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ROBOTIC SOIL SAMPLER FOR HAZARDOUS WASTE CLEAN UP

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ABSTRACT

An innovative field sampling system using LA-ICP-AES (laser ablation-inductively coupled plasma - atomic emission spectrometry) technology is currently being developed through an integrated team approach at Ames Laboratory to provide in-situ, real time analysis of inorganic hazardous waste. This sampling approach is conducted through a mobile testing facility which consists of an instrumentation vehicle called the Mobile Demonstration Laboratory for Environmental Screening Technologies (MDLEST), and an attached trailer called the Robotic Sampling Accessory (RSA). The RSA provides automated sampling capabilities through an attached three-degree-of-freedom robot that will be equipped with surface and subsurface sampling probes. The probes are currently being designed by a multi-disciplinary team consisting of engineers and scientists at Ames Laboratory, Iowa State University, and Lockheed. This system is expected to improve sample quality assurance, reduce sampling time and cost, and improve worker safety. Limitations and future areas of research for the MDLEST-RSA are also discussed.

1. INTRODUCTION

Today, there are approximately 28,000 hazardous waste sites that have been identified in the United States[1] and of those, 1,189 which present the most serious danger to health and the environment are on the Superfund list.[2] Twenty-two additional locations are being studied by the Environmental Protection Agency (EPA) as potential Superfund sites.[2] Based upon the efforts required for remediation of 13 uncontrolled sites, the Office of Technology Assessment (OTA) has estimated it will take 50 years and $300 billion to complete the cleanup operations.[1] This figure may be underestimated since the enormity of the waste problem is still being assessed, and a determination of the issue of "how clean is clean" has yet to be made. In any event, the cost is estimated at billions of dollars for clean up of all of the hazardous waste sites in the United States as mandated by the EPA.

This paper describes a new site characterization device currently under development to provide in-situ real time remote sampling capabilities to analyze contaminated soil. The sampling techniques uses an approach called laser ablation-inductively coupled plasma - atomic emission spectrometry (LA-ICP-AES) pioneered at Ames Laboratory. The sampling analysis system consists of an instrumentation vehicle called the Mobile Demonstration Laboratory for Environmental Screening Technologies (MDLEST), that pulls a trailer called the Robotic Sampling Accessory (RSA). Attached to the RSA is a three-degree-of-freedom SCARA (selective compliance assembly robot arm) system that will be equipped with surface and subsurface sampling probes. This paper provides a description of the laser ablation and the ICP-AES analytical technique, the MDLEST and RSA, and the team responsible for designing, fabricating, and testing this system. In addition, benefits and limitations related to this sampling approach, limitations, and future plans are also discussed.

2. DESCRIPTION OF LASER ABLATION-INDUCTIVELY COUPLED PLASMA - ATOMIC EMISSION SPECTROMETRY

The analytical sampling and analysis technique, termed inductively coupled plasma-atomic emission spectrometry (ICP-AES), was developed at the Ames Laboratory under the DOE sponsorship and is used in over 5000 laboratories throughout the world for trace elemental analysis.[3] This technique is accepted by the EPA and is the most widely used analytical technique for simultaneous multielement determination of more than 70 elements at concentrations ranging over nine decades (parts per billion to percent) with a precision of 1 to 2%.[4] Typically, the conventional sample is homogenized, ground, sifted, and dissolved in acid prior to being introduced as a liquid into the ICP. However, in this application, a laser is used to ablate the soil sample (effectively creating fine particulate matter) in an enclosed cell; these small sample particles are entrained in a gas stream that is then fed directly into the plasma source. The excited atomic emission from the ICP is analyzed in a spectrometer.

The concept for remote LA-ICP-AES is presented in Figure 1.[5] A beam from a tripled Nd YAG laser operating at 355 nm, is transmitted through a Ultraviolet grade, 600μm optic fiber to initiate ablation of a surface or sub-surface sample (see [1] in Figure 1). The ablated particles, which are generally several microns in diameter, are entrained in a stream of argon gas (approximately 1 liter/minute) and fed into the ICP plasma (see [2] in Figure 1). The excited atomic emission from the particles generated in the plasma, which is representative of the sample constituents, is transferred through an optical fiber to a spectrometer that provides data on 20 selected elements simultaneously (see [3] in Figure 1). The time required for the analysis of a single surface sample is approximately 15-20 minutes. A high resolution sequential spectrometer must be used to obtain information on the isotopic composition of radioactive samples.

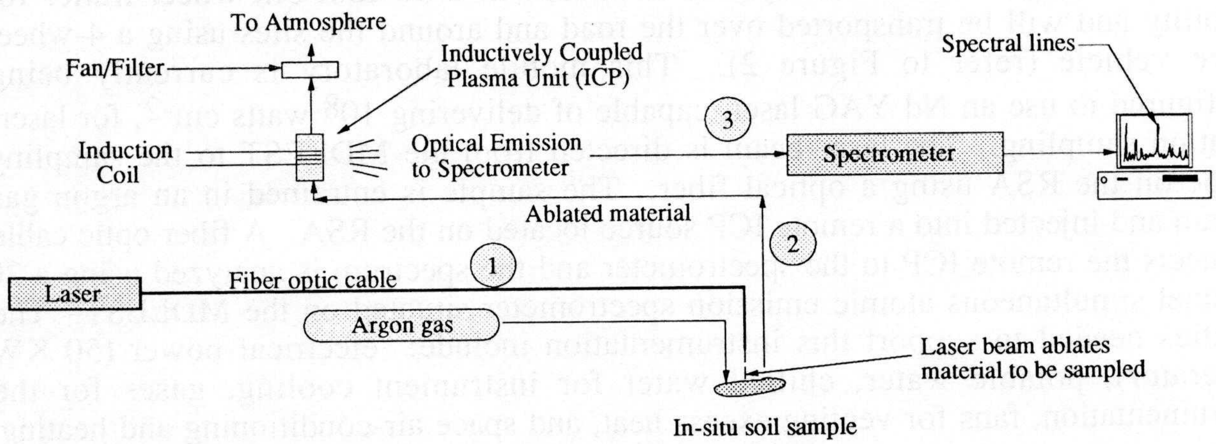

Figure 1: Concept for LA-ICP-AES

3. DESCRIPTION OF MOBILE DEMONSTRATION LABORATORY FOR ENVIRONMENTAL SCREENING TECHNOLOGIES (MDLEST) AND ROBOTIC SAMPLING ACCESSORY (RSA)

This sampling system consists of a MDLEST and RSA (refer to Figure 2). The MDLEST provides a mobile platform, completely self-contained with all the necessary utilities, to support the laser ablation-inductively coupled plasma-atomic emission spectrometry sampling methodology. The RSA is towed by the MDLEST and provides robotic surface sampling capabilities. A description of the MDLEST and RSA follows.

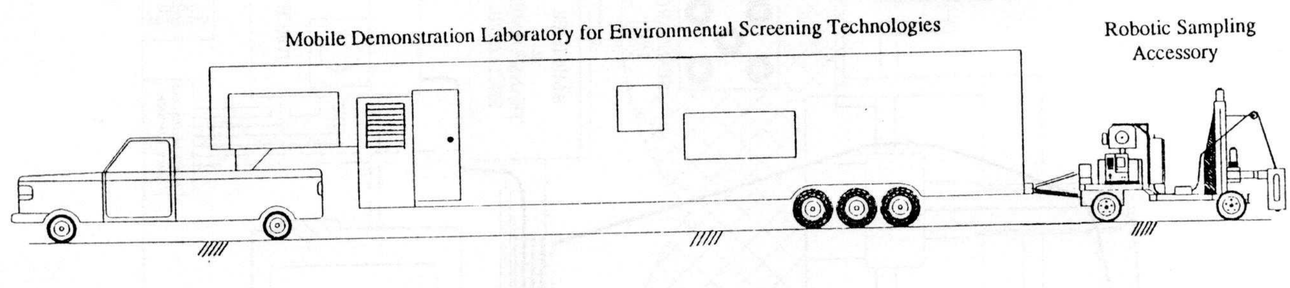

Figure 2: Mobile Demonstration Laboratory for Environmental Screening Technologies and Robotic Sampling Accessory

3.1 Mobile Demonstration Laboratory for Environmental Screening Technologies

The complete MDLEST system is housed in a 36 foot 5th wheel trailer for mobility and will be transported over the road and around the sites using a 4-wheel drive vehicle (refer to Figure 2). This mobile laboratory is currently being configured to use an Nd YAG laser, capable of delivering 10^8 watts cm^{-2}, for laser ablation sampling. The laser beam is directed from the MDLEST to the sampling probe on the RSA using a optical fiber. The sample is entrained in an argon gas stream and injected into a remote ICP source located on the RSA. A fiber optic cable connects the remote ICP to the spectrometer and the spectrum is analyzed using a 20 channel simultaneous atomic emission spectrometer situated on the MDLEST. The utilities needed to support this instrumentation include: electrical power (50 KW generator), potable water, chilled water for instrument cooling, gases for the instrumentation, fans for venting excess heat, and space air-conditioning and heating. Computers are used to control the instrumentation and monitor the utilities so that the integrated system will work together in a safe and efficient manner.

3.2 Robotic Sampling Accessory (RSA)

The RSA is pulled by the MDLEST and consists of a robotic arm, remote ICP source, surface and subsurface sampling probes, cleaning unit, standard sample unit. The RSA can be operated in either a manual or robotic sampling mode. Operations in the manual mode allows surface sampling in areas inaccessible to the robot arm. A decontamination unit for the sampling cell has also been included in the design. Figure 3 shows a preliminary top view design of the RSA with surface sampling probe attached.

Figure 3: Preliminary Design for Robot Sampling Accessory (top view)

3.2.1 Robot arm: The arm is a three-degree-of-freedom SCARA (selective compliance assembly robot arm) robot that was selected because it is well suited for surface and subsurface sampling applications due to the cylindrical axes that provides rapid, smooth motion plus the added feature of selective compliance. This means that the arm is extremely stiff in the vertical direction but has some lateral "give", thereby making it ideal for this sampling technique. The arm has two cylindrical axes (a and b-axes) and one linear axis (the z-axis). The two cylindrical axes provide the two degrees of freedom required to position the probe on the horizontal plane. Servo motors coupled to harmonic drive reducers produce the required torque to manipulate a 50 pound end effector up to 45 inches from the robot's base. The additional (third) degree-of-freedom provided by the linear axis produces the vertical positioning capability. A servo motor and ball screw assembly provide the power required to move the arm on a set of linear shafts. A master/slave controller is used to control the movements of the arm and provide positioning capabilities for the various probes (refer to Figure 4). The robot was designed and built by a mechanical engineering graduate student at Iowa State University.[4]

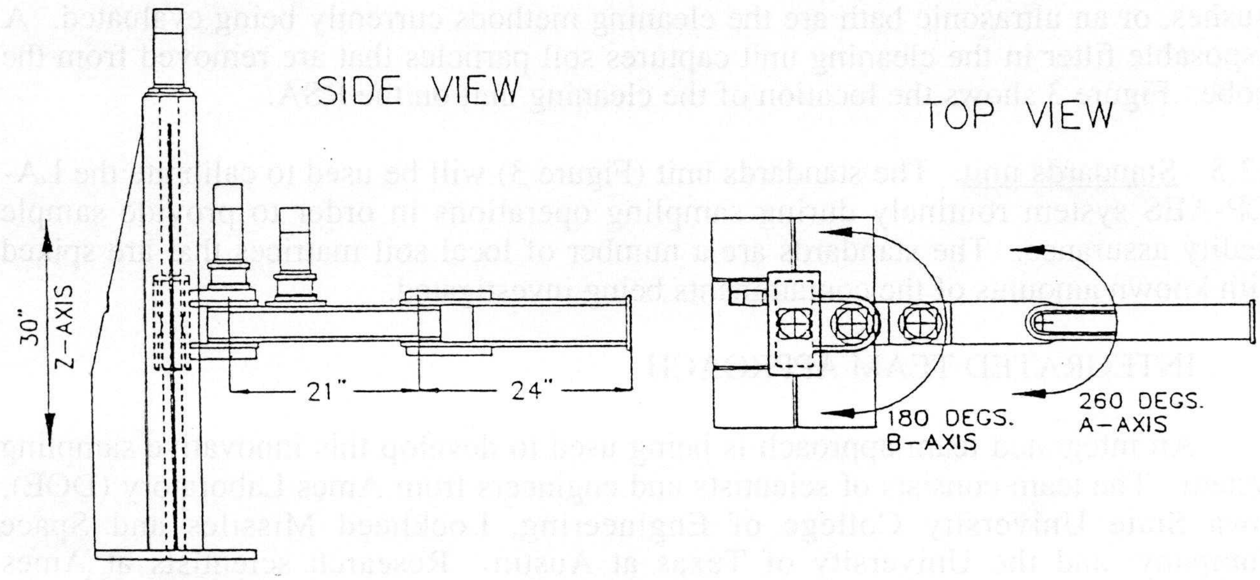

Figure 4: Three-Degree-of-Freedom Robot Arm

3.2.2 Surface sampling probe: A prototype surface sampling probe has been developed which is attached to the robot arm allowing the operator to screen surface soils for contaminants over approximately a 15 square foot area at each location. The robotic arm will be controlled from the MDLEST and a video camera system will be used to closely monitor the sampling operations. The ablation cell uses water to make a gas tight seal with the soil. A cleaning unit will be provided to remove contaminants from the ablation cell after each sample. For manual sampling, the surface probe can be detached from the end of the robotic arm and carried within a 50 foot radius of the trailer. This allows greater flexibility during the sampling operations especially in areas inaccessible to the robotic arm. Equipment contained within the probe consists of the rastering system, focusing lenses, laser output power sensor, ablation cell, argon transport system, and water sealing system.

3.2.3 Subsurface sampling probe: The subsurface sampling design concept involves the insertion of a small probe into a casing that has been previously punched into the ground. The casing provides the probe with access to any desired depth up to approximately 100 feet; the laser beam is focused on the soil through an opening in the casing side wall and the material is ablated and transferred to the remote ICP on the RSA. This subsurface sampling approach does not require large quantities of material to be brought to the surface and reduces the chances for cross-contamination between layers of soil as can be the case when using the conventional approaches involving augers, cone penetrometers, or split-spoon samplers.

3.2.4 Cleaning unit: The cleaning unit will be used to clean the surface and subsurface sampling probes after each sample is taken. Compressed gas, rotating brushes, or an ultrasonic bath are the cleaning methods currently being evaluated. A disposable filter in the cleaning unit captures soil particles that are removed from the probe. Figure 3 shows the location of the cleaning unit on the RSA.

3.2.5 Standards unit: The standards unit (Figure 3) will be used to calibrate the LA-ICP-AES system routinely during sampling operations in order to provide sample quality assurance. The standards are a number of local soil matrices that are spiked with known amounts of the contaminants being investigated.

4. INTEGRATED TEAM APPROACH

An integrated team approach is being used to develop this innovative sampling system. The team consists of scientists and engineers from Ames Laboratory (DOE), Iowa State University College of Engineering, Lockheed Missiles and Space Company, and the University of Texas at Austin. Research scientists at Ames Laboratory are providing valuable research assistance in support of the detailed design activities for the prototype system. Overall project planning and coordination is provided by Ames Laboratory's Technology Integration Program. Iowa State University's College of Engineering is providing students from the following areas: mechanical, electrical, computer, civil, and construction engineering. Approximately 20 students and three faculty are involved in this project. Lockheed is providing valuable systems engineering analysis and design layout for the subsurface sampling probe. To assist them in their design efforts, this company has sponsored three senior mechanical design projects at the University of Texas at Austin that have resulted in preliminary designs and specifications for the probe. We are currently seeking a team arrangement with a leading private industry drilling firm to assist in the design, fabrication, and testing of the casing for the subsurface sampling approach.

5. BENEFITS

Potential benefits of this sampling system include: improved worker safety, shorter analytical turnaround time, better sample quality assurance, and lower cost per sample. Worker safety is enhanced since samples (especially radioactive samples) need not be collected, catalogued, transported, and stored prior to analysis, thus reducing the chances of worker exposure. Also faster turnaround on sample analyses is available since the characterization is done in-situ and in near real time. Typically, it takes approximately six weeks to complete the conventional sample analysis process. Considering the vast number of waste sites in need of remediation, several million sample analyses will be necessary for characterization and monitoring during and after remediation. Presently, there are insufficient numbers of analytical laboratories to perform the necessary laboratory tests. In addition, quality assurance is expected to be higher using this new approach because there is less sample handling involved and an electronic audit trail maintains accurate records of all conditions during the sampling operation.

Furthermore, cost per sample is expected to be substantially lower. A survey was conducted to determine the cost of sampling, auditing, transporting, analyzing, and disposing of samples using the conventional approaches. Results indicate that the cost of analyzing a sample for nonradioactive inorganic elements ranges from $180-250 and the cost of analyzing a sample for radioactive elements, depending on the expected level of contamination, ranges from $800-$2,400 per sample. The cost of acquiring the sample, packaging, transporting, and maintaining an adequate audit trail for potentially hazardous samples typically costs an additional 40% of the analytical laboratory cost. Based on preliminary feasibility data, it is estimated that the MDLEST and RSA can reduce cost by at least 50%.

Other benefits from this project involve the invaluable learning opportunities created for faculty, staff, and students at the participating institutions and companies. This project has involved some 50 people working on various aspects of the system related to their field of expertise. A large number of students are working on this project in order to fulfill their senior engineering design requirements and three graduate students are fulfilling degree requirements at the masters and PhD levels. Additionally, faculty have been given research opportunities to participate on a cutting edge technology project and to work directly with several of the DOE nuclear facilities (e.g., Hanford, Fernald, and Savannah River). This project will have a major impact on the way site characterization and cleanup is performed and may lead to opportunities for commercialization.

6. LIMITATIONS

The current design may require some modifications to make it highly effective and efficient since this system has not yet been field tested and is considered a first generation prototype. A limitation of the present design configuration is that the MDLEST along with the RSA must be towed into the contaminated areas where samples are to be taken. Ideally, the MDLEST should remain in a noncontaminated area while the RSA operates on a tether in the contaminated zone. Members of the team are in the process of developing a remote-controlled tow vehicle to pull the tethered robotic sampling accessory around a hazardous waste site. Also, an electronic chain of custody needs to be developed to safeguard the data since there is no tangible audit trail during the sampling process. Furthermore, the ICP-AES approach is suitable for screening inorganic elements (e.g., uranium, thorium, chromium, and lead) but is not suitable for detecting volatile organic compounds (VOCs) (e.g., methanol, PCBs, and TCEs). Thus, the screening capabilities of the MDLEST and RSA would be enhanced by including an organics sensor.

7. FUTURE PLANS

Future plans involve adding new technologies to the mobile laboratory as they become available for demonstration. The next generation will most likely utilize a stationary mobile instrumentation platform situated in a safe area tethered to a robotic sampling accessory that will roam in the contaminated area taking samples. With further advances in miniaturization, it is conceivable to include all of the instrumentation on the robotic sampling accessory with the results stored in an on board computer and a radio-link from a command center controlling the sampling accessory. An organics detecting instrument is planned for inclusion in this system in order to increase the screening capabilities.

8. CONCLUSIONS

A new approach in screening soil samples for inorganic hazardous waste is currently being developed by an integrated team lead by the Ames Laboratory (DOE). This sampling approach is conducted through a Mobile Demonstration Laboratory for Environmental Screening Technologies and a Robotic Sampling Accessory that will provide in-situ, real-time screening of surface and subsurface soils. The benefits of this techniques include enhanced worker safety; higher sample quality assurance, lower cost, faster sample analysis; and versatility for use in a wide range of sampling applications. With future capabilities expected to include organic screening, the MDLEST and RSA represent a truly innovative approach to efficient site screening and characterization.

9. ACKNOWLEDGEMENTS

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