Delbeke, J.F.A. and Howell, J. and Eklund, G. and Peerani, P. and Janssens, W. (2008) *The real time mass evaluation system as a tool for detection of undeclared cascade operation at GCEPs.* In: 8th International Conference on Facility Operations-Safeguards Interface, 30 March - 4 April 2008, Portland, Oregon.

The Real Time Mass Evaluation System as a tool for detection of undeclared cascade operation at GCEPs

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Abstract

Given the flexibility of current cascade designs a real time mass monitoring system is preferred. However, if such a system is to be installed in a GCEP it must not impinge on plant operation or be intrusive. Since load cells are already part of the operational process and located outside the cascade hall their exploitation for safeguards purposes is an obvious development. The paper describes, through dynamic simulations, how tranients would be observed in real-time mass balances when a plant is re-configured for undeclared cascade operation.

Key words: RTMES, Safeguards, Gas Centrifuge Enrichment Plants

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1 Introduction

The classical safeguards approach for Gas Centrifuge Enrichment Plants (GCEPs) focusses on activities outside the cascade halls. Mass balances and enrichment levels are analysed according to a sampling plan. Extensive measures such as weighing and sampling of numerous cylinders is necessary and takes place a posteriori. Less resource intensive approaches might therefore be attractive.

The need for a real-time system gains more and more importance, given the increasing performance and flexibility of current countercurrent cascade designs. In particular, equilibrium times are very small compared to the time elapse between two random inspections, which can be in the order of weeks (Rezniczek, 2003). To enhance balance analysis and to comply with the IAEA's timeliness criterion (IAEA, 2002) new safeguards strategies therefore propose continuous monitoring of cascade operation (see, for instance, Dixon et al., 2007). Howell & Bedell (2007) have described how evaluating the consistency of this data can help address the specific needs of the IAEA's new safeguards approach to detect a variety of events: diversion of a significant quantity of uranium from declared feed, product or tails, undeclared production of HEU from declared or undeclared feed and production of undeclared LEU from undeclared feed. They suggest that there might be some delay in assimilating historical trends in the data before anything could be concluded.

Limiting the collection of continuous data to that output by load cells, located on stations outside the cascade hall, is considered a good compromise between the need for visibility and concerns about access to proprietary information. The Real Time Mass Evaluation System (RTMES) was previously put forward as an enhanced safeguards system for continuous collection of load cell data and corresponding evaluation of mass balances in GCEPs in real time. This system was shown to be ideally suited for real time detection of protracted diversion (Delbeke et al., 2007).

The suggestions of Howell & Bedell were based on the very simple assumption that the cascade outputs change instantaneously during a change in operating point. By modelling the transients in these outputs, we shall explain in this paper why the RTMES is far more responsive in indicating changes in cascade operation. It's detection power will be demonstrated with the particular case of throttling the feed flow for purpose of producing product at higher enrichment levels then declared. Although no assays are measured, the RTMES indicates which cylinders may contain product at enrichment levels that are higher than declared.

2 Transient variations in cascade hold-up

Assume that the operator decides to change the feed flow rate to cascade c in the following way:

$$F_c(t) = F_c(t_0)_c F_c^*(t);\ t > t_0 \wedge F_c^*(t) \neq 0 \tag{1}$$

where $F(t_0)$ is the steady state value at t_0 and $F_c^*(t)$ is the scaled scheduled change. The corresponding time domain response of the mass flow rates becomes:

$$P_c(t) = \begin{cases} P_c(t_0); t < t_0 + t_P \\ P_c(t_0)P_c^*(t);\ t > t_0 + t_P \end{cases} \tag{2}$$

for the product flow and

$$T_c(t) = \begin{cases} T_c(t_0); t < t_0 + t_T \\ T_c(t_0)T_c^*(t); t > t_0 + t_T \end{cases} \tag{3}$$

for the waste flow. Any change in mass imbalance, $\Delta M_v(t)$ can be attributed to one of two components: a change in hold-up, $\Delta H(t)$, or a constant leakage L:

$$\Delta M_v(t) = \Delta H(t) + \int_{t_0}^{t} L(t')dt' \tag{4}$$

If a permanent change in operating point is invoked, then a permanent mass imbalance $\Delta M_p(t)$ will be left after new equilibrium conditions have been reached:

$$\Delta M_p(t) \approx \Delta M_v(t) = \Delta H_\infty + \int_{t_0}^{t} L(t')\mathrm{d}t'; t \gg t_0 \tag{5}$$

Now, leakage is present anyway[1] so that the only real trace that is left from a transient is the rather small change in cascade hall inventory, ΔH_∞.However $\Delta H(t)$ can be relatively large, transiently, because the holdups in the enriching and stripping sections of the cascade respond very differently. Thus in many cases

$$\Delta H_\infty \ll \max(\Delta M_v(t)) \tag{6}$$

so that indications of a change in operating point are more likely to be detected if transients can be monitored. These can only be detected by continuous monitoring of mass flows. This explains the need for real time monitoring and evaluation of mass flows.

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[1] We assume that the changes in leakage are neglegible.

The detection probability depends on the shape of $\Delta M_v(t)$ that is determined by the transfer functions. These functions depend on centrifuge characteristics, cascade characteristics and initial conditions. To illustrate the principle of detecting the transient mass imbalance production at higher enrichment levels than declared shall be discussed.

3 Undeclared HEU production

The undeclared production of HEU from declared feed has been widely discussed as one of the diversion scenarios that are associated with the operation of GCEPs. If declared feed is used to produce an undeclared amount of HEU in a declared facility the operational characteristics of the installed declared cascades are likely to change. To study the specific case of reducing the feed flow rate of NatU to the cascades without changing feed points and/or interstage connections a centrifuge centered approach is used. In this approach the centrifuge response to local conditions is incorporated.

First the centrifuge operational domain is determined based on a mathematical solution method (Benedict, 1981; Dickinson, 1981) for an Olander mass velocity distribution (Olander,1981). In this paper centrifuges are studied with a rather high aspect ratio of *** and spinning with an angular velocity of about *** rad/ s. The physical properties of the process gas are taken from published literature (May, 1977; Dewitt, 1966). Some of the centrifuge parameters that were designed for declared operation can not be altered during the transient (such as centrifuge feed point). Therefore a condition of predesigned centrifuges is imposed. Therefore the internal circulation rate, the position of the feed inlet and the peripheral speed are kept at fixed values. As a consequence the operational domain of the centrifuge and its separation performance shall change. The results of the numerical simulations that determined the separation factor for this specific case are shown in Fig.[ADD FIGURENUMBER] (Delbeke, 2008).

Secondly, the characteristics of a reference cascade are determined by a model that is based on the calculation of a certain number of key parameters i.e.: stage separation factors and stage cuts. These parameters are necessary for the calculation of the interstage flows and assays under transient conditions (Cohen, 1951). In particular for determining the response of such a reference cascade to changes in the external feed flow it is assumed that the stage cut is a parameter that can be set by the operator. The appropriate choice for these cuts is such that interstage mixing is limited. For this study the transition from ideal to non ideal cascades is made by keeping the cut constant over the different stages in a certain section i.e.: θ_e and θ_s for the enriching and the stripping section respectively (Avgidou, 2004).

To limit the aforementioned interstage mixing losses the values of these cuts are continuously recalculated during the transient because the interstage flow conditions change continuously. The algorithm that is used for these calculations compares the actual cascade with what an ideal cascade would look like for the same boundary conditions. Then the values θ_e and θ_s are determined by weighing the ideal stage cuts against the actual interstage feed flow rates. It is worthwhile mentioning that the feed stage is included in the stripping section. The stage response, and in effect the cascade response, to a changing feed flow is then obtained by calculating the stage parameters as described above and then using the mass balance relations and the definitions of the separation factors. The changes in hold up in the different stages are incorporated by using a predefined function that varies with changing feed flow rates.

For this paper a reference cascade (one up one down) containing 150 identical machines is studied. This cascade produces LEU from NatU feedstock. The initial centrifuge distribution along the different stages is determined and shown in Fig..[ADD FIGURENUMBER]. The cascade feed flow rate that corresponds with optimum distribution is then found to be $0.02\,\mathrm{gUF_6/\,s}$ and the optimum production assays are 0.0413 and 0.00297 for the product and waste respectively. Three different cascade trips are simulated for which the feed flow rate is linearly reduced to 10%, 50% and 90% of the initial steady state value. The responses of the flow rates at the cascade's take off points are shown in Fig. [ADD FIGURENUMBER]. The corresponding variations in product assay are shown in [ADD FIGURENUMBER].

4 Response of the RTMES to undeclared HEU production

The RTMES analyses load cell data collected continuously from the autoclaves and cooling chambers located in the feed, tails and product stations of a GCEP. These load cells are often installed for operational purposes and their exploitation for safeguards purposes is an obvious development. The preferred rationale is to form instantaneous mass balances as quickly as possible, to alert an inspector if an issue is evolving. These balances can be likened to the conventional MUF statistic, and can be analysed in a similar fashion. To minimize likely measurement errors, a particular station load cell output would not be incorporated into the mass balance, if it is known that particular station is off-line at that time. The RTMES calculates an instantaneous imbalance:

$$x_i = \left[\sum_{j=1}^{N_F} (F_{i,j} - F_{i-1,j})\right] - \left[\sum_{j=1}^{N_P} (P_{i,j} - P_{i-1,j})\right] - \left[\sum_{j=1}^{N_T} (T_{i,j} - T_{i-1,j})\right] \qquad (7)$$

and a cumulative imbalance:

$$X_k = \sum_{j=1}^{k} x_j \tag{8}$$

where N_F, N_P and N_T are the number of feed stations, product stations and tails stations respectively. $F_{i,j}, P_{i,j}, T_{i,j}$ are the load cell data at time step i of station j .

To illustrate the response of the RTMES to these cases a cascade hall containing 8 of the aforementioned type of cascades is simulated. All of the present cascades are assumed to behave in an identical manner. For all scenarios it is assumed that the inter-stage connections of the cascade are not changed before, during or after the transient. The RTMES response is shown in FIG.[ADD FIGURENUMBER]. The temporary nature of the mass unbalance is visible in the mass balance plot where the effect of the virtual mass imbalance appears clearly. The first set of data is produced by simulating the response in a noise free environment. For the second set typical load cell noise was simulated and added to the pure signal. At this stage it is not clear if the magnitude of these errors has any practical significance.

In the case of a protracted diversion of a certain amount of nuclear material from the cascades a permanent imbalance shall be visible in the RTMES responses as was shown before. However, the effect is different in that way that for a protracted diversion the cumulative balance shall not restore itself as is the case for a cascade trip.

5 Conclusion

Real-time evaluation of load cell data by mass balancing is an attractive proposition, because it is not intrusive. It neither looks inside the cascade hall nor impinges on plant operation. In addition to its detection power for protracted diversion RTMES might be used for indicating undeclared cascade trips. For the scenario of undeclared HEU production from declared NatU feed that was studied in this paper clear symptoms are visible in both the balances. Although the mass imbalance is a temporary phenomenon, the cumulative imbalance stays present for the duration of the cascade trip. Detection of these imbalances can facilitate the safeguards inspections by indicating the product cylinders that are likely to contain enrichment levels higher than declared. In addition, given the real time features of the RTMES the alarm is triggered immediately, thus preventing replacement of the cylinder or shipping it of the plant.

Current research is focussing on multiparameter studies for determining the

RTMES response for different types of plants. These theoretical studies give insight into how various parameters influence the RTMES response. Nevertheless to validate this tool it is clear that access to real data is of uttermost importance.

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