RESEARCH AND DEVELOPENT OF RADIOXENON MONITORING SYSTEMS

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ABSTRACT

General Dynamics Advanced Information Systems (GDAIS) through its contract with the United States (U.S.) Army Space and Missile Defense Command (SMDC) is engaged in research and development, and deployment of a manufacturing prototype Automated Radioxenon Sampler / Analyzer (ARSA). A summary of the work performed this past year on the manufacturing prototype and on the U.S. participation in the International Noble Gas Experiment (INGE) will be presented.

An engineering prototype is deployed in Guangzhou, China as part of INGE. A more advanced manufacturing prototype ARSA is currently in the System Development and Demonstration phase and the design readiness review has been completed in accordance with the Department of Defense (DoD) 5000 acquisition model Technical Program Plan. Based on an initial Pacific Northwest National Laboratory (PNNL) design, the field version of the ARSA is being manufactured through a joint effort between Advanced Measurement and Technology (AMETEK) and GDAIS. By early June 2004, the manufacturing prototype ARSA build was approximately ninety-five percent complete. The mechanical assembly of the system is complete but remaining issues including the beta-gamma detector pulse processing electronics and xenon collection efficiency are being addressed. The system is scheduled to complete Factory Acceptance Testing and be installed at the RN75 monitoring station in Charlottesville, Virginia in August 2004. After installation at RN75, the ARSA will be subject to the Test and Evaluation Master Plan to be performed under the supervision of Sandia National Laboratories.

In addition to the development of ARSA hardware, GDAIS has developed advanced software to process and analyze the ARSA data. Most notably, GDAIS integrated the Multiple Isotope Component Analysis (MICA) algorithm into the Radionuclide Monitoring System (RMS) software. The enhanced RMS software will be installed at the U.S. National Data Center (USNDC) located at the Air Force Technical Application Center (AFTAC) during the fall of 2004.

OBJECTIVE

The primary objective of this research is to enhance the U.S. capability to detect nuclear detonations through the detection of radioxenon gases. The research performed by GDAIS centered on advancing both the hardware and software related to the Automated Radioxenon Sampler / Analyzer (ARSA) detection system. The primary objective was obtained through three program elements:

- Develop and deploy a manufacturing prototype ARSA based off the engineering prototype design;
- Continue to gain operational experience of the ARSA through participation in the INGE; and
- Advance the data processing algorithms used to analyze data from the ARSA and other radioxenon sensors.

Each program element will be described separately in the “Research Accomplished” section below.

HISTORIC PERSPECTIVE

The ARSA was originally designed by PNNL (Bowyer et al., 1998). This design was transitioned to DME Corporation who built the ARSA engineering prototype (ARSA001). ARSA001 along with system documentation and schematics was delivered and installed in a GDAIS facility in Charlottesville, Virginia in 2001. At this facility, GDAIS tested and evaluated the ARSA001 to assess its readiness for field deployment, to assess its ability to meet certification requirements, and to develop a manufacturing plan for future units. After several design modifications, ARSA001 was delivered to Guangzhou, China as part of the INGE in 2002 (Penn et al., 2002 and 2003). GDAIS was contracted by SMDC in 2003 to build the ARSA manufacturing prototype (ARSA002). After a competitive bid process, GDAIS selected the ORTEC division of Advanced Measurement Technology, Inc. (AMETEK) as its manufacturing partner.

RESEARCH ACCOMPLISHED

ARSA Manufacturing Prototype

During June 2003, the ARSA research and development task was reviewed by a joint audience representing DoD and the Department of Energy (DOE). GDAIS presented a Technical Program Plan (TPP) developed jointly with SMDC in accordance with DoD acquisition policy, directive 5000. The TPP outlines the execution strategy to build and install the ARSA manufacturing prototype in Charlottesville, Virginia. The ARSA system is currently in the System Development and Demonstration phase and has successfully passed the design readiness review. After the design readiness review was completed, the system was cleared to continue with the build of a manufacturing prototype.

The ARSA manufacturing prototype task is aimed at the production, installation, and performance validation of automated radioxenon detection equipment. The task leverages GDAIS experience along with operational experience of the engineering prototype (currently installed in Guangzhou, China) to produce a reliable design that meets all requirements identified in the TPP. The most notable requirement is the minimum detectable concentration of 1mBq of XE-133 per cubic meter (m^3) of air at standard temperature and pressure (STP).

The ARSA manufacturing prototype (ARSA002) build is a joint effort between GDAIS and AMETEK. The joint effort takes advantage of each company’s strengths to produce an end product that will be commercially available. GDAIS provides scientific and software support and AMETEK brings manufacturing and design expertise to the program. Both companies work together to provide documentation and configuration control.

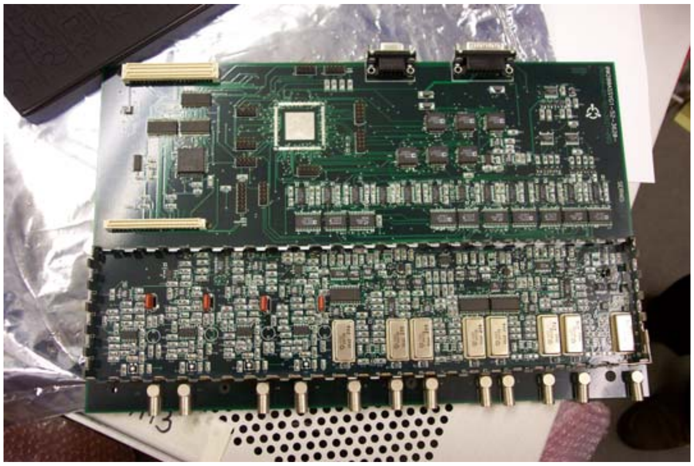
ARSA002 construction began in August 2003. Figure 1 shows the ARSA frame during the initial construction period. The production of the manufacturing prototype has gone well except for a few schedule setbacks. The majority of the setbacks were due to issues identified as program risks early on and ended up becoming more difficult to resolve than originally anticipated. The three issues that most notably affected the ARSA002 production were the state of the engineering prototype documentation, communications between the control computer and the process control hardware, and the need to have the system nearly complete before software testing could commence.

Figure 1: ARSA Manufacturing Prototype under Construction

The engineering prototype documentation received from DME that was to be used for the ARSA002 build was extensive; however, it contained many errors and was incomplete in several key areas. For the mechanical assembly, although the documentation was complete, it contained multiple errors. For example, the documentation would have incorrect placement of holes for fabricated parts so that after fabrication the part could not be assembled and would have to be reworked or replaced. Also, many errors were found in the layout of the wiring harness that resulted in wires crossing either rendering the component inoperative or destroy it. As the build continued, the drawings were marked for correction and the appropriate level of detail added so that after completion, the drawing set can be updated to reflect the current design.

The greatest issue associated with the drawing package was the state of the documentation for the radiation detector pulse processing electronics. The detector electronics package is composed of two custom electronic boards with analog and digital circuitry. The analog component was fairly well documented and even included data for commercial production of the printed circuit board. The digital component had major portions undocumented and was not consistent with a 75% complete prototype board that was delivered with the documentation. Once work began on the detector electronics, it was clear that the task required significantly more time than originally scheduled. It was not clear from the documentation and previous experience with the engineering prototype how some of the circuitry was operated. A team of experts was assembled to asses the electronics and determine a path forward. The team of experts evaluated the electronics for two weeks and came to the conclusion that the design had enough merit to continue with development and not start over. The board was then delivered to the AMETEK research and development (R&D) experts who have nearly completed the board design and fabrication. The board currently is connected to the detector and produces coincidence spectra but has a high dead time (~25%). The dead time is the time spent processing a pulse before a new pulse can be accepted. The issue of dead time is currently under investigation. The most likely cause is ground loop problems or a possible intermittent failing component on the electronics board. Figure 2 shows a picture of the completed electronics board and CS-137 spectrum used for calibration.

The communication issues between the control computer and the process hardware were numerous and sometimes difficult to diagnose. The process of solving the problem was taken in steps and first uncovered several infant failures in the hardware. The majority of hardware used in the ARSA002 build was spare parts from the ARSA001 build. The control computer talks to approximately 120 pieces of instrumentation for control and monitoring of the system. Each of the 120 pieces of instrumentation are connected to one of seven electronic backplanes that has an electronic brain (OPTO22 SNAP B3000) that interprets the signals and communicates directly with the control computer through an RS485 serial circuit. When the system was first initialized, it would automatically shut down within seconds due to a watchdog circuit built into each brain. If a brain did not receive a command within a set period of time, the watchdog circuit would shut down the brain and not allow further commands to be processed.



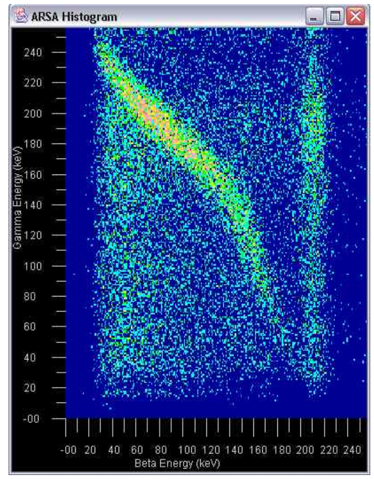


Figure 2: Detector Electronics Board and Calibration Spectrum

The infant failure experienced was determined to be an internal issue with the SNAP brain that shut off the receive buffers in the brain and tripped the watchdog circuit. Two brains were replaced because of this problem.

The next issue with the communication circuit was a very high level of error generation. Much time was spent seeking technical support from the hardware manufacturers and eventually all options were exhausted. Finally, a consultant was brought in to diagnose the system. The consultant determined the problem was a bad printed circuit board on one backplane that was disturbing communications to all of the backplanes. The board would not go into a fault state long enough to be picked up until it had pressure applied to a certain point as was done when the connection was being made.

The last problem with the communications was very elusive to find due to its intermittent nature. The system would lose communications for approximately 10 seconds causing the system to shut down with a frequency of occurrence ranging from hours to days. Technical support for the hardware vendors recommended testing different configurations of the hardware to resolve the issue. When this was unsuccessful, we developed a test that logged each command the system sent both internally by the control computer and externally through a computer placed on the circuit. The logs from the two computers were compared and it was determined that for a brief period of time the control computer would think it sent a command but it was never seen on the communication line. This showed that the problem was in either the control computer or the communications (RS485) circuit. A call was then placed to the operating system (OS) vendor, QNX, and after quite a bit of discussion they admitted that there is a problem with the new QNX OS serial driver and that a new driver was going to be formally released soon. In the interim, we were given a beta version of a fixed driver and this resolved the problem. Unfortunately there was no documentation of this problem in the public domain and it appeared that many of the QNX technical support personnel were not aware of it either.

Once the mechanical and communication issues were resolved, the system software was tested and several bugs were identified and repaired. Currently the system is running well and is producing approximately 1.5 cm^3 of xenon per 8 hour sampling period, exceeding the requirement of 1.0 cm^3. The only major remaining issue to be resolved is the dead time of the detector electronics.

Once complete the system will be tested as outlined in the Test and Evaluation Master Plan (TEMP) that was generated as part of the TPP. The TEMP consists of a Factory Acceptance Test (FAT) and a Requirements Verification Test (RVT). The FAT will be performed by GDAIS at the AMETEK facility with oversight from SMDC and Sandia National Laboratory (SNL). Testing is scheduled to begin in the second week of August. Upon successful completion of the FAT, the ARSA will be shipped to Charlottesville, Virginia where it will be installed at the RN75 monitoring station. An installation plan has been developed and is currently being evaluated by the U.S. station Configuration Control Board (CCB). Figure 3 shows the proposed configuration of RN75 after installation of the ARSA.

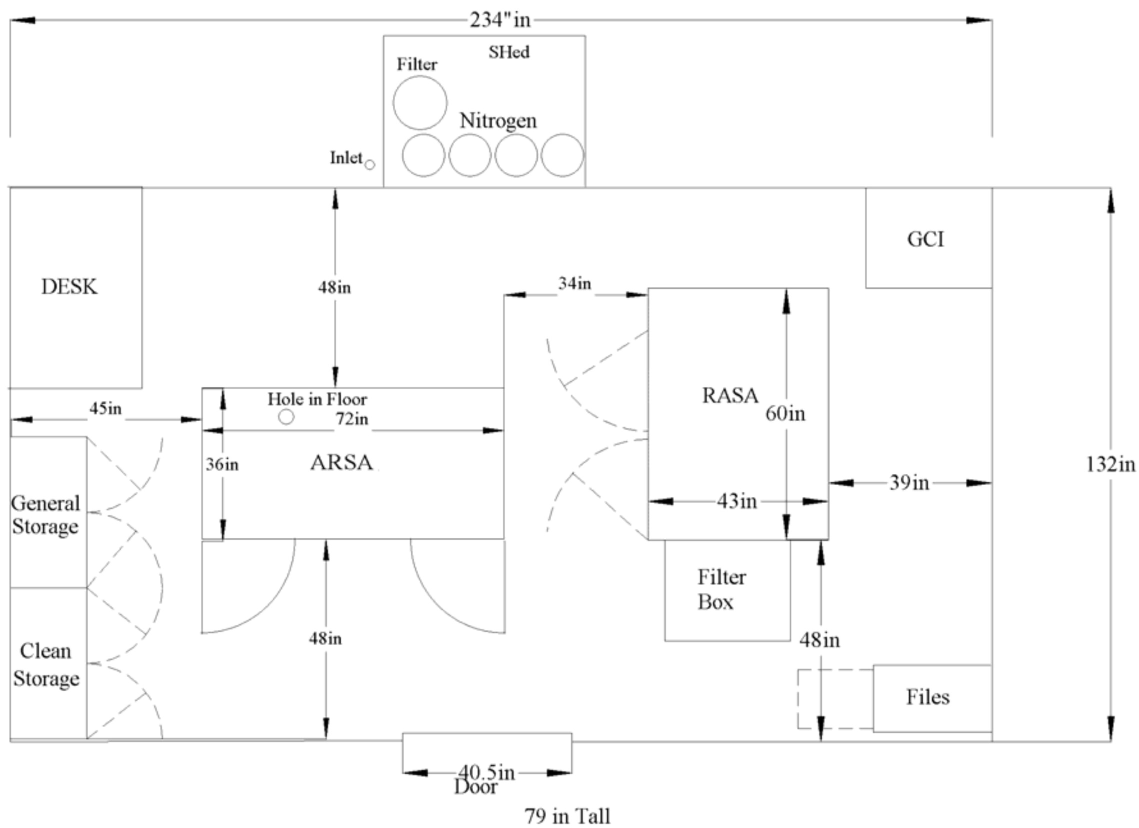


Figure 3: Proposed RN75 Layout after ARSA Installation

Once the unit is operational at RN75, SNL will conduct the RVT under the direction of SMDC to ensure that the system meets all design requirements. Once the system passes the RVT, the drawing and documentation package will be updated to reflect the final configuration and the system will be ready to be transferred to production. The RVT is tentatively scheduled for December 2004.

INGE Participation

ARSA001 was installed in Guangzhou, China in November 2002 (see Figure 4) and entered the International Noble Gas Experiment (INGE) Phase IIIA. The objective of Phase IIIA is to tune the system and have the vendors provide oversight to the local operators for operations and maintenance of the equipment. Phase IIIA lasted approximately nine months and the system experienced several issues that required intervention for the system to continue operation. These issues resulted in a total downtime of 80 days. The majority of the downtime was attributed to sensors monitoring the temperature of an activated charcoal bed. The sensors would fail intermittently causing the system to read an out of range temperature. This caused the safety systems to shut the system down automatically. The out of range temperature measurement and system shutdown occurred unexpectedly and too quickly for the system to record the fault at the preset data logging interval. Once the fault was diagnosed, the system was repaired and the system returned to normal operation. After resuming normal operation, the xenon collection was near zero. It was determined that during the diagnosis of the temperature sensors, the local operators had operated one of the collection traps without first evacuating oxygen from the trap. This caused the entire active element in the trap to burn making the trap ineffective. A new trap was fabricated and delivered to the local operators for installation in August 2003. Once the new trap was installed, the system returned to its original performance levels and the system entered into the International Noble Gas Experiment Phase IIIB.

Figure 4: ARSA Installed in Guangzhou, China

The INGE Phase IIIB utilizes the same equipment and personnel as Phase IIIA, but the level of effort from the vendors is greatly reduced. The vendors are required to perform regular scheduled maintenance of the systems. The local operators are required to perform all operations and unscheduled maintenance to the system including any diagnostics that need to be performed. The vendors have direct access to the system and can support the local operators only at the request of the INGE staff.

The last quarter of 2003 was uneventful with the ARSA performing well; the online time was approximately 83%. The downtime was primarily due to a faulty compressor. In December 2003, a scheduled maintenance trip was to be performed to replace system consumables and to check the system calibration. Approximately one week before our team left for China, the trip was cancelled by the local operators due to a schedule conflict. Due to additional schedule conflicts, it was decided that the local operators would have to perform the scheduled maintenance. The maintenance itself is a simple task of replacing filters, gaskets, and the air compressor as well as performing a thorough system leak test. The maintenance was performed by the local operators in early March 2004. After the scheduled maintenance, the system appeared to run well except that little xenon was being collected. The local operators continued to let the system operate without being able to correctly make a diagnosis. In addition, the system pressure began to drop slowly, and after a short power outage, the compressor was unable to maintain the required pressure and flow rate. The local operators then shut the system down. The INGE staff then contacted GDAIS to support the local operators.

Remotely, GDAIS was able to operate the ARSA and perform some limited testing on the system. It was determined that the air compressor capacity had degraded and that one of the xenon collection traps had been damaged. A new collection trap and a compressor rebuild kit were sent to China. Also, during remote testing the beta gamma coincidence detector electronics were found not to be responding. The beta gamma coincidence detector system is composed of a custom pulse processing electronics coupled to a multi piece scintillation detector. Several tests indicated the fault was either in the RS232 communications channel between the control computer and the electronics board or the electronics board itself. The only way we could diagnose the fault would be to travel to China.

In May 2004, GDAIS traveled to China to perform the repairs on the system. After the planned maintenance tasks were completed, the detector electronics board was examined. The communications and power to the board were found to be in working order. The fault appeared to be directly related to the electronics board; therefore, it was removed from the system and brought back to the U.S. for repair. The electronics board has been returned to manufacturer for repair and the exact fault has yet to be determined. The system is currently offline awaiting the repair and return of the electronics board. Because the electronics board is a custom part, no spare units are available.

From the last two years of operating the ARSA, it is evident that the system provides very sensitive measurements of atmospheric radioxenon, but maintenance and reliability are an issue for full time operation. Figure 5 shows the failures the ARSA has experienced in the last two years along with the associated number of days of downtime.

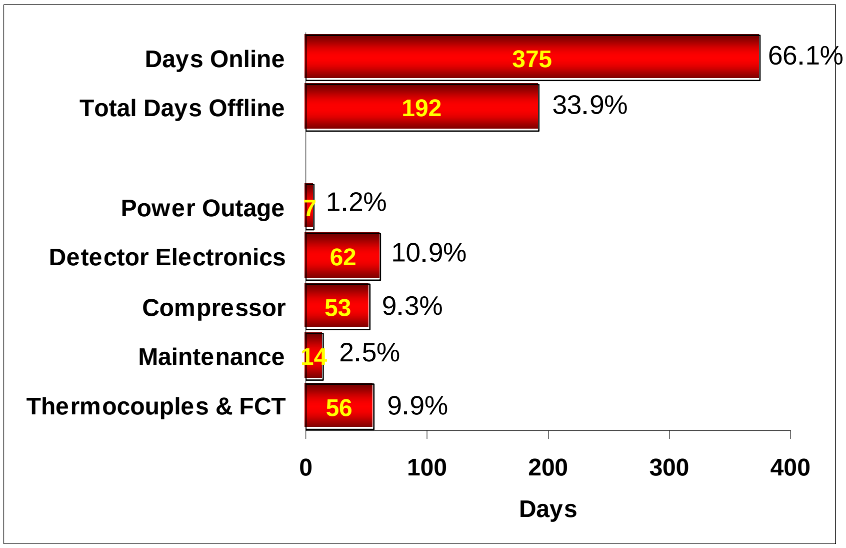


Figure 5: ARSA Reasons for Downtime

The data availability for the past two years is 66%. Much of this time was due to having no replacement parts at the site as well as local operators who are hesitant to work on the system because of its complexity. The solution to increasing the online time would be to carry a more significant level of spare parts on site as well as more extensive training for the local operators. Also, the local operators are not always aware when there is an imminent problem with the system such as a failing pressure from the compressor. Therefore, both an alert system that notifies the operator immediately after a failure has occurred and routinely inspecting the system data would significantly reduce the offline time of the system. Taking the proposed solution into consideration it is possible to reduce the offline time from the compressor, detector electronics, and thermocouples to 2 days each, one for diagnosis and one for repair. This would reduce the offline number of days to 27 and provide an online time of 95%.

Data Processing Algorithms

In addition to the development of ARSA hardware, GDAIS has developed advanced software to process and analyze the ARSA data. Most notably, GDAIS integrated the Multiple Isotope Component Analysis (MICA) algorithm into the Radionuclide Monitoring System (RMS) software. The development of the MICA algorithm was reported last year (Biegalski 2003). An overview of the MICA algorithm and a description of how it is integrated into the RMS software are presented here.

The current RMS component software used to analyze data from beta-gamma coincidence radioxenon sensors, such as the ARSA, is the program *rms_xanalyze* (Rynes 2002). This algorithm is based on a Region of Interest (ROI) approach not dissimilar from most high-resolution gamma spectroscopy algorithms, but applied in two dimensions. The main problem arising with the *rms_xanalyze* algorithm is that not all the physics of the problem are taken into account (such as XE-135 contributions in the E = 30 keV region), which can result in negative net counts or higher than necessary false positive detection rates for some radioxenons. The MICA algorithm was developed to improve the data processing for such beta-gamma coincidence data by accounting for all known physics and reduces the uncertainties involved in the results.

MICA involves the deconvolution of a sample signal into the contributions from each isotope (see Figure 6). MICA uses the entire isotopic signatures and not just ROIs; therefore, it is theoretically possible to obtain better minimal detectable concentration levels. Detector-specific responses for each possible isotope are used in the deconvolution. The responses can be generated using actual radioisotope sources counted on the detector, or they can be created using modeling techniques like the Monte Carlo N-Particle Extended (MCNPX) code. The geometry and materials of the detector must be known to produce good response files. Because only a small number of isotopes are detected in xenon samples, deconvolving a sample is not highly complex. Deconvolution of nuclear spectroscopy data is not a new concept. MICA is unique in that this methodology is applied to three-dimensional beta-gamma coincidence data. The MICA software contains activity concentration and minimal detectable concentration (MDC) calculations as well as nuclide identification methodology.

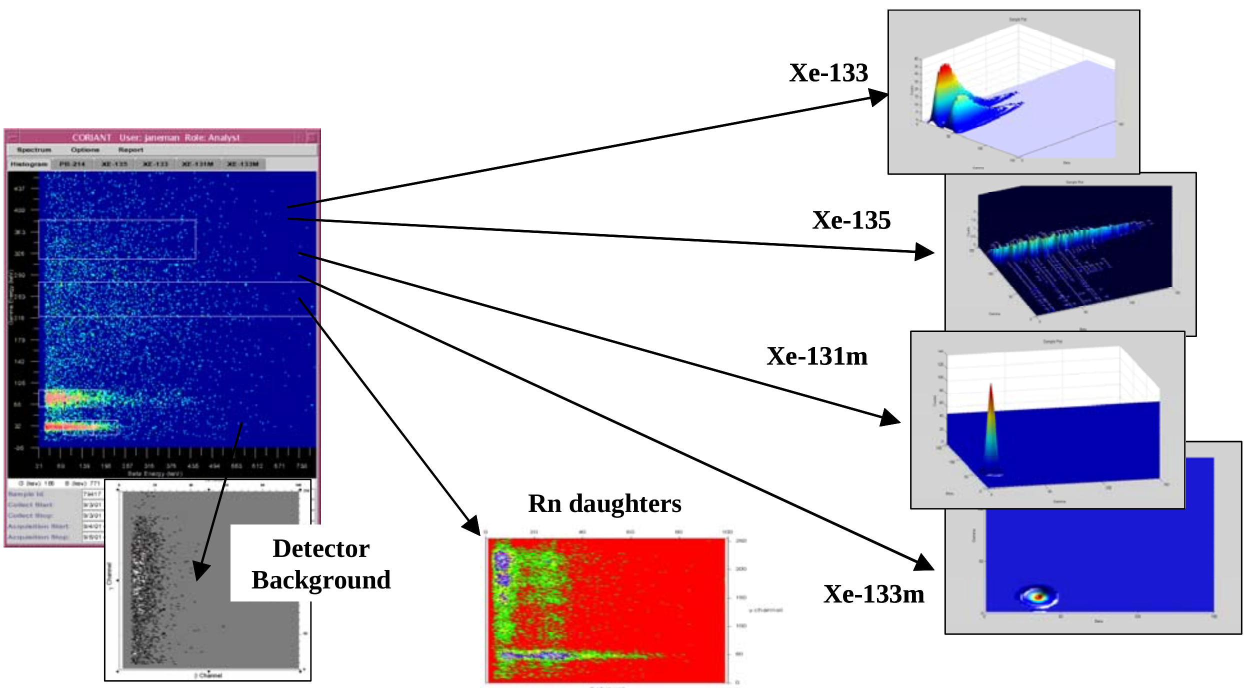


Figure 6: MICA Involve the Deconvolution of Sample Signals

The objective was to integrate the MICA algorithm into *rms_xanalyze* so that either the ROI algorithm or the MICA algorithm could be used from a single software application. The first step of this integration was to modularize *rms_xanalyze*. The new *rms_xanalyze* program flow is shown in Figure 7. It contains six modules that are executed sequentially. The functions of these modules are initialization, calibration, count calculation, concentration calculation, MDC calculation, and finalization. A major component of this work was the creation of a single data structure that contained all relevant variables and that could be passed between the modules. This modularity facilitates simple insertion of the MICA algorithm as well as the insertion of other algorithms into the baseline software at a later time. The new modular code was developed and tested against the RMS Validation Test. The new *rms_xanalyze* software produced the same validation test results as the old software.

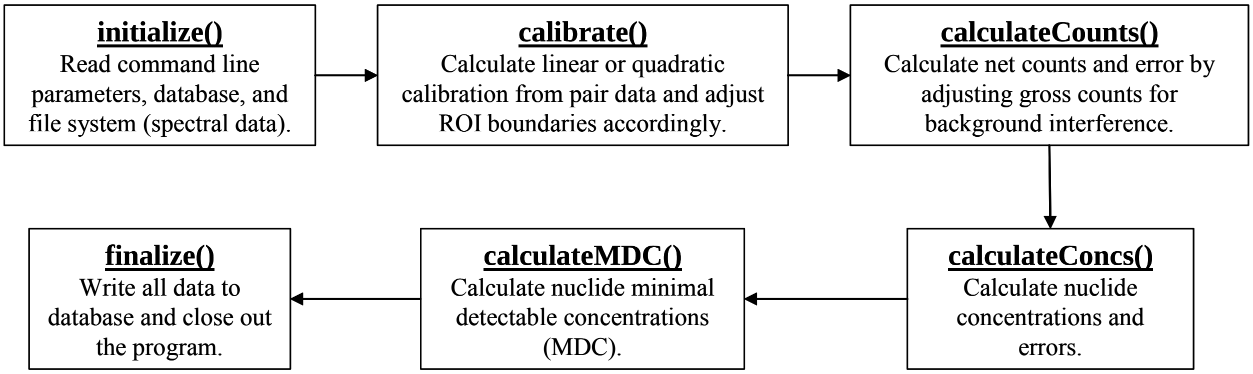


Figure 7: Processing Flow of Noble Gas Automatic Processing Software

The original MICA algorithm was developed in MATLAB, whereas *rms_xanalyze* is written in JAVA. The MATLAB algorithms that performed calibration, count calculation, concentration calculation, and MDC calculation were ported to JAVA and inserted into *rms_xanalyze*. The existing *rms_xanalyze* initialization and finalization algorithms were sufficient. The new *rms_xanalyze* with the integrated MICA algorithm was tested and it produced the same results as the MATLAB software. It should be noted that the MICA software (both MATLAB and JAVA) were tested with simulated detector response functions. Although the algorithm appears to work well using the simulated detector response functions, these functions have not yet been evaluated with a real detector system. This evaluation will most likely take place after the ARSA002 is installed in Charlottesville.

CONCLUSIONS AND RECOMMENDATIONS

The fabrication of the ARSA manufacturing prototype is near completion. The FAT is scheduled for early August and it should be installed and operating at the RN75 site by the end of September. The system is expected to meet or exceed all requirements. The delay in fabrication was caused predominately by inadequate documentation for the engineering prototype resulting in the redesign of several key components and by communication problems between the control computer and the process control hardware. The later problem was the result of faulty hardware and problems with the new QNX OS. It is recommended that the entire drawing packet be updated as soon as possible and that the drawing packet be updated on a regular basis so that these problems do not reappear in the next ARSA build.

The ARSA deployed in Guangzhou, China entered Phase IIIB of the INGE in September 2003. The system worked well from September through February when the gas processing system failed as part of scheduled maintenance by the local operator. During repair of the gas processing system, it was determined that the detector electronics board was also damaged. This board was returned to the U.S. for repair. Because this electronics board was a custom part produced by a vendor that no longer supports it, there are no spare units available and it is unlikely that the board can be repaired. It is recommended that we build a new board after the ARSA manufacturing prototype passes the FAT and install this board in Guangzhou as soon as possible.

The MICA algorithm has been integrated in the RMS software. The software is working according to its design. However, before this algorithm is installed in an operational environment at the USNDC, the MICA detector response functions must be validated against real spectra data. The detector response histograms will be improved by a combination of enhanced MCNPX modeling and direct radioxenon calibration measurements on a beta-gamma coincidence detector. The algorithm will then be tested with a large quantity of real sample data. The ARSA, soon to be installed in Charlottesville, will be used in these tests.

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