Consolidated Fuel Reprocessing Program

PROCESS AUTOMATION USING COMBINATIONS OF PROCESS AND MACHINE
CONTROL TECHNOLOGIES WITH APPLICATION TO A CONTINUOUS DISSOLVER*

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ABSTRACT

Operation of a continuous rotary dissolver, designed to leach uranium-plutonium fuel from chopped sections of reactor fuel cladding using nitric acid, has been automated. The dissolver is a partly continuous, partly batch process that interfaces at both ends with batchwise processes, thereby requiring synchronization of certain operations. Liquid acid is fed and flows through the dissolver continuously, whereas chopped fuel elements are fed to the dissolver in small batches and move through the compartments of the dissolver stagewise. Sequential logic (or machine control) techniques are used to control discrete activities such as the sequencing of isolation valves. Feedback control is used to control acid flowrates and temperatures. Expert systems technology is used for on-line material balances and diagnostics of process operation.

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SCOPE

Implementation of process automation technology has the potential to improve the quality of product materials and decrease the operating costs of nuclear fuel reprocessing plants. Although implementation of automation requires a higher initial investment compared to traditional loop-control, cost savings during operations are anticipated to result from decreased operating and analytical personnel, and less plant downtime. Many routine operations such as monitoring tank levels and transferring solution from a full tank to the next process step can be done by the computer rather than by operators. Process diagnostics can anticipate a process upset before it occurs and take action to avoid the upset or help the operator quickly pinpoint a problem. Automation of the continuous dissolver system makes for a good trial case because the system contains elements of most, if not all, process control situations found in the plant.

The dissolver system is comprised of the dissolver itself, two digester tanks, a hulls collection vessel, and assorted valves,

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pumps and steam jets. Operations within the envelope ranging from the dissolver feed chute and acid supply headers to the hulls collection vessel and clarifier feed surge tank are automated. The dissolver automation requests sheared fuel to synchronize operation of the shear with the dissolver, but does not control the shear directly.

CONCLUSIONS AND SIGNIFICANCE

Algorithms and software have been developed to operate the continuous dissolver system in an automated mode. The automation synchronizes operation of the shear (or dissolver feed house, whichever is in use) to ensure that the dissolver drum is at the proper angle of repose to accept feed material. In the dissolver uranium is separated from stainless steel segments (hulls) which are dumped from the dissolver on a fixed frequency. The hulls canister is replaced when it is full. Liquid product containing the dissolved fuel is continuously collected in a digester tank. When the receiving digester is full a batch of material is transferred to a second digester. The product is heated in the second digester for a specified time interval and then transferred batchwise to the feed adjustment system. Additionally, the feedrates of both strong acid and weak acid to the dissolver are controlled to maintain the concentration of both nitric acid and heavy metal in the dissolver product within specifications. Flowrates of acid are controlled by feedback control using standard proportional-integral algorithms. Sequential logic techniques are used to control the sequencing of isolation valves, rocking and

indexing of the dissolver drum, steam jet and pump transfers of liquid batches, and safe shutdown of the system in the event of an emergency. Logic to sample process conditions at a high frequency and to act (or branch) based on those conditions was included. Expert systems technology was used as an overlay to enhance control in two primary areas. First, material balances are performed by the computer to calculate new setpoints for acid flow rates, to estimate the status of the process up to one hour into the future, and to modify operating parameters (such as fuel feed rate) to ensure achieving product specifications. Second, diagnostics of the process are performed to pinpoint the cause any upset condition, the results of which are reported to the operator on a computer terminal so corrections may be initiated before significant impact is made on system operation.

Benefits realized from the use of automated dissolver operations include (1) reductions in manpower required to operate the system, (2) shorter delays in starting batch transfers which leads to a reduction in required surge capacity, and (3) product concentrations closer to the target values. During experimental campaigns with the dissolver, using automation to perform the routine operation tasks permitted the operators greater concentration on the data taking needs of the experiments. Automated operations have proven to be very desirable.

DESCRIPTION OF DISSOLVER SYSTEM

The dissolver system is comprised of the dissolver itself, two digester tanks, a hulls collection vessel, and assorted valves,

pumps and steam jets. A schematic of the system is shown in Fig. 1. The dissolver is of helical stage construction and contains eight stages. Segments of chopped fuel elements are fed in small batches to the dissolver and the fuel dissolves as the solids move stage by stage through the dissolver until the remaining stainless steel is discharged. Acid fed to the opposite end of the dissolver flows continuously, and countercurrently to the solids, through small holes separating the stages. Liquid flows from the dissolver and is collected in the first digester. The flow rates of both strong acid and dilute acid are controlled to achieve a specified concentration of nitric acid and dissolved uranium in the collection tank (first digester).

Chopped fuel elements (or material simulating such) are admitted to the dissolver through a feed chute. The material comes to rest on the first of two isolation valves just above the dissolver inlet. The dissolver drum is then set to the top-dead-center (TDC) position to align the opening in the dissolver drum with the feed chute. The upper and lower isolation valves are opened and closed in sequence to drop the material into the dissolver. Then rocking of the drum (a partial clockwise rotation followed by a partial counterclockwise rotation that repeats) resumes. Rocking provides agitation to enhance contact of the solid fuel with nitric acid and speed dissolution. Because each individual cropping of a fuel element results in a small volume of solid material, several croppings may be fed to the first stage before a transfer is made to the next stage. The average residence time in each stage is 30 min, and the dissolver contains 8 stages.

Rocking always occurs between shearing intervals to ensure rapid dissolution.

A dissolver stage is filled when a specific number of shear cuts have been fed. This depends on the size of the shear cuts, and the type of fuel being sheared and the desired loading of the dissolver. When the first stage is full, the drum is stopped at TDC, then rotated a full revolution to transfer solids to the next stage, and then rocking resumes. Operations continue in this manner until all stages are filled with solids. Then subsequent transfers discharge cleaned hulls into the discharge chute which is equipped with an isolation valve. Hulls are collected in the hulls collection canister. The canister is replaced when it is full. The canister is assumed to be filled when a specific number of discharges of hulls are made.

Strong nitric acid ($\sim 8\text{ M}$) is fed to the dissolver to leach the fuel from the stainless steel scrap. This liquor becomes more concentrated in dissolved fuel until it reaches the liquid discharge. Dilute acid (2 to 3 M) may be fed to the liquid discharge stage to prevent an acid deficiency in the first dissolution stage, which also slightly dilutes the uranium in the liquid product.

Liquid product is collected in the first digester tank. The tank is jacketed and while the tank is filling it is steam heated to about $100\text{ }^{\circ}\text{C}$ to aid further dissolution of any small undissolved particles that may be in the product. To ensure that the particles do not settle to the bottom of the tank, the liquid contents are sparged with either air or NO_x . When the tank is nearly full its

contents are transferred to a second digester. The transfer may be made using either a pump or steam jet. If the pump is used, the transfer is made straightaway. If the steam jet is to be used, the tank contents must first be cooled to under 55 °C. In this case the steam heating is discontinued and cooling water is admitted to the tank jacket. When sufficiently cooled the steam jet is activated and the transfer takes place. In addition, just before and just after a transfer, the spargers in both the sending and receiving tanks are turned off long enough for the liquid levels to stabilize to permit accurate measurements of liquid levels in the tanks. These readings are used to determine if there was any loss during the transfer.

As the contents of the first digester are being transferred to the second digester tank, the second digester is placed in the heating mode for further digestion of dissolver product. The digestion duration may be as long as six hours, but the product is transferred to the next process step before the first digester is filled and ready to be emptied again. Again, similar manipulation of spargers, switching of heating and cooling modes, and liquid level measurements are made. All these functions have been automated.

CONTROL SYSTEM ARCHITECTURE

A brief description of the control system for the Integrated Equipment Test (IET) facility is given here, followed by a qualitative description of the separation of control responsibilities.

The Distributed Data Acquisition and Control System (DDACS) provides for process control by both operator interface and automated methods, and for all data acquisition and handling functions required for the operation of the Integrated Process Development (IPD) chemical process facility, including the dissolver. The DDACS also provides monitoring and interlocking functions required for controlling the sequential operations of the various mechanical devices in the experimental area. In addition, the DDACS host computer is linked to another minicomputer and several personal computers to facilitate the analysis of experimental data. These combined features represent the form of process control that will be required for the integrated operation of a nuclear fuel reprocessing plant.

The distributed control concept is a method for physically spreading the responsibility for process control among several discrete controllers within a plant rather than concentrating it in a single piece of equipment. An obvious advantage of this configuration is that the failure of a single controller will affect only the specific area to which it is associated. A backup controller can be placed in-line for those areas where failure is particularly critical to the overall process operation.

As illustrated in Fig. 2, the DDACS control system is distributed in the sense that it is segmented at the process level into eleven unit controllers corresponding to the eleven unit operations identified for the IPD facility. To increase reliability, DDACS incorporates a hierarchical structure consisting of the unit process control modules (PCM's) which perform dedicated

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Figure 2. Control system architecture as related to the dissolver.

measurement, control, and logic sequencing functions. The PCMs are linked with a communications control module (CCM) which coordinates all system communications between the PCMs and a host minicomputer operating at the plant supervisory level. To assure flexibility, the various DDACS components are microprocessor-based and may be easily reprogrammed with appropriate control logic changes when needed.

At the top of the DDACS structure is the host computer, a PDP 11/70 (manufactured by Digital Equipment Corp.), which is used for software development, microprocessor database storage and loading, system monitoring, data acquisition and retrieval, and alarm message generation. The host also supports an operator control console incorporating six color Cathode Ray Tube (CRT) monitors and keyboards. Another important function of the DDACS host computer is to fetch real time process variables and transmit them to the safeguards host computer where material balances are performed as part of the tracking and control of special nuclear materials. Complex computations that cannot be done in the PCMs, but which are required for process control, are performed in the host computer.

At the bottom of the hierarchical structure are the PCMs. The primary functions of the PCMs are to monitor process variables, provide continuous control of process loops, and control sequential operation of mechanical devices. Hardware in the PCMs provide four types of input and output: analog input, analog output, digital input, and digital output. Since a typical PCM has the capability for interfacing with 250 external sensors and actuators, the total system has a capacity for controlling or monitoring about 2,700

devices.

The operator's console provides a "window" to the process through six CRT displays. These displays give the operator a view of the process through various levels ranging from a plant "overview" to a "single loop" display. In addition to the standard vendor supplied data displays, dynamic schematics of specific process units may also be displayed on the CRTs. These graphic displays consist of symbols, text, numerical values, and color coded icons which may be static or dynamically modified as process conditions vary.

Associated with each display on the console is a "function keyboard" which allows the operator to select different displays, and to generally interact with the process. For example, the operator is able to change set points, turn devices on or off, alter control parameters, and manually change controller outputs.

IMPLEMENTATION OF AUTOMATION

Control of the dissolver system is divided into three categories; (1) chemical process control and synchronization functions, (2) watchdog or plant monitor functions, and (3) drive motor system control. The host computer is the focal point for these activities. First, all chemical process control and synchronization functions are handled by a PCM. The automation module resides in a PCM and directly controls the actuation of valves, steam jets, pumps and changing of setpoints. When a complex material balance calculation is required to update values for setpoints, the PCM requests the calculation of the host

computer which returns the needed result. The host is also used for sending messages to the operator. The PCM level automation also controls the action of the shear (or feed house) and dissolver drum drive system indirectly by sending codes to the host computer, which relays the appropriate instruction to the respective controllers at the proper times. This ensures that all operations are coordinated.

Second, a watchdog algorithm resides in the host computer to monitor the process and the instrumentation. This algorithm warns the operator of failed equipment or instruments, sounds an alarm for abnormal operations or unexpected results, and attempts to inform the operator of the cause of any problem it detects. Should the dissolver system fail to return to normal limits of operation or if the detected problem is severe, the watchdog will automatically shut the system down to a safe condition.

Third, operation of the dissolver drum drive system is controlled by a separate system that interfaces with the host computer. When the motor controller is connected to the host, drum operation may be controlled either automatically by the automation program or manually by the operator at the console.

The Process Operation Diagram

In our work to automate portions of the IET chemical plant, we have found it convenient to control each well defined unit operation with a customized control module. The function of each module is described in a logic diagram referred to as a process operation diagram (POD). The POD contains the detailed step-by-

step logic required to control the process. It is independent of the programming language used to implement the automation and is concise enough to be useful to both the process control engineer who must program the control computer and the operator who works in the control room. One page from a set of diagrams describing the dissolver automation is shown in Fig. 3.

The control computers (ie. PCMs) in the IET facility have been programmed to cause all modules to be executed once per second. All modules are executed in sequential order until the table of executable modules is exhausted. Execution then resumes with the first module in the table at the start of the next one second time interval. All steps in a module are not necessarily executed; there is often an exit from a module because the next sequence of operations must wait on a physical operation to finish once initiated. Therefore, before control is transferred to the next module, each module sets a pointer (integer variable) that indicates where processing will resume when the module is next executed. The automation module for the continuous dissolver is subdivided into 26 submodules, each of which performs a logically separable function.

The operator enables the automation module by setting a software flag at the console keyboard. Dissolver operations then proceed automatically and continue until the operator decides to disable the automation by changing the state of the enable flag or if the plant watchdog program detects a critical condition and resets the enable flag automatically.

Sequential Logic

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Nearly all sequential operations are controlled using sequential logic with combinations of flags, counters, comparators and timers. When the module is enabled, solids handling operations and batch transfer of liquid product are performed automatically. Solids handling (ie., mostly dissolver operations) are summarized as follows:

1. The automation initializes by starting the drum rocking motion, sets the solenoid valves to place the first digester in the heating mode and to activate the spargers, and prints a message on the operators computer terminal indicating that automated operations have begun.

2. A material balance is requested of the host computer which immediately returns values for the flowrate setpoints of concentrated and weak nitric acid, the time between shear cuts, and the setpoint for the second digester's temperature. The material balance is called every 15 min to update these values to keep product concentration and plant throughput at the target values.

3. A check is made to determine if the shear system (or feed house system) is active. If so, a code is sent to the shear system to initiate a shear cut. If the shear is not active the operator is informed so the problem may be corrected.

4. The shear returns a code when the shear sequence is complete. The drum is then set to TDC.

5. Each isolation valve is opened and closed in turn to admit the sheared material to the dissolver. If the valves do not operate properly, as determined by examination of limit switches on the valve actuators, a diagnostic is printed at the operator console.

6. Rocking of the drum resumes.

7. After a specified number of shear cuts have been fed to the dissolver, a drum transfer is made. However, before the transfer, a check of limit switches is made to determine if a hulls canister is in place and ready to receive material. If the canister is in place, the transfer is made. Otherwise, the operator is informed and asked to correct the deficiency.

8. The isolation valve in the hulls discharge chute is opened, then closed to dump the hulls into the canister.

9. If the number of times hulls have been dumped into the canister exceeds a specific value, the operator is prompted to remove the canister and replace it with an empty one. The operator must inform the automation, by entering a code, that the canister exchange is complete and the automation checks the limit switches to ensure that the canister is properly aligned.

Steps 2 through 9 are repeated endlessly or until it is decided to halt operations.

Operation of the first digester tank is summarized as follows:

1. The liquid level in the tank is compared to the target level (a level established that means it is time to transfer the liquid to the next tank) every third second until the measured level reaches the target.

2. A setup flag is checked to determine whether the transfer of liquid to the second digester is to be made using a steam jet or a pump. If the steam jet is to be used, the digester tank is placed in the cooling mode to lower the liquid temperature. If the temperature is too high, the steam jet will cavitate and the

transfer cannot proceed.

3. The receiving tank is checked to determine whether there is sufficient space to receive all the solution to be transferred. If there is insufficient room, the operator is informed. Otherwise, the spargers are turned off and the liquid levels in each tank are measured and remembered.

4. The transfer is initiated by manipulating the necessary valves and switches (when the liquid temperature is low enough). The second digester is placed in the heating mode so that liquid may be reheated as it arrives.

5. The transfer is monitored while in progress by observing the rate of change in the liquid level in the sending tank.

6. When the liquid level drops to the empty mark, the transfer is terminated. The spargers are turned off to obtain accurate level readings in both the sending and receiving tank. If the volume of liquid received by the second digester is more than 5% different than the volume sent from the first digester, the operator is instructed to examine the system for problems (eg. spills).

7. Monitoring of the first digester is reset to begin again at step 1 above. A similar program segment that monitors the second digester is then enabled.

Each time the automation initiates an action in the field, the automation waits a period of time (depending on the action taken) to allow the physical system to respond. Then sensors are checked to verify that the action was completed. If the action was completed as expected then the automation continues to the next step. Otherwise, the operator receives a printed message at the

computer terminal reporting the offending device. The operator then has the option to instruct the automation to try again immediately or to go to the field, correct the problem, and then instruct the automation to continue. If the problem is severe enough an automatic shutdown is initiated and the operator must restart the system when all equipment have been repaired.

Feedback Control

Ordinary feedback control using proportional-integral (PI) algorithms are used throughout the IPD facility, but few are associated with the control of the dissolver system. Concentrated and dilute acid flow rates are controlled around setpoint values using flow control valves. Flow control valves are also used to control temperature by manipulating steam flow rates to the jackets of the digester tanks when they are in the heating mode. Setpoints for all these parameters are calculated automatically and passed to their respective controllers.

Expert Systems Technology

Expert systems technology has been utilized in two primary areas; on-line material balances and a system oversight monitor or, simply, watchdog.

Material balances are used to select flowrates of nitric acid that will result in proper product concentrations of uranium and nitric acid for a given throughput of uranium, as already mentioned. Because the shear undergoes a reload cycle at the end of each fuel assembly, there is a period when the uranium feed rate to the dissolver stops. This, together with the fact that the holdup time in the dissolver can be reduced somewhat without strong

adverse effect on the removal of uranium from the stainless steel, permits the metal throughput to be increased for short periods to maintain a desired average throughput. This means that the same material balance equations may be used to recalculate the acid flowrates on the fly to compensate for increasing the uranium feed rate (ie. shear chopping rate). Also small biases in flow measurements or perturbances to the system result in varying product batches, which can also be corrected by continuously monitoring the concentration in the product collection tank (first digester) and making appropriate changes to the acid flow rates. With the instrumentation available for normal control, monitoring the rate of change of both total product quantity, and uranium and acid concentrations to determine what the product concentrations will be up to one hour into the future is feasible. Performance has been enhanced by calculating these future values and making small adjustments to cause product to reach target concentrations.

The watchdog is used as an extra layer of process monitoring and supervisory control. The PCMs in which the automation runs are limited to the size of program that can be installed. Rather than burden the automation with process checks that do not need to be done once per second, the watchdog was developed to monitor the entire process, and it runs in the host computer where program size is of less concern. Many of the features in the watchdog emulate actions an experienced operator would take to specific process conditions. The watchdog was programmed to run at a frequency of once per minute and performs the following:

1. Checks the status of the PCMs to verify that program execution

has not halted.

2. Verifies proper operation of all sensors associated with the dissolver operation. The design of the instrumentation system is such that any instrument failure causes a flag associated with the read datum to indicate failure. If the failed instrument has a backup instrument, the problem is merely reported. If a critical component fails, the dissolver is set to shutdown into a safe condition. (The verification of sensor operation does not guarantee that the calibration is correct. The only way to do this is to check the readings against other indicators if they exist.)

3. Liquid levels in all tanks are checked to be sure there is no impending overflow. Temperatures are also checked to verify that the process is near nominal conditions. Flow elements are examined to determine if there is a partial or a complete blockage.

4. Diagnostic codes from the dissolver motor controller are intercepted and interpreted. Rather than send an error code to the operator, the watchdog prints an English language message describing the problem the motor control is experiencing.

Any instrument failure is reported to the operator. If the operator corrects the problem, the watchdog recognizes this and reports that the failed equipment has been repaired and is back on-line. Serious problems may result in either a partial or total shutdown of the dissolver system. For example, if the hulls canister is full and the operator fails to replace it with an empty canister, then fuel feeding, drum transfers, and isolation valve operation are suspended but liquid handling operations continue. As another example, if the product line becomes plugged and there

is danger of a spill, the entire dissolver operation is shutdown. Some problems must persist for up to 15 min before corrective action is taken to ensure that the instrument reading is not erroneous. In these cases the operator is informed of the problem with the warning that shutdown will occur within a specified time if corrections are not made.

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1. L. D. Ladd, et. al., "Overview of a Continuous Rotary Dissolver Concept with Concentration on Motor Control and Fabrication Techniques," Proc. Nuclear Engineering Division of the AIChE National Summer Meeting, August 1991.

- Fig. 1. Process and instrumentation diagram for the prototype dissolver.
- Fig. 2. Control system architecture as related to the dissolver.
- Fig. 3. Example page of POD from dissolver automation showing operation sequence of an isolation valve.