A MODULAR APPROACH FOR AUTOMATED SAMPLE PREPARATION AND CHEMICAL ANALYSIS

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ABSTRACT

Changes in international relations, especially within the past several years, have dramatically affected the programmatic thrusts of the U.S. Department of Energy (DOE). The DOE now is addressing the environmental cleanup required as a result of 50 years of nuclear arms research and production. One major obstacle in the remediation of these areas is the chemical determination of potentially contaminated material using currently acceptable practices. Process bottlenecks and exposure to hazardous conditions pose problems for the DOE. One proposed solution is the application of modular automated chemistry using Standard Laboratory Modules (SLM) to perform Standard Analysis Methods (SAM). The Contaminant Analysis Automation (CAA) Program has developed standards and prototype equipment that will accelerate the development of modular chemistry technology and is transferring this technology to private industry.

DEPARTMENT OF ENERGY ENVIRONMENTAL EFFORT

The environmental program has become one of the fastest growing segments of the DOE. The DOE and its predecessor agencies have been responsible for developing and maintaining the U.S. nuclear deterrence capability for more than 50 years. With the apparent need for deterrence reduced, the DOE is addressing issues involving the reduction of its nuclear stockpile. In addition to re-configuring the nuclear production complex, the DOE is addressing the environmental issues associated with nuclear power production and nuclear arms research and manufacture.

In 1993, DOE earmarked 25% of its budget for environmental work. The largest share of the environmental budget is allocated to remediation contractors at the various DOE sites. However, attention and dollars have been devoted to the development of new technologies to aid in the cleanup process. This effort is being organized within the Office of Technology Development (OTD). The OTD, through the Robotics Technology Development Program (RTDP), is developing robotic technologies currently unavailable. These technologies will make the remediation effort proceed more quickly, more safely, and more economically. The DOE and its contract laboratories make several million chemical, biological, and radiological determinations per year, and this number is expected to grow to approximately 10 million per year by 1995. Because of the unique characteristics of some DOE waste (e.g., the presence of radio-nuclides), offsite characterization is sometimes impractical. The sheer magnitude of the analysis load dictates an automated production approach to its solution.

CONTAMINANT ANALYSIS AUTOMATION PROGRAM

The Contaminant Analysis Automation (CAA) program was formed in 1990. The mission of the CAA program is to reduce the cost of the remediation effort by developing automation technologies that will reduce the need for human interaction. The program consists of a team of chemists and engineers from national labs, educational institutions and private industry. A by-product of reducing human interaction will be increased quality of the characterization by reducing operator caused variance in the analysis and reduced operator exposure. By developing machines that run continuously, more efficient use can be made of existing facilities, and improvements in the sample turn-around time will be realized.

Once the CAA team identified the priority analysis methods needing immediate attention to assist in the environmental remediation process, they set about to find solutions. Initial research revealed that standardized modular instrumentation and equipment, both hardware and control software, were necessary if automated systems were to be beneficial.

MODULAR CHEMISTRY

The concept of automated modular chemistry is very simple in theory. The idea is that the physical motions involved in the preparation and analysis of a sample can be reduced to discreet tasks, that these tasks can be emulated, and then replaced by interchangeable automated modules. A small number of these interchangeable modules can be configured to allow many different, complex processes to be automated.

Conceptually, all samples, whether they are analyzed in real time or using more traditional sampling methods, undergo three general categories of operations: first, preparation, second, analysis, and third, data interpretation. These steps combine to perform an analysis on an environmental sample. When a procedure is verified as yielding correct results, it is classified as a Standard Analysis Method or SAM. The steps of a SAM are depicted graphically in Figure 1.

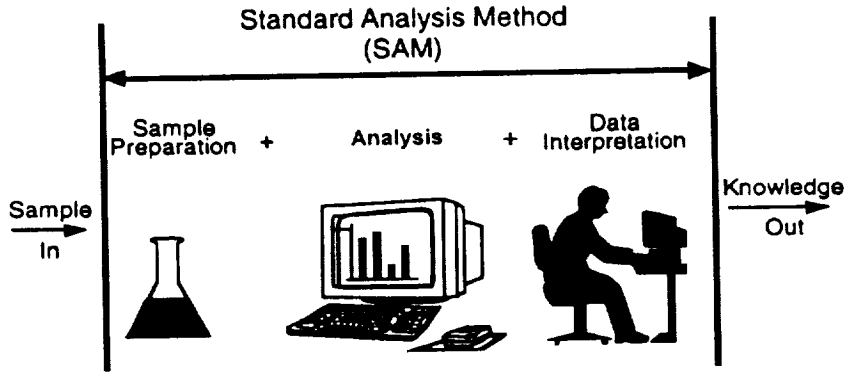

Figure 1. Standard analysis method.

In actual practice, a wide variety of sample preparation procedures, analysis equipment, and comparison data is used to determine whether a sample is contaminated. The condition of the sample, the chemicals of interest, and the regulatory requirements determine the combination of preparation, analysis, and interpretation tools used to make this determination. Each different configuration of modules constitutes a different SAM.

Embedded within the three general categories of process operations presented above are the sample-specific methods. These methods are procedures that govern sample processing and ensure uniform results. The approved protocol of the sample-specific method, such as the methods of EPA SW-846, are closely followed. One method, or combinations of several sample-specific methods, are used to perform a sample preparation, with the combination differing from sample to sample. These sample-specific methods are composed of the discreet tasks above and are generally performed by a technician or chemist. These tasks are arranged into the following classes of Laboratory Unit Operations (LUOs):

- Manipulation
- Measurement
- Data Management
- Separation
- Conditioning
- Documentation
- Transfer and Transport

Examples of LUOs include marking and recording a beaker, weighing a sample and recording the weight, moving a beaker, pouring a beaker, adding a solvent, or filtering a liquid sample. From an automation perspective, some LUOs will require a single module to perform, while other modules may combine multiple LUOs. A logical grouping of LUOs that together perform an operation of an analytical protocol is defined as a Standard Laboratory Module (SLM).

STANDARD LABORATORY MODULE

To illustrate an example of a sample preparation SLM, consider the task of "dissolve" in an analytical protocol. The process begins with the removal of the cap from the vessel containing the sample. This is a manipulation LUO. The next step is to add a dissolving agent (an acid or a solvent). This is a liquid handling operation. The cap is then replaced, resulting in another instance of a manipulation LUO. Waiting for the reaction to reach completion is a conditioning LUO. Finally, the first three LUOs are repeated as necessary to bring the resulting solution up to a target concentration. These steps may be combined into a single or multiple SLMs. A second example, that of an interpretation SLM, is the sequence of LUOs associated with taking the analytical instrument data and reducing them to an analytical result. This might require retrieving spectral data from a sample, and then comparing that data to standards and determining if the sample is contaminated, based on regulatory standards.

SLMs can be predominantly hardware, software, or both. For sample preparation functions, SLMs tend to be more hardware oriented, while in the data-handling and interpretation arena, they are more software intensive. The Standard Laboratory Module is the primary building block of the CAA program. The intent behind the SLM is to create an instrument with standardized interfaces, both mechanical and control.

SLM Boundaries

The boundaries of an SLM are by no means easy to identify in all cases; however, defining and standardizing these boundaries is a critical parameter of the standardization effort. Guidance for the logical grouping of LUOs into the inner boundaries of an SLM comes from an examination of analytical methods performed in the laboratory. Another grouping approach is to gather LUOs that are physically carried out in sequence into an SLM. Other potential SLM boundaries occur at branch points in the preparation and cleanup process. The EPA sample specific methods often can be encompassed in a single SLM. The SLM boundaries are also heavily influenced by commercially available equipment and the concerns to make an SLM that can be used outside of an automated system. A graphical representation of the boundary inputs, and outputs of a generic SLM is presented in Figure 2.

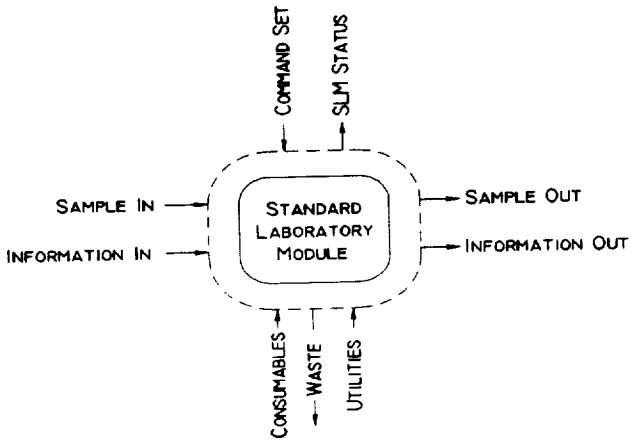

Figure 2. SLM and boundary interfaces.

Interface Standards

One solution to the interface problems is to redefine and reinvent the chemistry to improve the standardization effort; however, this would require years of research and development, and then additional years of validation work. In its initial charter, the CAA decided that, from the DOE standpoint, the most benefit would be realized from developing uniform automation protocol for existing chemistry rather than developing new chemistry protocols. This will result in a more immediate benefit as well as enhance the development of new analysis technology. The approach taken by the CAA team is to use a varied interface protocol. The SLMs will use input/output format conducive to the current manual method. This will slightly reduce the wide plug and play philosophy since not all SLMs will receive input from all other SLMs. However, a relatively short implementation time will expedite the use of existing commercial technology and equipment.

The interface connections to an SLM fall into four categories: First, Sample/Information In, Second, Sample/Information Out, Third, Utilities/Consumables/Waste, and Fourth, Communications. The major obstacle to defining an interface standard is determining the optimal size and format of sample input and output. This is due to the fact that when performing the methods manually, the technician is unaffected by the size of the container, or the amount of fluid in it. The technician can easily compensate for variances in the process. Automation is not quite so amiable. An example of one possible input is a 150 mL sample in a 300 mL beaker. The sample will also fit in a 500 mL beaker, but not in a 100 mL beaker. The input could be limited to 300 mL beakers, this is neither logical nor feasible as sample input size may vary between 0.5 mL and 500 mL. As illustrated, the interface standardization is limited by the current technology and methods. Several solutions are being investigated.

The current CAA approach defines a set of glassware standards that will be supported by the SLMs. This is not an unlimited configuration, but specifies a group of containers that will be used for ranges of sample volumes. However, when designing an SLM, the developer must carefully examine those modules that will receive and send samples. As new methods are developed, this disparity in sample format and size will be reduced.

One possible sample interface standardization solution is the use of direct sample transfer. In this method, the sample is transferred from SLM to SLM via connected tubing. This has distinct advantages and disadvantages. The use of tubing removes a large portion of the glassware from the system, and removes the associated problems. However, this adds the requirement for transfer stations to route the samples to the SLMs as required. The SLMs could be directly plumbed, but this might preclude the easy use of multiple SAMs on a single system. The SLMs being developed at the national laboratories have the provision to allow tube transfer. This feature will allow tube transfer concepts to be developed and evaluated.

Generally, sample preparation SLMs will require the same types of utilities, such as power, compressed air, vacuum, and solvents. These SLMs will also require waste disposal provisions such as off-gas, rinse, sample waste, and heat. An interface standard is under development that outlines what will be provided by the system, and what will be the flowrates, voltages, etc., for the utilities. It includes connector sizes and port connections. All SLMs will not have the same needs; thus they will not be required to provide connection provisions if the particular utility is not needed by that SLM.

The communications interface standards will be RS-232 and IEEE-488. A communications protocol is being defined. While the command requirements for different SLMs will not be the same, the command structure will be uniform to expedite development. This will include protocol for status reporting, information and data transfer, and remote control of the SLMs by the system controller.

To maintain a "plug and play" approach, a requirement was added that an SLM should not require a "knowledge" of or the existence of another SLM. Each SLM should be able to carry out its intended operation without relying upon another SLM. However, each SLM interacts with a controller through a standard interface as part of an automated system.

One major concern of a modular system is that a byproduct may be the creation of instruments that are not functional outside of the system. To reduce this problem, the ability to function independently, or in "stand-alone mode" is being developed. At this point, this is not a requirement, but function that has generated much interest. This feature also makes the technology and instrumentation developed by the DOE laboratories more desirable to commercial interests. The stand-alone feature is also very useful when the SLMs are brought into the laboratory for validation. Also, as SLMs are acquired, they can be used individually before assembling several into automated systems. This stand-alone capability also improves the desirability of the instrument by making it more adaptable.

AUTOMATED MODULAR PREPARATION AND ANALYSIS SYSTEM

One critical part of the definition of the SLM boundary standards is the determination of system conditions. This arrangement of SLMs is referred to as the Automated Modular Preparation and Analysis System (AMPAS). Inclusive in the AMPAS are both the software that coordinates the entire procedure and the hardware support that enables a SAM to function autonomously within the system.

The AMPAS will provide the means to perform LUOs that may or may not fit into a particular SLM. A specific example of such an LUO is the transportation of samples and consumables. This operation may cross the boundaries of many SLMs and therefore cannot be considered an SLM. In the current prototype system, this function is performed by a robot. These support devices are called Standard Support Modules (SSMs). While modularized, these devices do not fit the complete definition of the SLM. Individual SLMs have a knowledge of the SSMs when applicable. An example is the case where a robot is depositing a beaker into an SLM. The SLM must verify that the robot arm has been removed prior to beginning processing. Additionally, when the SSM is the supply source, the SLM must know if sufficient material is available to complete the process. SSMs are directed by the system controller and generally will not be used in a stand-alone fashion.

The consumables and service required by each SLM are coordinated and controlled by the AMPAS controller. The AMPAS will include supply resources for disposables, clean labware, disposal of labware, reagent reservoirs, and other system resources such as compressed air, potable water, vacuum, power, and heating, ventilation, and air conditioning (HVAC).

AMPAS CONTROL SYSTEM

With the AMPAS, a chemist will be able to acquire and link SLMs to follow the script of the method being performed. In other words, the chemist is operating at the chemical operation level in dealing with subtasks, such as "weigh sample," "dissolve," "extract," "separate," "measure," "interpret," etc., and not operating at the hardware or software level.

Before the AMPAS controller instructs an SLM to "dissolve," it must first be able to ascertain that enough acid is available to complete the task. It will check the acid-supply SSM, then either proceed or report that it cannot do so and state a cause. The real-time control system software runs VxWorks on a VME backplane with a VME card dedicated to each SLM. Commercial versions of the SLMs may have onboard processors rather than external VME cards for the real-time hardware control and external communication.

A UNIX-based platform was chosen for implementing the AMPAS control system software on the basis of its real-time capabilities and its multitasking features. The control software is written in the C++ language. A multi-tasking environment allows the system to process multiple samples. The system interfaces with the site facility through any existing laboratory information management system (LIMS). A methods manager provides translation from high level methods requested by the chemist into lower level scripts of SLM commands necessary to carry out the requested chemistry. The software architecture is shown in Figure 3.

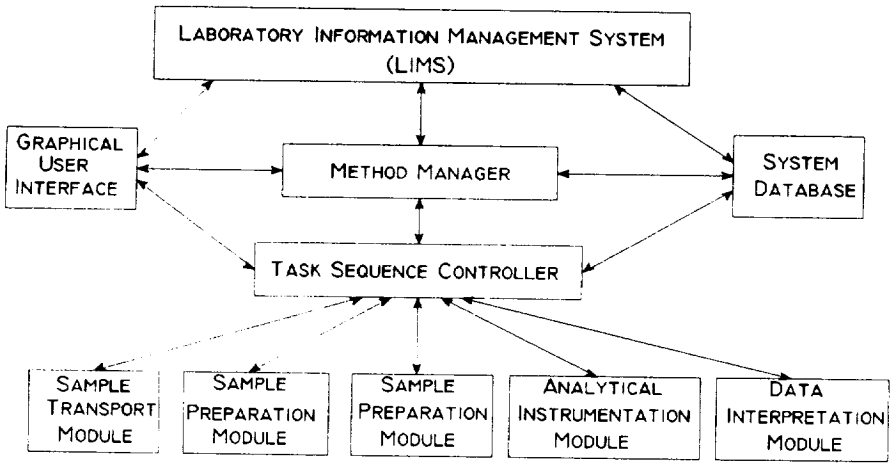

Figure 3. Automated modular preparation and analysis system.

The task-sequence controller performs script processing, scheduling, and supervisory control of the SLMs in the system by communicating with the dedicated SLM processors. The system database serves as information storage for the automated laboratory, providing a detailed audit trail for all phases of preparation and analysis. The user interface provides operator access to the LIMS, method manager, database, and task sequence controller.

TECHNOLOGY EVALUATION AND VALIDATION

The EPA procedures for extracting, cleaning, and identifying polychlorinated-biphenyls (PCBs) in soil samples were chosen as targets for the initial automation into SLMs. To evaluate the feasibility of the requirements, modules have been built to preliminary standards. A prototype AMPAS is being developed for use as a test bed that will allow insertion of

completed SLMs for performance and compatibility testing. Two sample preparation methods selected to provide the largest impact were U.S. Environmental Protection Agency (EPA) Methods 3540 (Soxhlet Extraction) and 3550 (Sonication Extraction). These methods were selected to use as test fixtures for the standardization and modularization technology.

SLMs that perform Soxhlet extraction, sonication extraction, sample drying and filtering, and gel permeation chromatography (GPC) cleanup (EPA Method 3640) were demonstrated in an integrated, hood-enclosed system in March 1992. Two rail robots were used to move samples between the SLMs. The test bed layout is shown in Figure 4.

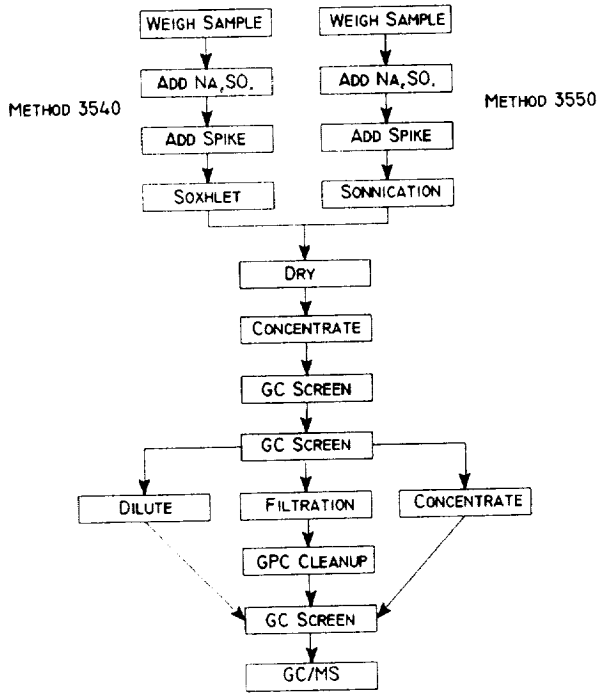

Figure 4. System test bed.

Currently, the remaining SLMs required to perform the steps in an automated PCB sample analysis are under development. A gas chromatography instrument is being incorporated into the SLM protocol, and the requirements for automated data analysis are being established. An integrated system carrying out a fully automated semivolatile organic SAM, that targets PCBs will be demonstrated in 1994. Other protocols will soon be addressed, including the acid digestion sample preparation methods and radiological methods not currently covered by EPA protocols.

In the initial attempts at automation, the manual steps were followed closely. While this approach did not result in the most efficient equipment, it did allow for automation that shows the chemistry can be automated and allows for easier validation to existing approved techniques. The completed SLMs are undergoing chemical validation tests in the DOE environmental laboratories. These tests will ensure the automated sample preparation meets the quality control criteria in the EPA methods. Validated SLMs will gain approval from the

DOE's Lab Managers Branch for their use in the DOE Methods Compendium. The Lab Managers Branch also will pursue EPA approval to use these devices to carry out EPA methods.

TECHNOLOGY TRANSFER AND COOPERATIVE RESEARCH

The automation of chemistry is not new, nor is it exclusive to the CAA program. The intent is not to redefine or reinvent the chemistry being used, but rather to define a standard for the equipment used to perform the chemistry. In terms of technology, the CAA found two needs, the lack of standardization, and the lack of a concerted effort and governing body for standardization.

The CAA team realized at the inception of the program that the DOE did not have the means or the resources to develop the modules needed to address the analysis problems. To accomplish the goals, required the use of existing technology by teaming with many organizations. The automated equipment needed to do most of the chemical analysis is widely available. However, the equipment does not work together, does not communicate, and is not conducive to automation.

Some modules developed to date used commercially-available equipment adapted to fit the SLM formalization. Several equipment manufacturing companies currently are working with the CAA program on a cost-sharing basis to develop SLMs or convert existing devices and instruments into SLMs. ABC Laboratories developed the GPC SLM from a pre-existing automated GPC device. The Sohxlet Extractor SLM was adapted from commercial manual equipment.

The CAA team also concluded that in order to develop sufficient quantities of automated systems for DOE's needs would require a system integrator. The role of the system integrator is to find potential customers, access their needs, and then configure and support the AMPAS operations. A second duty of the system integrator is to ensure that SLMs required for SAMs are readily available. To expedite the integration effort, the CAA program has partnered with U.S. Industry. The CAA program has selected Lockheed and Hewlett-Packard (Lockheed/HP) to act as the sole AMPAS Integrator to supply and support fully-automated laboratories to the DOE and commercial markets.

The DOE Headquarters-Office of Technology Development (DOE HQ) and Los Alamos National Laboratory (LANL) are in the process of completing a "Guidance Document" for the CAA program. This Document will detail the programmatic and technical interactions of all CAA participants. Additionally, the Document will describe the program management chain-of-command and recognize that DOE HQ will lead the effort utilizing LANL as a coordination focus. DOE HQ will not own any intellectual property rights.

Lockheed/HP has put into place a new organization to focus on commercial products to develop, manufacture and support CAA system and equipment. The CAA/Lockheed/HP team has initiated the technology transfer activities including, requirements definitions, lessons learned, system development and other value added activities. Fairness of Opportunity guidelines will be followed during the SLM partner selection process to select the most appropriate SLM manufacturer/s. The criteria/guidelines for the partner selection process will be determined by CAA/Lockheed/HP and the subject laboratory.

Participants

LANL is the lead laboratory in the CAA coordination area of the OTD. The other national laboratories, involved in the CAA effort include Pacific Northwest Laboratory (PNL), Idaho National Engineering Laboratory (INEL), Sandia National Laboratories (SNL), and Oak Ridge National Laboratory (ORNL). In addition to government agencies and private industry, numerous universities and educational institutions are involved in the CAA program. The DOE currently is also working with the National Institute of Standards and Technology as part of its Consortium on Automated Analytical Laboratory Systems (CAALS) to develop these standards. The CAA model is being tested by CAALS as a candidate standard.

CONTINUING DEVELOPMENT

Current efforts of the CAA program include the refinement of the test bed, development and review of interface requirements, development of the additional SLMs required to complete target SAMs, and transfer of the program technology to private industry. Research is underway to further identify chemical laboratory needs and wants. This will direct the development of new modules, systems, and technologies. Work is continuing with EPA and individual state certification agencies to expedite and refine the CAA technology to meet approval requirements.

The CAA/Lockheed/HP team has initiated joint discussions with the Department of Defense (DOD) to jointly configure a CAA system to assist in environmental compliance activities. The Air Force is working with the CAA team to provide sample analysis requirements, system requirements, support and cost/benefit evaluation. The DOD has initiated discussion of a multi-agency cooperation effort on the development of environmental technologies.

Once the standardization technology has been transferred to private industry, the CAA teams will concentrate on research and development of new technology to further improve the automation of sample preparation, analysis, data interpretation and information processing of environmental remediation activities.