# An Advanced Control System for Fine Coal Flotation

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## Abstract

Over the past thirty years, process control has spread from the chemical industry into the fields of mineral and coal processing. Today, process control computers, combined with improved instrumentation, are capable of effective control in many modern flotation circuits. Unfortunately, the classical methods used in most control strategies have severe limitations when used in froth flotation. For example, the nonlinear nature of the flotation process can cause single-input, single-output lines to battle each other in attempts to achieve a given objective. Other problems experienced in classical control schemes include noisy signals from sensors and the inability to measure certain process variables. For example, factors related to ore type or water chemistry, such as liberation, froth stability, and floatability, cannot be measured by conventional means.

The purpose of this project is to demonstrate an advanced control system for fine coal flotation. The demonstration is being carried out at an existing coal preparation plant by a team consisting of Virginia Polytechnic Institute and State University (VPI&SU) as the prime contractor and J.A. Herbst and Associates as a subcontractor. The objectives of this work are: 1) to identify through sampling, analysis, and simulation those variables which can be manipulated to maintain grades, recoveries, and throughput rates at levels set by management; 2) to develop and implement a model-based computer control strategy that continuously adjusts those variables to maximize revenue subject to various metallurgical, economic, and environmental constraints; and 3) to employ a video-based optical analyzer for on-line analysis of ash content in fine coal slurries.

The project, which originally started in August of 1995, has been on hold for the past year due to a change in the prime contractor. The process of novating the contract to VPI&SU began in July of 1996, and a new contract has only been in place since August of 1997. Thus, this paper summarizes work carried out during the first year of the project when VPI&SU served as a subcontractor. This work includes calibration tests conducted using the video-based sensor and a sampling campaign carried out at the test site. A summary of the data collected to date is presented and future plans are discussed.

## Introduction

Process control, as we know it, began to appear in the mineral processing industry some 30 years ago. These initial implementations were simple extensions of PID loops for controlling level and flow that had become common place in the chemical processing industry. As instrumentation and computer technology improved, control systems for maintaining particle size in grinding circuits and product grade in flotation circuits began to appear. This eventually led to more advanced circuit and plant-wide control systems for optimizing performance and maximizing throughput.

Unfortunately, the implementation of process control in the coal preparation industry, particularly as it pertains to froth flotation, has not yet reached the level of the mineral processing industry. This can be attributed to several factors. For example, the classical methods used in most control strategies have severe limitations when it comes to froth flotation. The nonlinear nature of the flotation process causes single-input, single-output lines to battle each other in attempts to achieve a common objective. Other problems experienced in classical control schemes are noisy signals from sensors and the inability to measure certain process variables. Factors related to changes in coal type or process water chemistry, for example, cannot be measured by conventional sensors. The implementation of process control in the area of coal flotation has also been impeded by the lack of appropriate sensing technology. Although a number of nuclear-based slurry analyzers are available, none has seen widespread acceptance by the industry. This is largely due to the fact that nuclear sensors are very expensive for the limited amount of accuracy available.  Other factors generally cited as inhibiting the use of nuclear slurry analyzers include the inability to handle variations caused by multiple seam processing and complicated sampling systems.

This project is attempting to address the problems cited above through the testing of an advanced model-based control system for fine coal flotation.  A video-based sensor for on-line ash analysis, developed by VPI&SU under U.S. DOE Grant DE-FG22-94PC94226, is being employed as the primary sensing device in this investigation.  The proposed control strategy will monitor flotation performance through on-line analysis of ash content; and, based on the economic and metallurgical performance of the circuit, adjust variables such as reagent dosage, aeration rate, and pulp level to compensate for feed and other process disturbances.  The first phase of the project will involve simulating and modeling the performance of the flotation circuit and identifying alternative control strategies.  After analysis and selection of the best control strategy, the selected strategy will be implemented at an operating preparation plant, and an intensive evaluation will be performed.

This project, which originally began in August of 1995 and was scheduled to be completed in two years, has been on hold for the past year due to changes in the organizational structure of the project team.  The process of novating the contract to VPI&SU as prime contractor began in July of 1996, and a new contract has only been in place since August of 1997.  This paper provides a description of the project and summarizes work carried out to date while VPI&SU was a subcontractor.

## Project Description

### Objectives

The objectives of this project are:  1) to identify, through sampling, analysis, and simulation, those variables that can be manipulated on-line to maintain grades, recoveries, and throughput rates at levels set by management; 2) to develop and implement a model-based computer control strategy that continuously adjusts those variables to maximize revenue subject to various metallurgical, economic, and environmental constraints, and 3) to employ a video-based analyzer for use in on-line analysis of ash content in fine coal slurries.

### Organization

The project organization originally consisted of three members as shown in Figure 1.  Control International, Inc. served as prime contractor with responsibility for the control system, Virginia Tech served as subcontractor with responsibility for the ash sensor, and Cyprus-Amax Maple Meadow served as subcontractor providing the test site.  With changes and corporate restructuring that occurred at Control International in the spring of 1996, the contract was novated to Virginia Tech as prime contractor while J.A. Herbst and Associates replaced Control International as the subcontractor responsible for control system development.

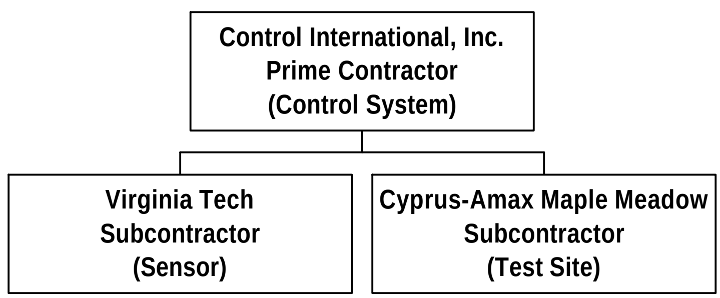


**Figure 1.  Project organizational structure.**

### Project Tasks

The project was originally divided into 10 tasks to be completed over a period of two years beginning in August of 1995. From July of 1996 until July of 1997, the project was on hold while a new contract was awarded to Virginia Tech.  Because of the delays encountered in the novation process, work is now scheduled to resume in August of 1997, and the project is scheduled to be completed by March of 1999.  The following is an overview of the work to be performed.

*Task 1 - Project Planning*:  This task includes the preparation of a detailed project work plan, the preparation of project reports, and the overall management of the project.

*Task 2 - Sampling and Data Analysis*: This task involves a sampling campaign to determine the dynamic response of the flotation circuit at the Maple Meadow test site and to collect data for constructing a mathematical model. A schematic diagram of the test site is shown in Figure 2. As shown, samples are being collected from all streams around the circuit. Three types of sampling tests are being performed: 1) Factorial Design - to determine the effects of feed rate, reagent dosage, and pulp level on flotation performance and to establish model parameters; 2) Residence Time Distribution - to provide a measure of the flotation bank time constant; and 3) Batch Flotation - to provide a means of characterizing the variability inherent in the feed. All data are being material balanced prior to their use in the model.

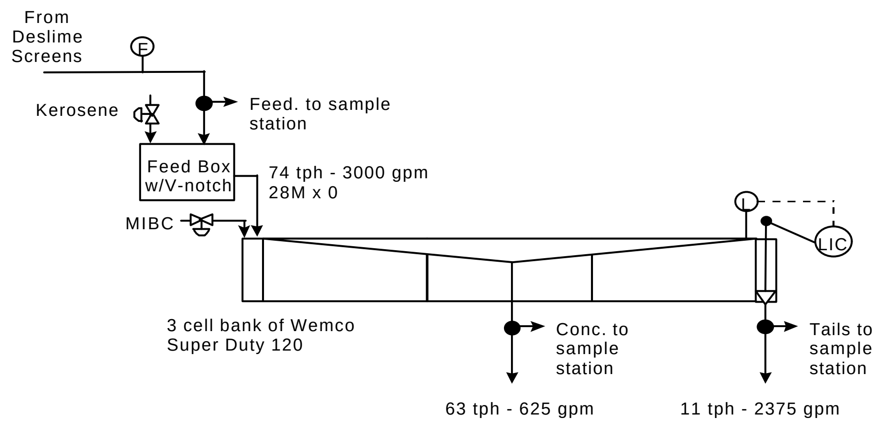


**Figure 2. Schematic diagram of the Maple Meadow flotation circuit.**

*Task 3 - Model Building and Computer Simulation*: The purpose of this task is to use the data from Task 2 to produce a dynamic model of the flotation circuit for testing control strategies and implementing a model-based control scheme. The model being used in this investigation is shown schematically in Figure 3. In this figure, particles of size *i* and composition *j* exist in four possible states: 1) free in the pulp, 2) attached to bubbles in the pulp, 3) free in the froth, and 4) attached to bubbles in the froth. The number of particles of size *i* and composition *j* per unit volume in any of the four states is denoted by $y_{ij}$. The interphase transfer rate constants, *k*, are also shown.

The population balance framework is an excellent approach for modeling particulate systems that cannot be solved using the usual continuity and rate expressions. A number balance is developed from the general conservation equation:

accumulation = input - output + generation

and is applied to particles having a specific set of properties $\{z_1, z_2, \ldots, z_J\}$. In this balance, input and output terms represent changes in the number of particles in the specified property interval resulting from convective flow, while the generation term accounts for particles entering and leaving the specified property interval as a result of individual kinetics. The macroscopic form of the population balance model is applicable when the vessel is well mixed or when residence time distribution information is available. The overall number balances in each of the four states are:

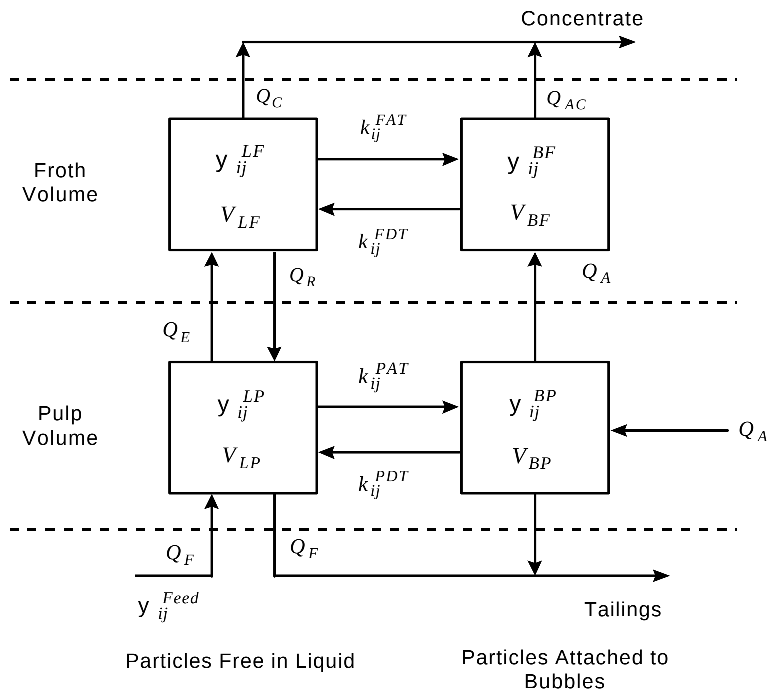


**Figure 3. Schematic diagram of the froth flotation model.**

Free in the pulp:

$$\frac{d}{dt}\left(V_{LP} y_{ij}^{LP}\right) + k_{ij}^{PAT} V_{LP} y_{ij}^{LP} - k_{ij}^{PDT} V_{BP} y_{ij}^{BP} = Q_{Feed} y_{ij}^{Feed} - Q_T y_{ij}^{LP} + Q_R k_{ij}^{R} y_{ij}^{LF} - Q_E y_{ij}^{LP} \qquad (1)$$

Attached in the pulp:

$$\frac{d}{dt}\left(V_{BP}\psi_{ij}^{BP}\right)+k_{ij}^{PDT}V_{BP}\psi_{ij}^{BP}-k_{ij}^{PAT}V_{LP}\psi_{ij}^{LP}=Q_{A}\psi_{ij}^{BP}-Q_{AT}\psi_{ij}^{BP} \tag{2}$$

Free in the froth:

$$\frac{d}{dt}\left(V_{LF}\psi_{ij}^{LF}\right)+k_{ij}^{FAT}V_{LF}\psi_{ij}^{LF}-k_{ij}^{FDT}V_{BF}\psi_{ij}^{BF}=Q_{E}\psi_{ij}^{LP}-Q_{C}\psi_{ij}^{LF}-Q_{R}k_{ij}^{R}\psi_{ij}^{LF} \tag{3}$$

Attached in the froth:

$$\frac{d}{dt}\left(V_{BF}\psi_{ij}^{BF}\right)+k_{ij}^{FDT}V_{BF}\psi_{ij}^{BF}-k_{ij}^{FAT}V_{LF}\psi_{ij}^{LF}=Q_{A}\psi_{ij}^{BP}-Q_{AC}\psi_{ij}^{BF} \tag{4}$$

where $\psi_{ij}^{LP}$ is the number of particles free in the liquid in the pulp per volume of liquid in the pulp, $\psi_{ij}^{BP}$ is the number of particles attached to bubbles in the pulp per unit volume of air in the pulp, $\psi_{ij}^{LF}$ is the number of particles free in the liquid in the froth per unit volume of liquid in the froth, $\psi_{ij}^{BF}$ is the number of particles attached to bubbles in the froth per unit volume of air in the froth, and $\psi_{ij}^{Feed}$ is the number of particles in the feed per unit volume of liquid in the feed. The interphase transfer rates are dependent on particle properties and the chemical and physical environment of the flotation cell where $k_{ij}^{PAT}$ is the particle attachment rate constant in the pulp, $k_{ij}^{PDT}$ is the particle detachment rate constant in the pulp, $k_{ij}^{FAT}$ is the particle attachment rate constant in the froth and $k_{ij}^{FDT}$ is the particle detachment rate constant in the froth. The input flows are: 1) the feed of particles into the flotation cell, $Q_F\psi_{ij}^{Feed}$, where $Q_F$ is the liquid volume flowrate, and 2) the return flow rate of particles draining from the froth carried by the water, $Q_R k_{ij}^{R}\psi_{ij}^{LF}$, where $Q_R$ is the volumetric flowrate of water draining from the froth and $k_{ij}^{R}$ is a dimensionless classification constant representing the segregation that occurs in the draining liquid in the froth. The output flows are: 1) the flowrate of particles leaving through the tailings port, $Q_T\psi_{ij}^{LP}$, where $Q_T$ is volumetric flowrate of liquid in the tails, and 2) the flowrate of particles entrained by the water flow, $Q_E\psi_{ij}^{LP}$, where $Q_E$ is the volumetric flowrate of water to the froth transported in the bubble film and wake.

*Task 4 - Sensor Testing*: The purpose of this task is to design and calibrate an industrially-hardened version of the video-based slurry analyzer developed under U.S. DOE Grant DE-FG22-94PC94226. A schematic of the analyzer is shown in Figure 4. The major components include an image analyzer, a sample sump and presentation tube, a mixer, and an illumination system including a fiber-optic illuminator, a line conditioner, and a multimeter. The line conditioner minimizes fluctuations in the voltage provided to the illuminator, while the multimeter measures the resistance from a photocell inside the sample presentation tube. The multimeter is only used on

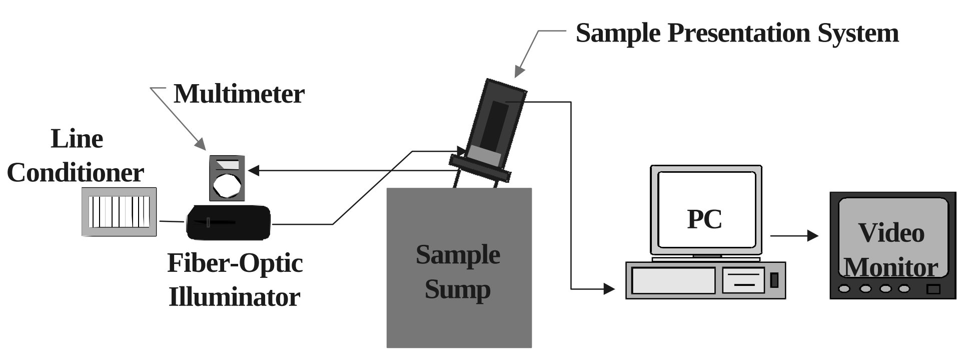


**Figure 4. Schematic diagram of the video-based coal slurry analyzer.**

start-up to establish the initial sensor illumination conditions. Once the light is calibrated, an illumination standard automatically compensates for minor fluctuations. The entire system is controlled by custom-made software.

The basic operating scenario for the sensor is as follows. Slurry is continuously fed to the sample sump from a line coming from the flotation tailings stream. A solenoid air valve is actuated, permitting the acquisition of fresh slurry into the sample presentation tube. The slurry level rises rapidly to the focal plane of the camera, and an image of the slurry surface is captured. The frame-grabber in the computer digitizes the image into gray-level information and displays the image on the television monitor. The software controlling the sensor uses average values obtained from multiple images to perform the necessary calculations that yield slurry ash content. The slurry ash content is then displayed to the operator in an appropriate format. The entire operation takes approximately 15 seconds per image or 5 minutes for an analysis based on 20 images.

*Task 5* - *Sample Analysis and Characterization*: This task involves the analysis and characterization of samples obtained from three sampling campaigns: 1) the initial campaign to characterize the flotation circuit (Task 2), 2) the campaign to assess the performance of the control system (Tasks 7 and 8), and 3) the campaign to calibrate and install the video-based slurry analyzer (Task 4). Overall, nearly 2000 samples are to be analyzed for ash and percent solids.

*Task 6* - *Equipment Procurement and Installation*: This task involves the development of equipment specifications, the purchasing of required equipment, the development of system interfaces, and the installation of the control system. All work performed under this task is based on the outcome of previous tasks and the availability of instrumentation at the plant site.

*Task 7* - *Operation and Testing*: The purpose of this task is to test the advanced control system over an extended period (6 - 9 months). Included in this task are system start-up, operator training, data collection, and control strategy evaluation. Current plans call for testing every two weeks so the results of the previous test can be available before the next test begins.

*Task 8* - *System Evaluation*: The purpose of this task is to use the data collected under Task 7 to compare various control strategies from a technical and economic perspective. The coal company participating in this project is expected to be a major contributor to this evaluation.

*Task 9* - *Decommissioning*: This task involves the removal of all contractor-installed materials upon completion of Task 8. Alternatively, all or part of the control system may be made available to the coal company for purchase.

*Task 10* - *Final Report*: This task involves the submittal of a Draft Final Report to DOE for review and comment.

## Status and Accomplishments

Prior to the novation of this contract, work was primarily conducted in Task 2 (Sampling and Data Analysis) and Task 4 (Sensor Testing). The major findings from this work are presented here.

Figure 5 shows the results of a ten-test factorial design conducted around the Maple Meadow flotation circuit where the feed rate, reagent dosage and pulp level were varied among low, high, and normal levels. As shown, the product ash content remained nearly constant at 5-7%, although the feed ash varied from 10-22%. At the same time, the tailings ash was quite low, varying from 40-50%. Clean coal yield was found to vary from 70-85%, although it occasionally dropped below 60%.

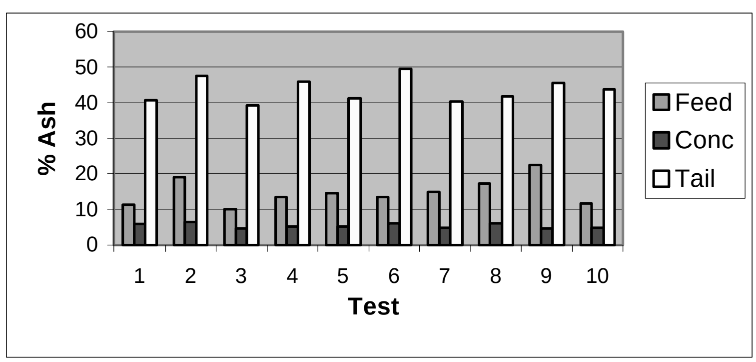


**Figure 5. Performance characterization of the Maple Meadow flotation circuit using a ten-test factorial design.**

The size analyses of the feed, concentrate, and tailings, shown in Figure 6, reveal that the material is relatively coarse with nearly 50% of the mass in the +100 mesh class. This is probably due to the fact that the feed to the circuit comes from 28-mesh deslime screens which are generally inefficient in making a precise size cut. On the other hand, a size-by-size ash analysis revealed that the ash was very evenly distributed in all classes with the exception of the -400 mesh class, which was slightly higher in ash content.

In general, the factorial design test seemed to reveal a flotation circuit that was producing a relatively consistent product in spite of a coarse particle size and variations in feed ash. On the other hand, clean coal yields appeared to fluctuate and were relatively low with respect to the quality of the feed.

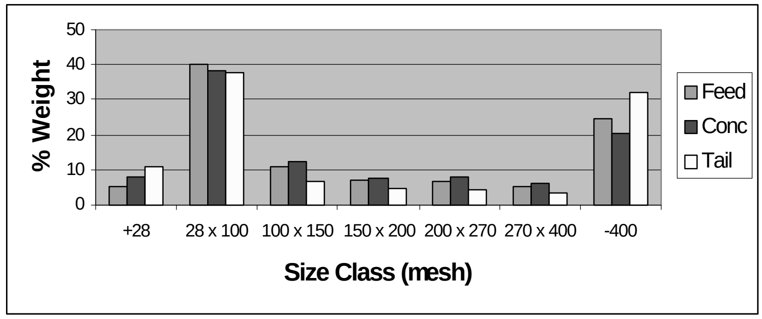


**Figure 6. Size analyses around the Maple Meadow flotation circuit.**

The coarse particle size and low ash content in the flotation tailings raised some concern with respect to the performance of the video-based analyzer. Typically, the analyzer works best on slurries containing greater than 65% ash. Below this value, the change in gray level per unit of ash is less significant and the analyzer loses sensitivity. This was indeed the case at Maple Meadow. Each percentage change in ash content was found to represent one unit of gray level. This level of sensitivity might be tolerable if the accuracy were reasonable; however, the data scatter was such that the sensor was deemed unreliable. It is suspected that the difficulty in suspending coarse particles in the sample presentation tube was responsible for the data scatter. Based on these results, an alternative plan of leasing a nuclear-based ash analyzer was considered.

## Contract Modifications and Future Plans

In January, 1997, the contract was novated from Control International to Virginia Tech. Negotiations between Virginia Tech and DOE were then conducted for the next six months prior to the official award in August, 1997. During that time, the Maple Meadow mine closed, making it necessary to locate another test site. At present, Pittston Coal Company has agreed to provide the flotation circuit at the Moss No. 3 preparation plant. This contract change has been discussed with the DOE COR, and work is underway to obtain official approval. Although the change will require another sampling campaign, it will ultimately save time in sensor calibration since the video-based sensor was originally developed at this site and was found to perform exceptionally well. As shown in Figure 7, the ash content in the tailings stream at Moss No. 3 is considerably higher than at Maple Meadow. Furthermore, the calibration results are excellent with a 90% prediction interval of 72.7 ± 3.5% ash. A kick-off meeting at the Pittston site is scheduled for August 22, 1997, and a sampling campaign is expected to take place in early September.

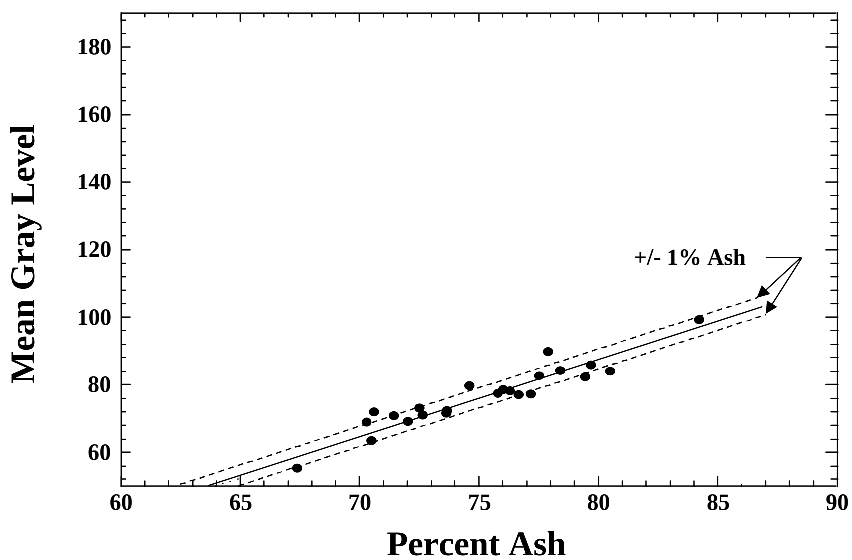


**Figure 7. Video sensor calibration results at the Moss No. 3 site.**

## Acknowledgments


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