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An Application of the Controllable Unit Approach (CUA) to Analyzing Safeguards Measurement Systems

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ABSTRACT

The controllable unit approach (CUA) is a material control and accountability methodology that takes into account the system logic and statistical characteristics of a plant process through the formulation of closure equations. The methodology is adaptable to plant processes of varying degrees of design and operational complexity. No alteration or modification of a process is required to apply the methodology. Cost/benefits of refinements in, or changes to, the proposed measurement system are obtained as incremental cost.

To encourage improved safeguards accountability, the U. S. Nuclear Regulatory Commission (NRC) has been considering the use of performance oriented regulations to supplement those currently used. The study, sponsored by NRC/Office of Standards Development, evaluated CUA methodology to meet performance oriented regulations. For this study, the criterion is defined as the detection of a material loss of two kilograms of SNM with 97.5% confidence. Specifically investigated were: the timeliness of detection, the ability to localize material loss, process coverage, cost/benefits, and compatibiltiy with other safeguards techniques such as diversion path analysis and data filtering. The feasibility of performance-oriented regulations is demonstrated.

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DISCLAIMER

To fully use the system of closure equations, a procedure was developed to formally integrate the effect of both short-term and long-term closure equations into an overall systems criterion of performance. Both single and multiple diversion strategies are examined in order to show how the CUA method can protect against either strategy. Quantitative results show that combined closure equations improve the detection sensitivity to material loss, and that multiple diversions provide only diminishing returns.

INTRODUCTION

The controllable unit approach [1] (CUA) is a material control and accountability methodology that takes into account the system logic and statistical characteristics of a plant process through the formulation of closure equations. These material balance equations model inputs, outputs, inventories, holdups and possible losses or diversions. They depend upon fixed measurement points in the process. The methodology is adaptable to plant processes of varying degrees of design and operational complexity, exemplary of present and future facilities. Application of the method does not require alteration or modification of an applicant's process. Because base-case calculations are a natural first step in the evaluation scheme, the cost/benefits of refinements in, or changes to, the proposed measurement system for purely safeguards purposes are easily obtained as incremental cost.

To encourage improved safeguards accountability, the Nuclear Regulatory Commission (NRC) has been considering the use of performance oriented regulations to supplement those currently used. In the area of material control and accountability, for instance, one such performance oriented criterion could be the assurance that a given loss of material be detected within a specific time frame. The present study, sponsored by NRC/Office of Standards Development, evaluated CUA methodology to meet performance oriented regulations. For purposes of this study, the criterion is defined as the detection of a material loss of two kilograms of SNM with 97.5% confidence. Specifically investigated were: the timeliness of detection, the ability to localize material loss, process coverage, cost/benefits, and compatibility with other safeguards techniques such as DPA (diversion path analysis) and data filtering. In addition, this study was undertaken as a first step in providing the NRC with the methodology and information to:

1. Support development of safeguards regulations that emphasize performance requirements,

2. Assess license applications, and

3. Inspect processes.

Like many successful management systems, the CUA methodology iteratively compares the actual situation to the need. In this study, the performance of the proposed or existing measurement system is compared to the material control criterion. Then, additions or refinements to the measurement system or process are iteratively compared to the criterion until it has been met. This systematic comparison can efficiently ensure that a complicated process measurement system will perform to the level as specified by the need. Furthermore, because the existing or proposed system is mathematically modeled with the CUA method, modifications to the process for any reason can be tested quickly for their effect on material control before implementation. A summary flow diagram of the CUA methodology is shown in Figure 1.

PROCESS MODEL

A process model [1] was developed to provide a severe test of controllable unit methodology. The process model was based primarily on a commercial high-throughput (200 MT) mixed-oxide fuel fabrication plant similar to that proposed by Westinghouse [2] and further described by Science Applications Inc. [3]. Modeling techniques were developed to include as much realism into the model process as possible. Simultaneous operation modes, randomly varied process streams, and flow, time, and event-dependent hold-up functions are examples of the realistic features of the process model.

EFFECTIVENESS OF MULTIPLE CLOSURE EQUATIONS AND VULNERABILITY ASSESSMENT

To fully use the system of closure equations generated to describe and control the process, a procedure was developed to formally integrate the effect of both short-term and long-term closure equations into an overall systems criterion of performance. The objective is to maximize the detection sensitivity within a given detection time period. In this assessment of the value of using multiple closure equations, the following situations were accounted for:

1. The combination of independent non-overlapping closure equations to obtain an overall performance criterion;
2. Possible overlap between several closure equations;
3. Possible correlated variables between different closure equations.

Each closure equation requires an associated hypothesis test procedure. For explanatory purposes assume a closure equation of the simple form

$$M_1 = X_1 - X_2,$$

with the distributions of errors in measurements X_1 and X_2 normal with zero means and variances σ_1^2 and σ_2^2 respectively. Then M_1 is $N(0, \sigma_1^2 + \sigma_2^2)$ assuming no losses in this control area. Next form a one-sided hypothesis test:

H_0: Null Hypothesis (No Diversion) $M_1 \leq L_1$

H_1: Alternative Hypothesis (Diversion has occurred at the Q_1 level) $M_1 = Q_1$

A threshold C_1 is obtained to effect the hypothesis test. H_0 is accepted if $M_1 < C_1$, and rejected otherwise.

Let M_1 be the measured CEI (closure equation imbalance), whereas CEI_1 is the actual material diverted; then Type-1 (α_1) and Type-2 (β_1) errors are defined as:

$$P(M_1 > C_1/CEI_1 = L_1) = \alpha_1$$

$$P(M_1 > C_1/CEI_1 = Q_1) = (1 - \beta_1);$$

where α_1 is the probability given no diversion has occurred that the measured CEI (M_1) exceeds the threshold C_1, and is sometimes called the "false-alarm" error probability; and $(1 - \beta_1)$ is the probability given a diversion at the Q_1 level that the measured CEI (M_1) exceeds the threshold C_1, and is referred to as the "power" of the test. The probability that a diversion has occurred but the hypothesis test has failed to detect it is given by β_1.

Assume for each control region that α, L, Q, and measurement error variances are given, so that the error β and the required threshold C can be obtained from the two equations presented above. It will be assumed for the analyses that each control region hypothesis test is designed independently, and thus all of these parameters are determined before computing overall error probabilities.

For the case of n non-overlapping independent closure equations (situation one), the overall probability that a diversion at a given level has occurred, but has not been detected by any of the closure equations, can be obtained as

$$\begin{aligned}\text{Overall Probability of nondetection} &= \prod_{i=1}^{n} \text{Prob} \begin{array}{c}\text{nondetection in the } i^{th} \\ \text{closure equation}\end{array} \\ &= \prod_{i=1}^{n} \beta_i\end{aligned}$$

The product of the β_i follows from the observation that all n potential independent diversions must go undetected for overall nondetection.

A schematic for overlapping closure equations is shown in Figure 2. If a diversion D_2 should occur in area 2, it could be detected by either closure equation. Yet closure equations I and II may or may not be correlated depending upon their specific form. For example, if they are of the form:

Model A	Closure Equation
$M_1 = X_1 - X_3$	I
$M_2 = X_2 - X_4$	II

it is clear that they are uncorrelated, in that they do not have any measurement values in common. But the closure equations in Figure 2 might also appear as:

Model B	Closure Equation
$M_1 = X_1 - X_2 - X_3$	I
$M_2 = X_2 + X_3 - X_4$	II

in which case M_1 and M_2 are clearly correlated when they share measurements X_2 and X_3 in common. In such cases, if the underlying measurement errors are Gaussian the resulting closure equation imbalances M_j can be described by multivariate Gaussian distributions. Probability calculations are considerably more complicated, but can be evaluated numerically.

On the other hand, whether the closure equations are correlated or not, the effect of overlap can be handled simply. In Figure 2, assume diversions D_1, D_2 and D_3 have occurred in areas 1, 2, and 3 respectively. Then since it is assumed that all measurement errors have zero mean Gaussian distributions, the distributions for M_1 and M_2 have means of $(D_1 + D_2)$ and $(D_2 + D_3)$ respectively. Thus the controlling effect of the overlap shows up in a relatively simple way in the imbalances, and a diversion in area 2 shows up in the means of *both* M_1 and M_2. Because this diversion D_2 occurs in both means, it is much more liable to be detected.

As an example consider the determination of the overall probability for Model A given diversions D_1, D_2, and D_3 in areas 1, 2, and 3 respectively shown in Figure 2. A worst case analysis requires examination of all possible partitions of Q into D_1, D_2, and D_3 where

$$Q = D_1 + D_2 + D_3$$

and $$D_1 + D_2 \geq Q_1$$

and $$D_2 + D_3 \geq Q_1.$$

If either of these inequalities is *not* valid, then we will consider that *no diversion has occurred in the corresponding region at all*, and a much simpler problem results.

With these assumptions the maximization of the probability of nondetection is given by

$$Z = \underset{\substack{D_1, D_2, D_3 \\ D + D + D = Q}}{\mathrm{Max}} \left[\int_{-\infty}^{C_1} f_1(M_1)\, dM_1 \int_{-\infty}^{C_2} f_2(M_2)\, dM_2 \right]$$

which rewritten in terms of the usual normal distribution notation using normalized variables becomes

$$Z = \Phi\left(\frac{C_1-(Q-Q_2)}{\sigma_I}\right) \cdot \Phi\left(\frac{C_2-Q_2}{\sigma_{II}}\right)$$

where for brevity $\sigma_I^2 = \sigma_1^2 + \sigma_3^2$

$$\sigma_{II}^2 = \sigma_2^2 + \sigma_4^2.$$

A numeric example is selected using data from the first stage of the mixed oxide process, controlling this process from the initial weighing of incoming nuclear material until material enters the MO_2 subblend silo. Only short term closure equations [1]

S-1, S-3, S-4, S-5, S-9, and S-10

are considered. For the specific data, see Table 4.8 and Table I.1 in Reference 1.

These results are shown in Figure 3 where it is clear that multiple diversions provide only diminishing returns for the potential divertor even without the increased risk and logistic difficulty taken into account.

RESULTS

Comparative results for CUA [1] and MUF/LEMUF [4] as applied to the mixed-oxide process are given which show that CUA provides an improvement factor of 3 for detection sensitivity and a greater improvement for timeliness of detection.

Results to date indicate that the methodology will be highly effective in timely detection of SNM material loss and in material control. Specifically through the CUA methodology accountability and process data have been used effectively to meet the following principle objectives of this study.

- Demonstration that the detection capability for material loss of SNM in the mixed-oxide process is 2 kg at a detection probability of 97.5% with a false alarm rate of three per year. This applies to either a single-event material loss or to random accumulative material losses up to a two-month period.
- Identification of the area and approximate time (generally within a shift) of the suspected diversions.

These results were accomplished without modification of the plant process or operations from the original model. Furthermore, the application of this concept provides the user with the added benefit of estimating the cost and effectiveness of additional measurements or measurement points anywhere in the process. Currently, CUA is being applied to an existing high-throughput operating plant.

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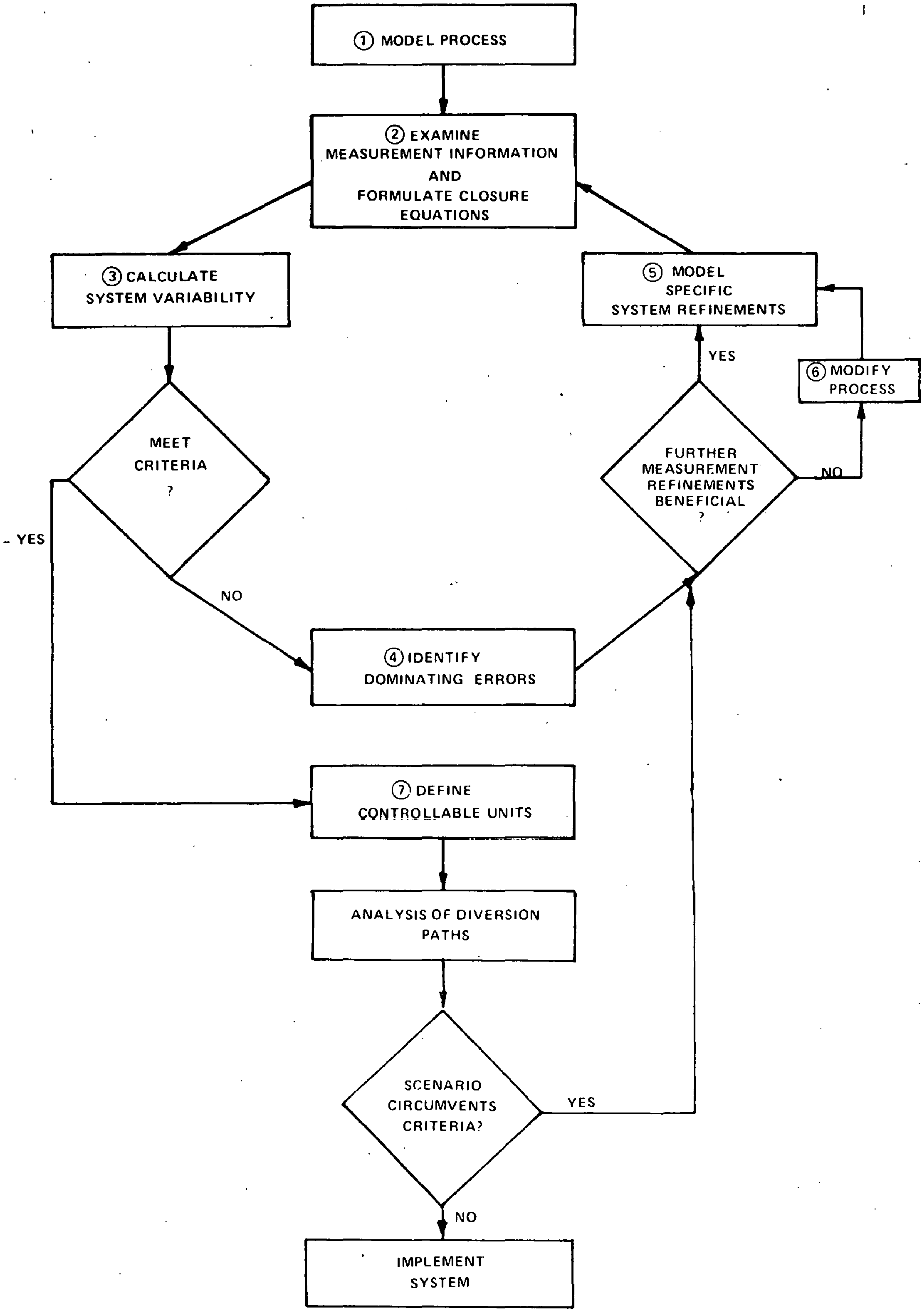

FIGURE 1 - CUA methodology is a systematic approach to material control.

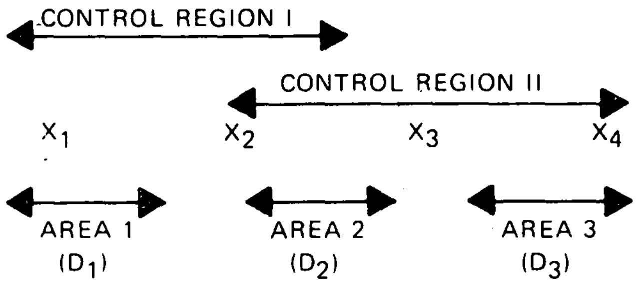

FIGURE 2 - A schematic for the overlapping but uncorrelated closure equation model shows the control regions and diversion area.

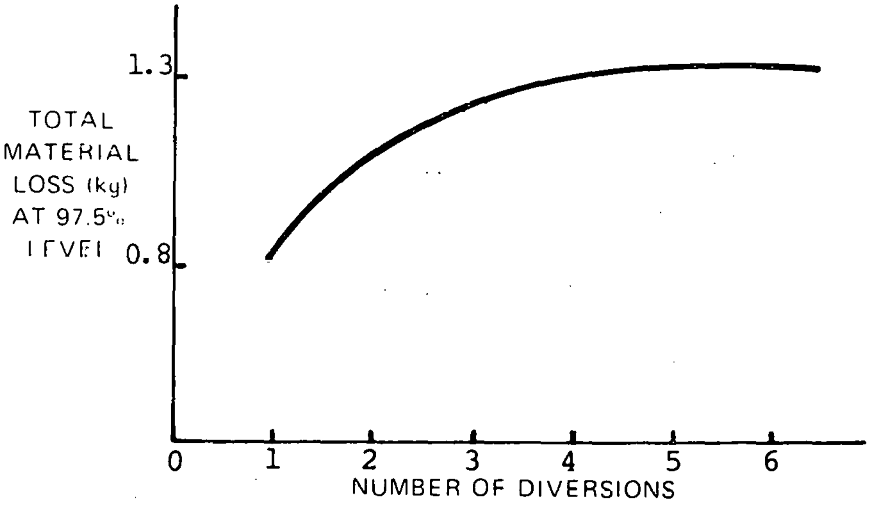

FIGURE 3 - Computations show that multiple diversions reach a point of diminishing returns.

FIGURE CAPTIONS

Figure 1. CUA methodology is a systematic approach to material control.

Figure 2. A schematic for the overlapping but uncorrelated closure equation model shows the control regions and diversion areas.

Figure 3. Computations show that multiple diversions reach a point of diminishing returns.