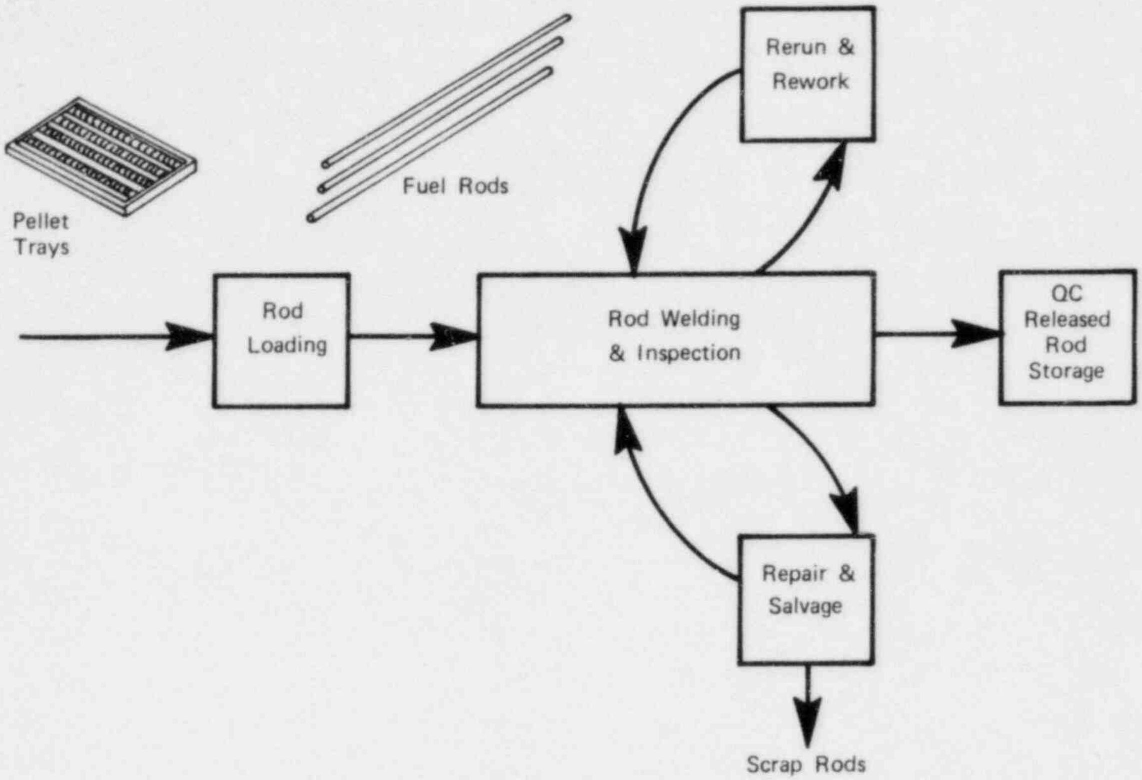

FIGURE A-4 - Flow diagram of fuel rod fabrication and inspection operations.

There were two different treatments of reject rods. Some rods were merely recycled through one or more of the inspections steps and could be accepted or rejected again; other rods were transferred to a rod repair and salvage station. Generally these latter rods were cut open, repaired, rewelded, and resubmitted to rod inspection. Occasionally, some of the reject rods were scrapped, and the pellets were sent to scrap processing for recovery.

Part of the rod storage area consisted of a "fuel rod archive." As a rule, several rods from every contract were placed into permanent storage in the archive. Only rarely were archive rods removed and opened for any reason; no removals from archives occurred during the study period.

A.5 FUEL ELEMENT ASSEMBLY

A flow diagram of the fuel element assembly operations is given in Figure A-5. QC released fuel rods in channels were transferred, as needed, to the element assembly area. The rods from each channel were stacked in a prescribed matrix to form a single fuel element. Usually, an additional channel of rods was retained in the assembly area to provide "filler" rods for all assemblies in a contract. This enabled the assemblers to replace any rod that could not, for any reason, be used in an assembly. Any reject rods from the assembly area were returned to the rod inspection area for recertification or repair. After completion of a contract, any unused rods in the filler channels were generally transferred to other contracts.

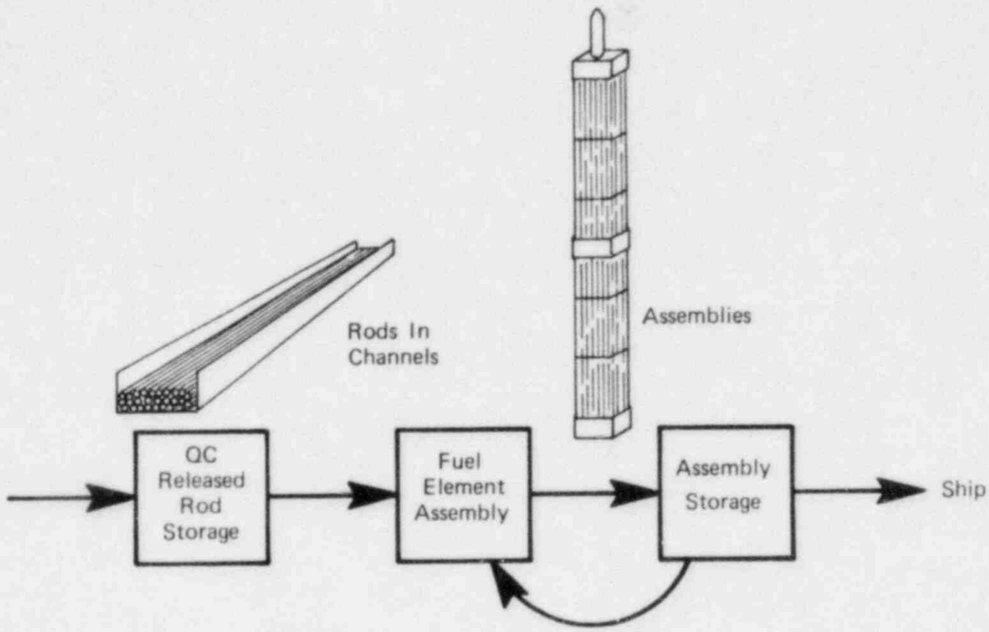

FIGURE A-5 - Flow diagram of fuel element assembly operations.

Once the rod matrix was loaded, nozzles and other hardware were welded in place, and the element was inspected, assigned a serial number, then weighed and placed in storage. QC-released assemblies would either be washed, packaged, and shipped, or they would be held in storage for indefinite time periods awaiting customer approval for shipment.

Since individual fuel rods were not weighed after fabrication, determination of the amount of UO_2 in a completed assembly was obtained by weighing the entire assembly. Records of the lot average weight of all the individual pieces of hardware that went into a given assembly were kept in computer files. After the assembly was completed, the cumulative hardware weight was subtracted from the gross weight of the assembly to obtain the net weight of UO_2.

Occasionally, it was necessary to disassemble a fuel element, either for repair or for salvage. The fuel rods from disassembled elements were removed intact and returned to the rod inspection area for recertification. Direct transfer of rods from the assembly area to the repair and salvage area was very rare.

A.6 SCRAP RECOVERY AND WASTE PROCESSING

A flow diagram of the scrap processing facility is given in Figure A-6.

There was a single scrap and waste processing area associated with all operations at the low-enrichment plant. All scrap materials not recycled within one of the production modules were sent to scrap processing for recovery or disposal. These materials included wet and dry ADU; green scrap; sintered or hard scrap and clinkers; green and sintered pellets; equipment cleanouts; ammonia solutions; liquid effluents from scrubbers and centrifuges; liquid waste from cleanout solutions; floor sweepings; mop water; uranium materials contaminated with grease, oil, or solvents; and general trash containing trace quantities of uranium.

Scrap processing operations could be divided into two categories, i.e., solid and liquid. Solids consisted of four basic types of material. These types included materials that could be converted to U_3O_8 and reblended for the pelleting operations without further purification (such as powders or pellets of known enrichment); materials that required dissolution and reprocessing to uranyl nitrate (UNH) for reintroduction to the conversion process; combustible wastes that were incinerated and the uranium recovered from the ash; and low level noncombustible wastes that were packaged and shipped for burial.

Liquid scrap and wastes from the conversion operations were passed through in-line scrubbers and filters to remove as much of the uranium as possible. However,

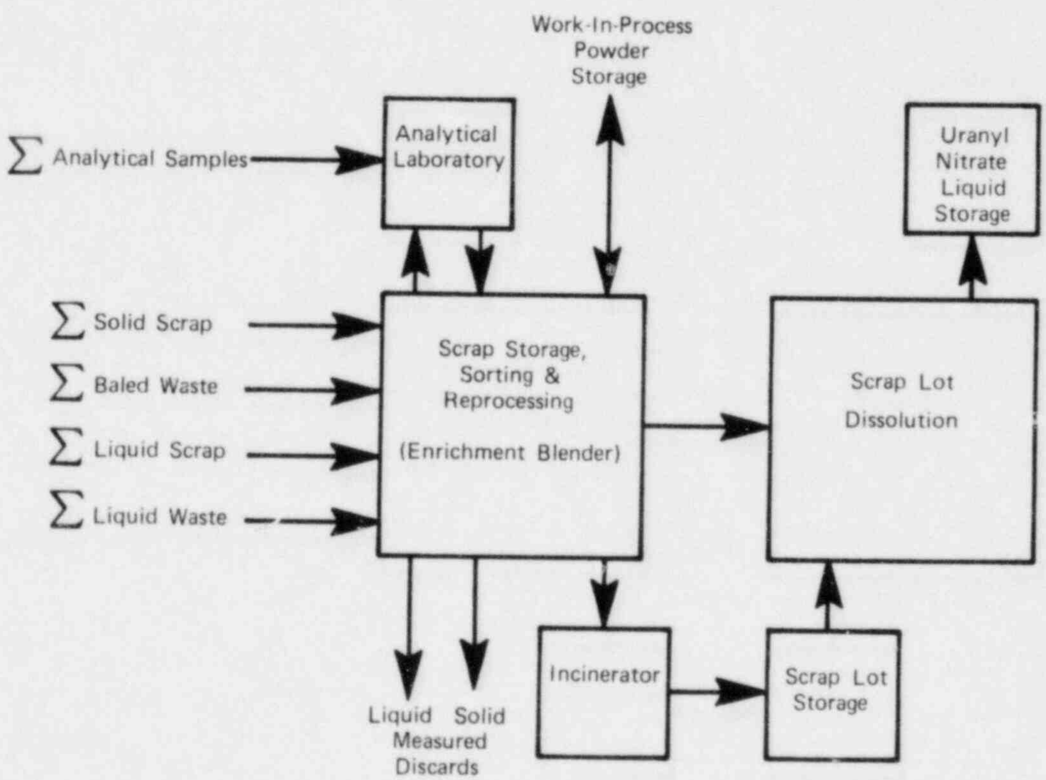

FIGURE A-6 - Flow diagram of scrap recovery and waste processing operations.

even with this pretreatment, there were still significant quantities of material remaining in suspension. The scrubbed liquids were pumped into a series of "quarantine tanks", flocculents were added, and the material was held sufficiently long for the suspended uranium to settle out. When the uranium concentration in the liquid was reduced below the permissible discard level, the water was pumped into a lagoon and eventually discarded. The quarantine tanks were shut down occasionally to recover the precipitated uranium.

There were two blending operations associated with the scrap recovery operations. Materials converted to usable U_3O_8 were frequently blended with other U_3O_8 to achieve homogeneity. These "subblends" were rarely used directly in the pelleting operation, but rather were mixed with virgin UO_2 in the pelleting powder preparation area prior to compaction. Other materials, particularly those of unknown or nonstandard enrichment, were occasionally blended with higher or lower enrichment material to achieve a desired intermediate enrichment. Enrichment material was blended in a twinshell blender in the scrap area. The licensee preferred to use only materials in which the isotopes were chemically homogeneous, so enrichment blends were almost always dissolved and converted to UNH for processing.

All materials shipped offsite, both liquid and solid, whether for disposal or for offsite recovery, were analyzed for uranium content, and the shipments were documented as transfers or measured discards.

Appendix B

Specific forms used for modeling and data acquisition

Table B-1 presents an outline of the information requested from the process engineers to enable Mound to construct the model of the low-enrichment process.

Table B-2 is a copy of the Process Operation Point data sheets used by the licensee to transfer model and flow information to Mound.

B.1 DATA COLLECTION

As was noted in Chapter 4, the process was first divided into 98 control units with closure equations. Measurement node identification for these equations was transmitted to the licensee to allow him to set up a system to recover the information from historical files for one year of operation. This period, it was felt, would provide a good test; the time would cover two physical inventory periods, and there were only minor process changes during the period.

The licensee was asked four questions concerning the data for each of the 400+ measurement nodes:

1. Were the data recorded?

2. How frequently were the measurements taken?

3. Were the data retained?

4. Were the retained data readily available?

The same questions were applied to informal inventories in the 98 control units.

B.2 REVISIONS TO THE PROGRAM

A review of the data requested by Mound revealed that a sizable fraction of the data requested were taken for the benefit of line operators and were not normally stored in the licensee's computer system. Also, many of the data entries were retained for only a short time and discarded; other data were retained but not computerized, so that retrieval would require a hands-on file search through document archives; and still other data were stored on computer, but were subject to periodic updating so the original data were no longer available.

Consequently, the scope of the data collection phase of the project was changed to utilize specific data from an upcoming six-month inventory period. This change necessitated the restructuring of the control unit configuration to be supportable by the data that would be available. With these modifications, the number of control units was reduced to 37, as was noted in Chapter 5.

Ideally, with a project of this magnitude, all input data forms should be designed to facilitate computer entry of all recorded data. Accomplishment of this in a large-scale production plant without disturbing production schedules is not a trivial task. Forms must be designed and prepared, operating personnel must be trained to fill out the forms properly, a system must be set up to ensure that all forms are correctly filled out and are collected on time, and the system must be tested to ensure that there are no compromises of product quality or material control. Because it was necessary to maintain a minimum impact of this study on the licensee's production schedules, none of these procedures could be implemented in the time available. Consequently direct copies of data sheets, computer printouts, etc. were employed.

Many of the data entry forms and keyboard entry sheets received from the licensee did not give data in a format suitable for computerization at Mound. Because there were still questions about the utility of some of the data requested, it was decided that Mound would accept all data in the form normally recorded by the licensee. With the exception of card decks of the bracketing formal inventories which were already in a compatible format, these data would then be formatted and encoded on magnetic tape to facilitate computerization. The types and quantities of forms received in support of this project are listed in Table B-3.

A summary of the number of forms received and encoded is given in Table B-4.

TABLE B-1

OUTLINE OF INFORMATION REQUIRED FOR EACH OPERATING PROCESS MODULE

A. Operating Schedules

   1. Production cycles

      a. Various operational modes
      b. Number of shifts per day and number of days per week
      c. Average fraction of downtime

   2. Runout cycles

      a. Frequency
      b. Average holdup after runout

   3. Cleanout cycles

      a. Different cleanout modes
      b. Frequency
      c. Average holdup after each cleanout

   4. Scheduled downtimes

      a. Weekends
      b. Holidays
      c. Physical Inventories

B. Flow Diagram of Each Production Cycle

   1. Including all significant steps, flow pathways, analytical samples taken, measurements made

   2. Including all scrap, waste, recycle, material rejection, recovery, etc.

C. Process Description - A running account of the process and flow streams that describes the operation of each module from a material control viewpoint.

D. Chemical and Physical Forms for Each Step in the Flow Streams.

E. Units of Flow For Each Stream - e.g., kilograms, liters, batches, cylinders, powder packs.

TABLE B-1
(continued)

F. Estimated Material Balances for Each Step in the Flow Diagram for the Entire Inventory Period.

1. Identify each operational mode.
2. Estimate typical inputs and outputs for each step.

G. Estimated Typical Amount of In-process Material for Each Step in the Flow Diagram.

1. Estimated for each operational mode.
2. Including connecting pipelines.

H. Estimated Holdup for Each Step in the Flow Diagram.

1. Maximum (before cleanout)
2. Removable holdup (removed during cleanout)
3. Residual holdup (remaining after cleanout)

I. Analytical Samples Withdrawn

1. Location of sampling ports on the flow diagram
2. Type of analysis performed at each point
3. Sampling schedule
4. Amount of material removed
5. Analytical turnaround time
6. Identification of QC hold stations awaiting analysis
7. Measurement control system

    a. Analytical random and systematic errors
    b. Sampling random and systematic errors
    c. Frequency and replication of calibrations
    d. Standards used with stated uncertainties

J. In-Line Measurement

1. Location of measurement points on the flow diagram
2. Type of analysis performed at each point
3. Frequency
4. Type of measurement (i.e., full stream or selected samples)
5. Typical gross and tare of weight measurements
6. Measurement control system (same as I-7 above)

K. Unscheduled Downtime

1. Fraction of time for each step in the flow diagram
2. Frequency of malfunction and average repair time

L. Equipment Capacities

1. Maximum and operating capacities of each major piece of equipment.

2. Maximum and operating capacities of each storage area.

M. Maximum and Normal Flow Rates Through Each Flow Stream During Operation.

TABLE B-2

PROCESS OPERATION POINT DATA SHEET

SHEET 1 OF 2
PAGE ______

OPERATING MODE: ______

EQUIPMENT OR OPERATION: ______

IDENTIFICATION: ______

A. OPERATING SCHEDULE:

PRODUCTION: ______ ______

RUNOUT: ______ ______

CLEANOUT: ______ ______

DOWN FOR INVENTORY: ______

HOLIDAYS: ______

OTHER: ______

D. CHEMICAL AND PHYSICAL FORMS: ______

E. UNITS OF FLOW: ______

F. MATERIAL BALANCE:

INPUT: ______

______

______

______

OUTPUT: ______

______

______

TABLE B-2
(continued)

PROCESS OPERATION POINT DATA SHEET

SHEET 2 OF 2
PAGE ______

G. MATERIAL IN PIPELINE: ______

H. HOLDUP:

MAXIMUM: ______

REMOVABLE: ______

RESIDUAL: ______

K. DOWNTIME:

FRACTION OF TIME AVAILABLE: ______

FREQUENCY OF MALFUNCTION: ______

AVERAGE REPAIR TIME: ______

L. EQUIPMENT CAPACITY:

EQUIPMENT: MAXIMUM: ______

OPERATING: ______

STORAGE AREA: MAXIMUM: ______

OPERATING: ______

M. NORMAL FLOW RATE: ______

TABLE B-3

LIST OF DOCUMENTS KEY ENCODED FOR CUA

Mound File #	File Function	Form Title	No. Of Pages	No. Of Records Encoded
General				
RD	Material Receipts & Ship's	Nuclear Material Transfer Form	1,050	6,000
P7	Internal Material Movements	Production Control Tickets	2,450	2,450
Conversion				
C1	UF_6 Cylinder - Full Load	UF_6 Cylinder Status Record	20	430
C2	UF_6 Cylinder - Heel Load	UF_6 Cylinder Heel Record	20	320
C3	UNH Mode Input	UNH Drum Usage Record	210	3,000
C4	All Conversion and Blender Transactions	Computer Printout Conversion Operations	2,100	105,000
C7	UF_6 Cylinder Identification	Conversion Line Daily Status	100	300
C9	UF_6 Cylinder Identification	UF_6 Cylinder Use Record	450	On Hold
CF	UF_6 Full Cylinder Pad Inv.	UF_6 Cylinder Status Record	200	200
CH	UF_6 Heel Pad Inventory	UF_6 Heel Record	200	200
CS	Conversion Line Closure Schedule	UF_6 Cylinder Use Record Conversion Line Daily Operations Summary and Conversion Line Daily Status	15	400
Pelleting				
P1	Sintering Furnace Material Movements	Sintering Furnace Logs	1,500	On Hold
P2	Sintering Furnace Material Movements	Pellet Density Logs	1,500	22,500
P3	Pelleting Operations	Detail of Pelleting Form	500	4,000
P9	UO_2 Blend Summary	Derived from Conversion Operations Printout, Analysis Request, and Detail of Pelleting Form		

TABLE B-3

LIST OF DOCUMENTS KEY ENCODED FOR CUA
(continued)

Mound File #	File Function	Form Title	No. Of Pages	No. Of Records Encoded
Rod Fabrication and Element Assembly				
R2	Rod Loading & Welding, QC Rel.	Rod Traceability Document (Card 2)	10,000	20,000
R3	Rod Rerun, Repair, QC Rel.	Rod Traceability Document (Cards 3 and 3A)	2,000	4,000
R4	Rod In-process Inventories	Detail of Rod Area	100	200
R7	Rod Side Streams	Archive & Computer Pull Lists	65	260
RA	Rod Repair Inventory	Rod Repair Status	40	280
R3	Rod Scrap Schedule	Rod Traceability Document (Card 3, Scrap)	40	100
RB	Element Assembly Schedule	Fuel Assembly Build Schedule and Fuel Assembly Cycle Control	240	2,400
RF	Transfer of Rods to Element Assembly	Uranium Inventory Control Log	50	1,000
Scrap Processing and Recovery				
S1	Scrap Inventories	Scrap Status Reports	20	80
S2	Liquid and Solid Waste Disposal	Nuclear Material Transfer Summary (Measured Discards)	20	250
S3	Incinerator Ash Into Scrap Storage	Analytical Chem. Request (Incinerator Ash)	100	100
S4	Off-Site UNH Analysis	UNH Drum Analytical Request	100	100
	In-house UNH Analyses	UNH Tank Analysis	15	15
Analytical Laboratory				
A1	Analytical Sample Input	Analytical Sample Log Book	100	On Hold

TABLE B-4

DATA COLLECTION AND ENCODING SUMMARY

No. of Form Types	25
No. of Pages Encoded	21,650
No. of Encoded Records	173,400
Est. No. of Encoded Data Points	1,700,000

Appendix C

Computerization of data

To handle the large quantity and variety of data expected and to provide for maximum versatility in selection of data from a variety of files, Mound employed the Statistical Analytical System (SAS)* in conjunction with an in-house IBM 360/65 computer.

In order to utilize the data received, it was necessary to store the information in file formats that would permit correlation of each datum with a specific measurement node in the process. Furthermore, it was necessary that data be identifiable as to appropriate date and time of movement or at least be assignable to some specified time period. Also, because of independent parallel process modules at several points in the plant, data applicable to nodes in these parallel processes must be identifiable as to their proper lines.

A representative flow diagram showing the steps that were followed for data encodment, verification, sorting, and creation of transaction files is given in Figure C-1.

*SAS is a software package available from the SAS Institute, P. O. Box 10066, Raleigh, N.C. 27065, for use with IBM 360 and 370 series computers. The package included capabilities for information storage and retrieval, data modification and programming, statistical analysis, file handling, and report writing.

Each form was screened and formatted in such a manner so that only the pertinent information was encoded. This type of information included the types of material, identification numbers, quantities and purities involved, the types of transactions, plant locations (including line numbers where needed), dates and times of transactions, contract numbers, and enrichments.

The specific data were entered as 80-character alphanumeric records on a series of primary magnetic tapes. These tapes were the main source of all subsequently compiled data files. After encoding, the original data sheets were filed in a manner which facilitated retrieval of any specific form so that suspected transcription errors could be rectified. Since many of the forms were reproductions of handwritten entries, and since some of the licensee's computer printouts contained duplicate entries, screening and data verification programs were developed to identify and rectify errors on data tapes. Each file was scanned for known types of errors, duplicates, and/or superfluous information. Errors on original data sheets were corrected only if the errors were obvious and the correct values were equally obvious (e.g., an item serial number with transposed digits with the correct number verifiable elsewhere). The errors were amended, and corrected files were restructured on another tape. In this manner, original data tapes were kept intact (mistakes and all) to provide an absolute backup for the data system.

In cases where individual files were spread over two or more tapes, the edited files were merged to identify discrepancies or

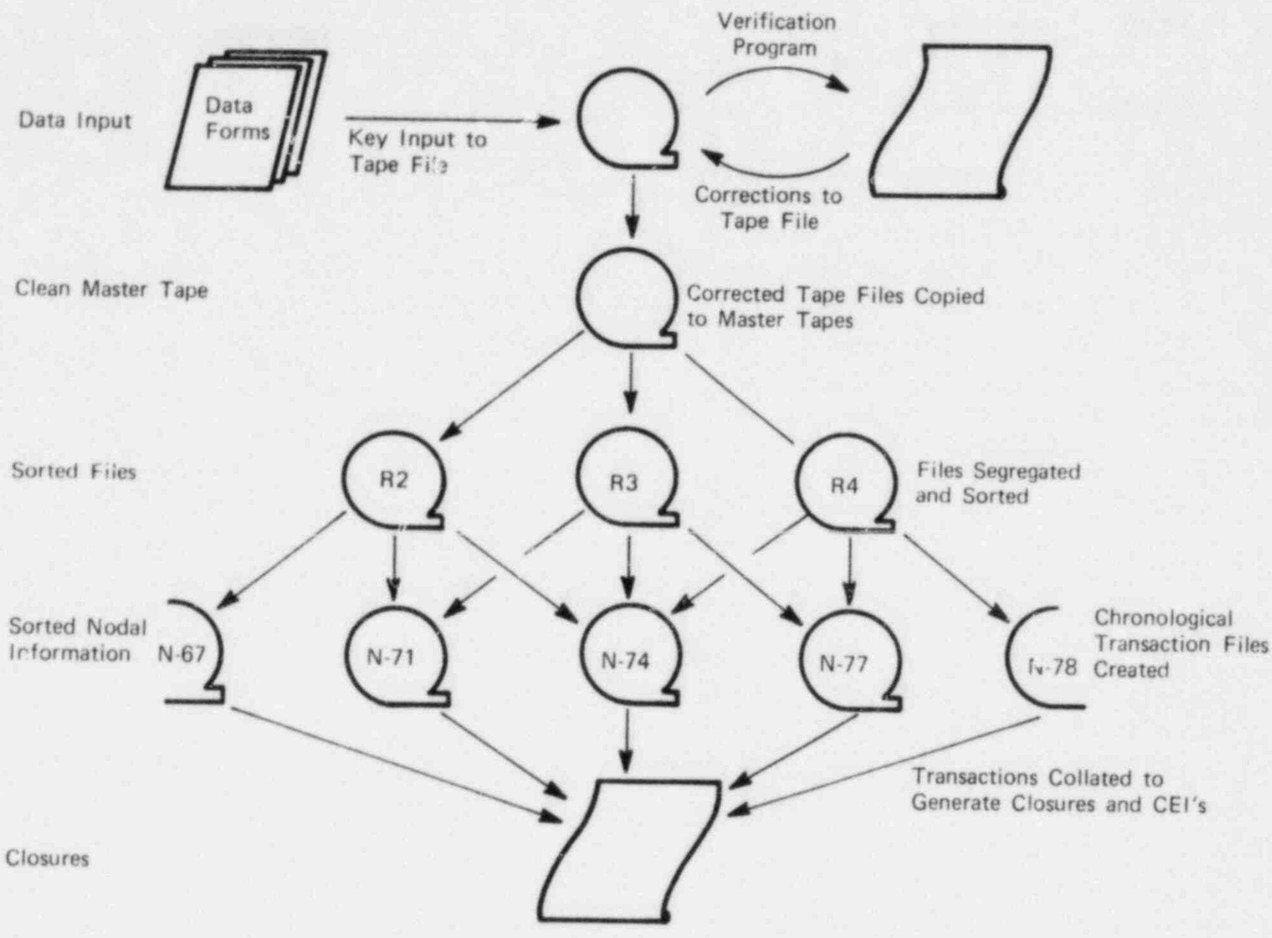

FIGURE C-1 - Scheme for generation of equation closures from process data sheets.

duplications that cross tape boundaries. Edited tapes were modified as many times as necessary to obtain valid data files, and backup copies of edited files were retained.

Edited tapes were then merged into two types of files, "transaction" files and "inventory" files. The transaction files, which contain all data pertaining to material movement through each measurement node in the process, were compiled in chronological order for the specific nodes. The inventory files, which contain all periodical inventory information (including the two plant-wide physical inventories) and material status information (determined by in-process measurements or by predictors), were compiled in chronological order for each control unit in the plant.

The final step in the program was to compute closures for each equation. This was done by summing the beginning inventory (and/or material status) with all transactions occurring within a closure period for each node comprising a given equation. These summations were used to calculate in-process inventories of material in each control unit at the closure times. The calculated inventories were compared to measured or predicted ending inventories, and the magnitude of the differences between calculated and measured (or predicted) inventories was the closure equation imbalance (cei's). A comparison of cei's with cei standard deviations would indicate, at some confidence level, whether specific outliers were the result of a probable variation of the measurement system or were an indicator of unidentified material movement or incorrect data.

Appendix D

Variability tables for low-enrichment plant model

This appendix includes variability tables for every generic closure equation derived from the model of the low-enrichment plant. Flow and inventory error components of each closure equation are listed along with the total propagated error. The total errors do not include uranium-235 error information since these components were calculated only for the six-month long-term equation.

Table D-1 represents equations in the conversion and blender areas; Table D-2 represents the pelleting area equations; Tables D-3 and D-4 represent the equations in the fuel-rod-fabrication and element-assembly areas; and Table D-5 represents the scrap recovery operations, the UNH receipt and storage area, and the long-term six-month plant-wide closure equation.

TABLE D-1

Closure Equation Variabilities in the Conversion Area

Absolute Error Components - Normalized Units

Equation & Control Unit		Bulk		Uranium		Predictor		Total Error Normalized Units
		Random	System	Random	System	Random	System	
UF_6 Cylinder Storage (CU-1)	Flows	-0-	-0-	-0-	-0-	-0-	-0-	-0-
	Inventory	-0-	-0-	-0-	-0-	-0-	-0-	
Conversion, UF_6 Mode (CU-4a)	Flows	0.80	0.25	0.57	0.27	6.35	-0-	45.57
	Inventory	-0-	-0-	-0-	-0-	45.12	-0-	
Conversion, Recycle Mode (CU-4b)	Flows	0.03	0.18	-0-	-0-	11.33	-0-	45.80
	Inventory	-0-	-0-	-0-	-0-	44.38	-0-	
Conversion, UNH Mode (CU-4c)	Flows	0.03	0.20	-0-	-0-	8.16	-0-	44.93
	Inventory	-0-	-0-	-0-	-0-	44.09	-0-	
Line & Floor Storage (CU-6)	Flows	0.10	0.03	-0-	-0-	9.57	-0-	14.92
	Inventory	0.09	0.04	11.46	0.01	-0-	-0-	
Conv. Product Storage (CU-8)	Flows	1.15	0.52	0.81	0.21	-0-	-0-	5.23
	Inventory	-0-	-0-	-0-	-0-	5.01	-0-	

TABLE D-1
(Continued)

Closure Equation Variabilities in the Conversion Area

Equation & Control Unit		Absolute Error Components - Normalized Units						Total Error Normalized Units
		Bulk		Uranium		Predictor		
		Random	System	Random	System	Random	System	
Blender (CU-9)	Flows	0.31	0.27	0.16	-0-	4.21	-0-	4.41
	Inventory	-0-	-0-	-0-	-0-	1.24	-0-	
Blender OC Storage (CU-11)	Flows	0.90	0.07	0.45	0.03	-0-	-0-	1.01
	Inventory	-0-	-0-	-0-	-0-	-0-	-0-	

TABLE D-2

Closure Equation Variabilities in the Pelleting Area

Equation & Control Unit		Absolute Error Components - Normalized Units						Total Error Normalized Units
		Bulk		Uranium		Predictor		
		Random	System	Random	System	Random	System	
Pelleting (CU-13)	Flows	0.25	0.17	0.28	0.09	8.12	-0-	34.42
	Inventory	-0-	-0-	-0-	-0-	33.45	-0-	
Pellet Tray Storage (CU-18)	Flows	-0-	-0-	0.04	0.24	0.10	1.67	6.47
	Inventory	-0-	-0-	-0-	-0-	0.28	6.24	

TABLE D-3

Closure Equation Variabilities in the Fuel Rod Fabrication Area

Equation & Control Unit		Absolute Error Components - Normalized Units: Bulk Random	Bulk System	Uranium Random	Uranium System	Predictor Random	Predictor System	Total Error Normalized Units
Rod Load & Weld (CU-20)	Flows	.01	-0-	-0-	-0-	0.14	1.13	10.30
	Inventory	-0-	-0-	-0-	-0-	10.23	-0-	
Rod QC Inspection (CU-22)	Flows	0.06	-0-	-0-	-0-	0.25	-0-	0.36 <1 Rod
	Inventory	0.12	-0-	-0-	-0-	0.23	-0-	
Rod QC Storage (CU-23)	Flows	-0-	-0-	-0-	-0-	-0-	-0-	0.29 <1 Rod
	Inventory	-0-	-0-	-0-	-0-	0.29	-0-	
Rod Repair & Salvage (CU-28)	Flows	-0-	-0-	-0-	-0-	0.15	-0-	15.85
	Inventory	15.85	-0-	-0-	-0-	0.20	-0-	
Rod Archives (CU-27)	Flows	-0-	-0-	-0-	-0-	0.03	-0-	0.03 <1 Rod
	Inventory	-0-	-0-	-0-	-0-	-0-	-0-	

TABLE D-4

Closure Equation Variabilities in the Fuel Element Assembly Area

Equation & Control Unit		Absolute Error Components - Normalized Units: Bulk Random	Bulk System	Uranium Random	Uranium System	Predictor Random	Predictor System	Total Error Normalized Units
Element Ass'y & Inspection (CU-24)	Flows	-0-	-0-	-0-	-0-	-0-	-0-	0.29 <1 Rod
	Inventory	-0-	-0-	-0-	-0-	0.29	-0-	
Element QC Storage & Ship (CU-25)	Flows	0.24	0.64	0.74	8.51	0.08	-0-	8.65[a] <1 Ass'y
	Inventory	-0-	-0-	-0-	-0-	-0-	-0-	

[a] This error is not normally observed since it is completely correlated with inputs and outputs to the control unit.

TABLE D-5

Closure Equation Variabilities for the Scrap Area and Miscellaneous

Equation & Control Unit		Absolute Error Components - Normalized Units: Bulk Random	Bulk System	Uranium Random	Uranium System	Predictor Random	Predictor System	Total Error Normalized Units
Scrap & Waste Processing (CU-29)	Flows	2.06	7.82	222.63	6.15	280.12	-0-	585.32
	Inventory	26.66	146.97	437.90	19.68	-0-	-0-	
UNH Drum Storage (CU-3)	Flows	-0-	.01	.01	-0-	.01	-0-	1.15
	Inventory	0.08	0.28	1.11	0.02	-0-	-0-	
6-Month Plant-Wide Closure	Flows	14.81	68.34	69.52	73.58	-0-	-0-	1048[a]
	Inventory	179.18	381.86	863.75	400.33	-0-	0.25	

[a]Normalizing base, Plant LEID = 1000 Normalized Units for the inventory period.

Appendix E

Summary of closure equation information

A list of closure equations for the low enrichment uranium fuel plant is given in Table E-1; the plant-wide closure equation network is shown in Figure E-1. Block diagrams of the individual control units are given in Figures E-2 through E-6. Details of the measurement nodes, types of measurement used, uranium variabilities, and mathematical listings of each closure equation are given in Tables E-2 through E-6. A summary of the long-term (six-month) plant-wide closure equation is given in Table E-7.

TABLE E-1

LIST OF CLOSURE EQUATIONS FOR LOW-ENRICHMENT PLANT

		# of Equations
Conversion		
S-1.	UF_6 Cylinder Storage	1
S-4a.	Conversion - UF_6 Mode	
S-4b.	Conversion - Recycle Mode	> 1
S-4c.	Conversion - UNH Mode	
S-6.	Off-stream Line & Floor Storage	>1
S-8.	Product Storage	>1
S-9.	Blender	1
S-11.	Product Powder QC Storage	1
Pelleting		
S-13.	Pellet Preparation	> 1
S-18.	Pellet Tray Storage	> 1
Fuel Rod Fabrication		
S-20.	Rod Loading	1
S-22.	Rod Welding, QC Inspection, and Rerun & Rework	1
S-23.	Rod QC Storage	1
S-27.	Rod Archives	1
S-28.	Rod Repair & Salvage	1
Fuel Element Assembly		
S-24.	Fuel Element Assembly and QC Inspection	1
S-25.	Fuel Element Storage and Shipment	1
Scrap and Waste Treatment		
S-29.	Scrap and Waste Processing, Analytical and Health Physics Labs, & UNH Receipt and Storage	1
L-1.	Plant-Wide Six-Month Inventory Period	1

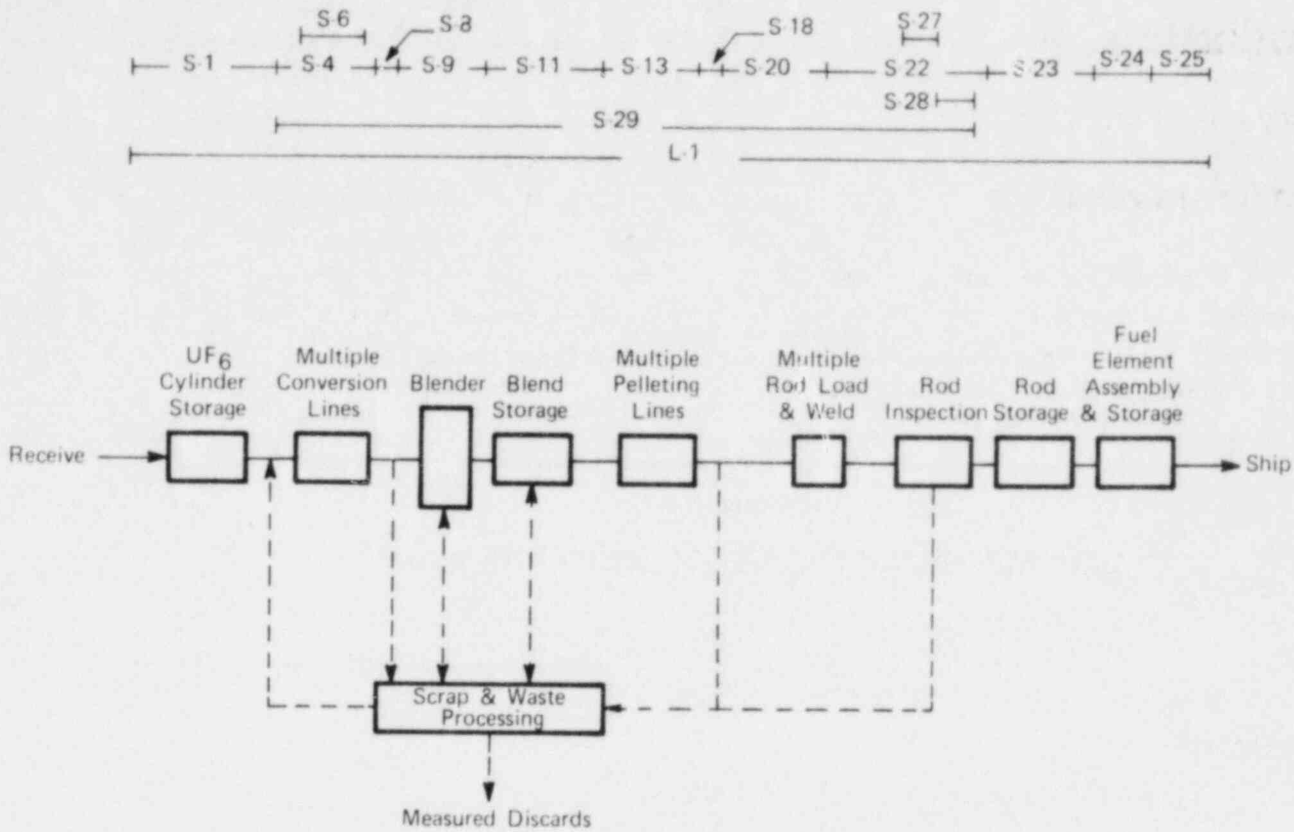

FIGURE E-1 - Process flow diagram showing plant-wide closure equations.

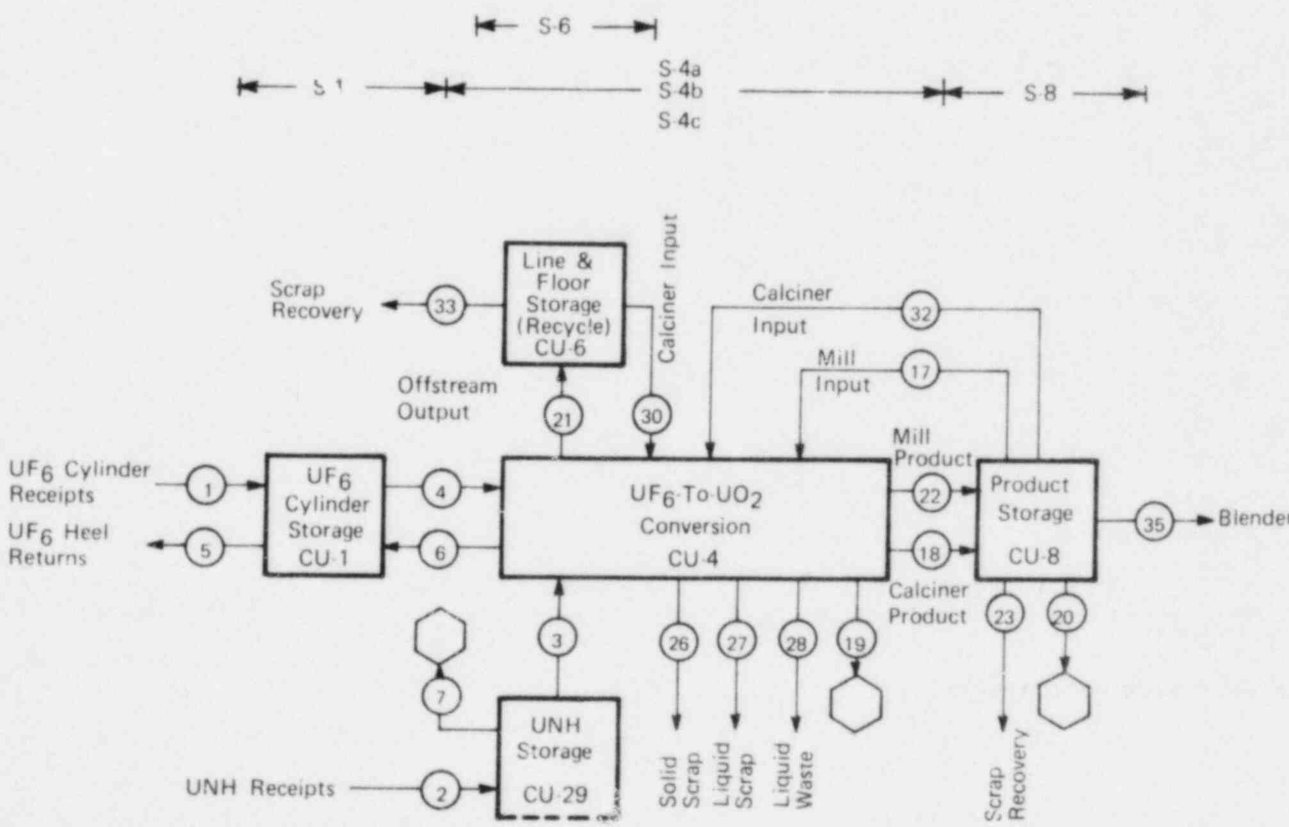

FIGURE E-2 - Control units and closure equations for each conversion line.

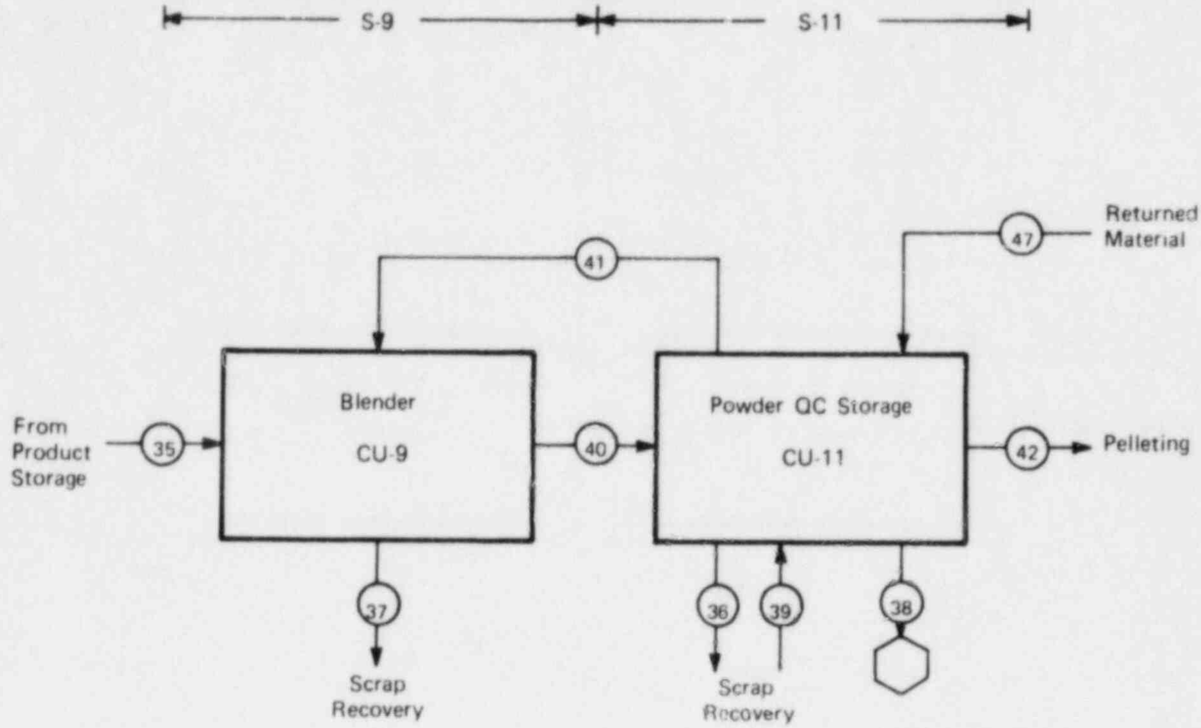

FIGURE E-3 - Control units and closure equations for blender, powder QC storage, and experimental conversion process.

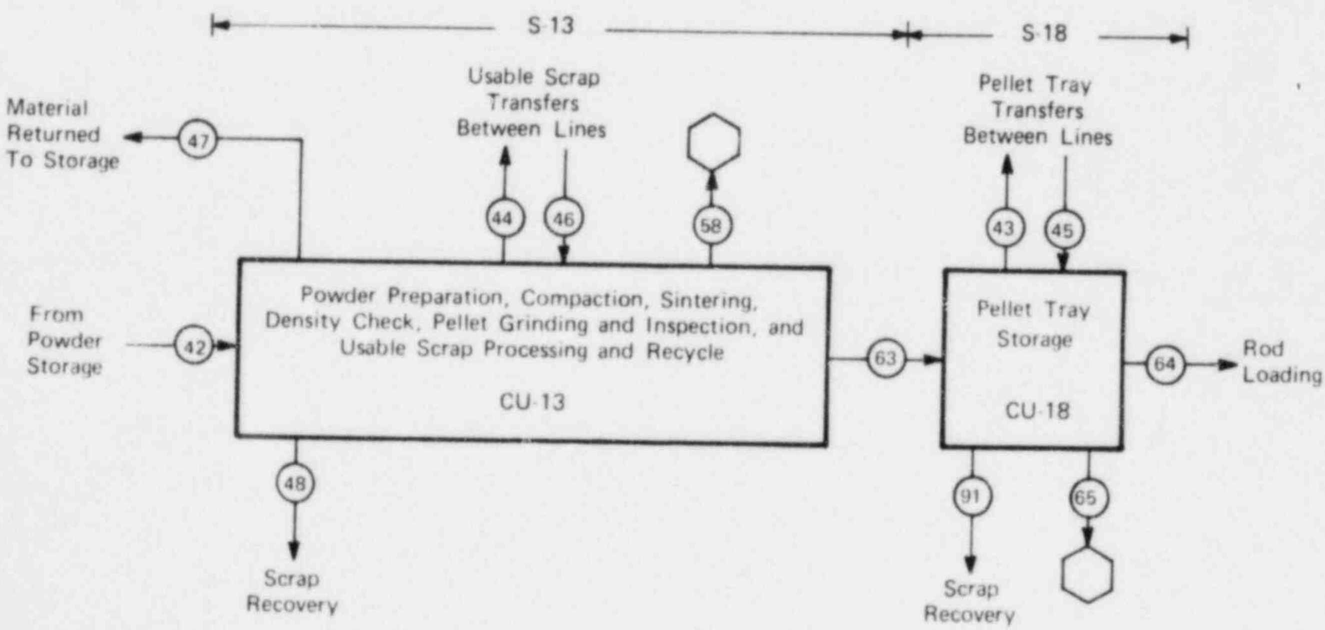

FIGURE E-4 - Control units and closure equations for pelleting lines.

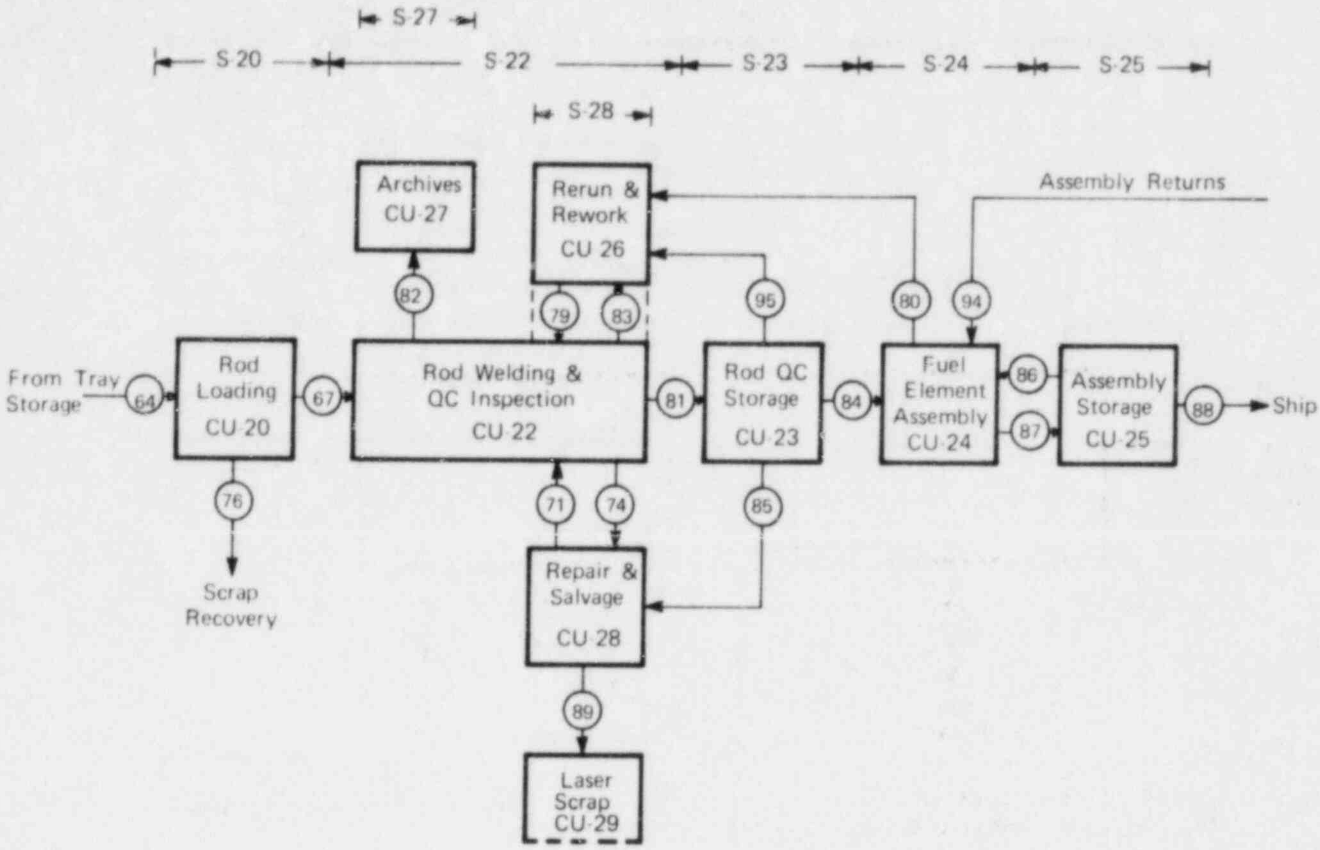

FIGURE E-5 - Control units and closure equations for rod fabrication and element assembly.

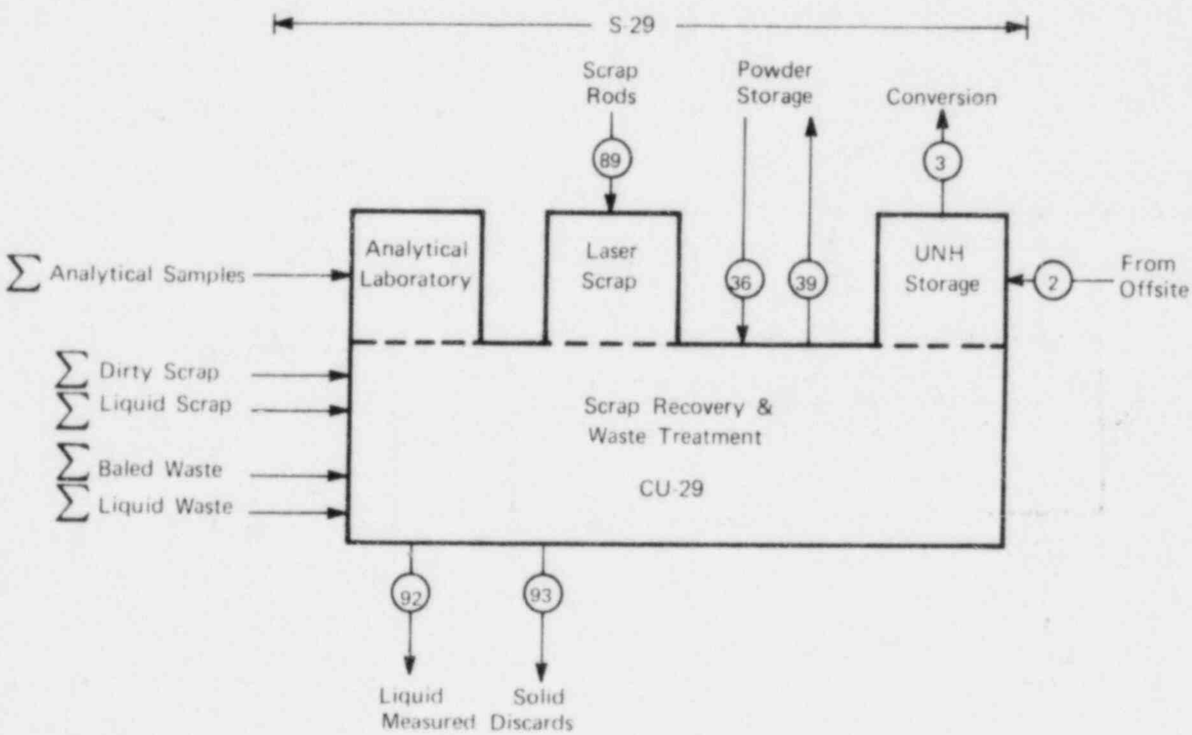

FIGURE E-6 - Control unit and closure equation for scrap recovery and waste processing facility.

TABLE E-2

CLOSURE EQUATIONS FOR CONVERSION LINES

Equation #	Description	Control Unit	Variability Normalized Units
S-1	UF_6 Cylinder Storage	CU-1	-0-

Node #	Measurement Type
1	ID #, Wt
4	ID #
5	ID #
6	ID #, Wt

$$cei = \sum(1) + \sum(6) - \sum(4) - \sum(5) - \Delta H\ (CU\text{-}1)$$

Equation #	Description	Control Unit	Variability Normalized Units
S-4a	Conversion, UF_6 Mode	CU-4	45.59
S-4b	Conversion, Recycle Mode		45.82
S-4c	Conversion, UNH Mode		44.94

Node #	Measurement Type
3	Est. Wt.
4	ID #
6	ID #, Wt.
17	ID #, Est. Wt.
18	ID #, Wt.
19	Wt.
21	ID #
22	ID #, Wt.
26, 27, 28	Estimators
30	ID #, Est. Wt.[a]
32	ID #, Est. Wt.[a]

$$\begin{aligned} cei = {} & \sum(3) + \sum(4) + \sum(17) + \sum(30) + \sum(32) \\ & - \sum(6) - \sum(18) - \sum(19) - \sum(21) - \sum(22) \\ & - \sum(26) - \sum(27) - \sum(28) - \Delta H\ (CU\text{-}4) \end{aligned}$$

[a] Inventory Work-off

TABLE E-2

CLOSURE EQUATIONS FOR CONVERSION LINES
(continued)

Equation #	Description	Control Unit	Variability Normalized Units
S-6	Line and Floor Storage	CU-1	-0-

Node #	Measurement Type
21	ID #, Wt.
30,	ID #, Est. Wt.[a]
33	Wt.

$$cei = \sum(21) - \sum(30) - \sum(33) - \Delta H\ (CU-6)$$

Equation #	Description	Control Unit	Variability Normalized Units
S-8	Conversion Product Storage	CU-8	5.23

Node #	Measurement Type
17	ID #
18	ID #, Wt.
20	WT.
22	ID #, Wt.
23	Wt.
32	ID #
35	ID #

$$cei = \sum(18) + \sum(22) - \sum(17) - \sum(20) - \sum(23) - \sum(32) - \sum(35) - \Delta H\ (CU-8)$$

[a]Inventory Work-Off

TABLE E-3

CLOSURE EQUATIONS FOR BLENDER AND POWDER QC STORAGE

Equation #	Description	Control Unit	Variability Normalized Units
S-9	Blender	CU-9	4.42

Node #	Measurement Type
35	ID #
37	Wt
40	ID #, Wt.
41	ID #

$$cei = \sum(35) + \sum(41) - \sum(37) - \sum(40) - \Delta H\ (CU\text{-}9)$$

Equation #	Description	Control Unit	Variability Normalized Units
S-11	Powder QC Storage	CU-11	1.01

Node #	Measurement Type
36	Wt.
38	Wt.
39	Wt.
40	Blend ID #, Avg. Wt.
41	Blend ID #, Avg. Wt.
47	Blend ID #, Avg. Wt.

$$cei = \sum(39) + \sum(40) + \sum(47) - \sum(36) - \sum(38) - \sum(41) - \sum(42) - \Delta H\ (CU\text{-}11)$$

TABLE E-4

CLOSURE EQUATIONS FOR PELLETING LINES

Equation #	Description	Control Unit	Variability Normalized Units
S-13	Pellet Preparation	CU-13	34.44

Node #	Measurement Type
42	ID
44	Wt.
46	Wt.
47	Wt.
48	Wt.
58	Wt.
63	Count, Avg. Wt.

$$\text{cei} = \sum(42) + \sum(46) - \sum(44) - \sum(47) - \sum(48) - \sum(58) - \sum(63) - \Delta R\ (\text{CU-13})$$

Equation #	Description	Control Unit	Variability Normalized Units
S-18	Pellet Tray Storage	CU-18	6.47

Node #	Measurement Type
43	Count
45	Count
63	Count
64	Count
65	Wt.
91	Wt.

$$\text{cei} = \sum(45) + \sum(63) - \sum(43) - \sum(64) - \sum(65) - \sum(91) - \Delta R\ (\text{CU-18})$$

TABLE E-5

CLOSURE EQUATIONS FOR FUEL ROD FABRICATION AND ELEMENT ASSEMBLY

Equation #	Description	Control Unit	Variability Normalized Units
S-20	Rod Loading	CU-20	10.3

Node #	Measurement Type
64	Tray Count
67	Rod Count
76	Wt.

$$cei = \sum(64) - \sum(67) - \sum(76) - \Delta H\ (CU\text{-}20)$$

Equation #	Description	Control Unit	Variability Normalized Units
S-22	Rod Welding, Inspection & R&R	CU-22 CU-26	1 rod

Node #	Measurement Type
67	Rod Count
71	Rod Count
74	Rod Count
80	Rod Count
81	Rod Count
82	Rod Count
95	Rod Count

$$cei = \sum(67) + \sum(71) + \sum(80) + \sum(95) - \sum(74) - \sum(82) - \sum(81) - \Delta H\ (CU\text{-}22,26)$$

Equation #	Description	Control Unit	Variability Normalized Units
S-23	Rod QC Storage	CU-23	1 rod

Node #	Measurement Type
81	Rod Count
84	Rod Count
85	Rod Count
95	Rod Count

$$cei = \sum(81) - \sum(84) - \sum(85) - \sum(95) - \Delta H\ (CU\text{-}23)$$

TABLE E-5

CLOSURE EQUATIONS FOR FUEL ROD FABRICATION AND ELEMENT ASSEMBLY (continued)

Equation #	Description	Control Unit	Variability Normalized Units
S-27	Rod Archives	CU-27	1 rod

Node #	Measurement Type
#82	Rod Count

$$cei = \sum(82) - \Delta H\ (CU\text{-}27)$$

Equation #	Description	Control Unit	Variability Normalized Units
S-28	Rod Repair and Salvage	CU-28	15.86

Node #	Measurement Type
71	Rod Count
74	Rod Count
85	Rod Count
89	Scrap Weight

$$cei = \sum(74) + \sum(85) - \sum(71) - \sum(89) - \Delta H\ (CU\text{-}28)$$

Equation #	Description	Control Unit	Variability Normalized Units
S-24	Element Assembly & Inspection	CU-24	1 rod

Node #	Measurement Type
80	Rod Count
84	Rod Count
86	Ass'y Count
87	Ass'y Count
94	Ass'y Count

$$cei = \sum(84) + \sum(86) + \sum(94) - \sum(80) - \sum(87) - \Delta H\ (CU\text{-}24)$$

Equation #	Description	Control Unit	Variability Normalized Units
S-25	Element Storage & Shipment	CU-25	10 rods

Node #	Measurement Type
86	Ass'y Count
87	Ass'y Count
88	Ass'y Count, Wt.

$$cei = \sum(87) - \sum(86) - \sum(88) - \Delta H\ (CU\text{-}25)$$

TABLE E-6

CLOSURE EQUATION FOR SCRAP RECOVERY AND WASTE PROCESSING FACILITY

Equation #	Description	Control Unit	Variability Normalized Units
S-29	Scrap Recovery	CU-29	585.6

Type	Node #	Measurement Type	
Analytical Samples	19	Wt.	
	20	Wt.	
	38	Wt.	
	58	Wt.	
	65	Wt.	
UNH Off-Site	2	Wt., Analy	1.22
Dirty Scrap Solid	23	Wt.	
	26	Wt.	
	33	Wt.	
	36	Wt.	
	37	Wt.	
	48	Wt.	
	76	Wt.	
	89	Rod Count	
	91	Wt.	
Liquid Scrap	27	Estimated	
Liquid Waste	28	Estimated	
Baled Waste	(Gen)	Estimated	
Effluents	3	Drum Ct., Analy., Est. Wt.	
	39	Wt., Analy	
	92	-Scan, Con'c	
	93	-Scan, Wt.	

$$\text{cei} = \sum(2) + \sum(19) + \sum(20) + \sum(23) + \sum(27) + \sum(28) + \sum(33) + \sum(36) + \sum(38) + \sum(48) + \sum(58) + \sum(65) + \sum(89) + \sum(91) + \sum(\text{Gen}) - \sum(3) - \sum(39) - \sum(92) - \sum(93) - \Delta H\ (\text{CU-29})$$

TABLE E-7

LONG TERM EQUATION FOR SIX-MONTH PLANT-WIDE CLOSURE

Equation #	Description	Control Unit	Variability Normalized Units
L-1	Plant-Wide Inventory-to-Inventory	All Control Units	1048

Node #	Measurement Type
1	ID #, Wt., Analy.
2	Wt., Analy.
5	ID #, Wt.
88	ID #, Wt.
92	-Scan, Conc'n
93	-Scan, Wt.

$$cei = \sum(1) + \sum(2) + \sum(88) - \sum(5) - \sum(92) - \sum(93) - \Delta H\ (Inv)$$

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