

## ***BOA II:***

# ***Pipe-Asbestos Insulation Removal Robot System***

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## **I. ABSTRACT**

The *BOA* system is a mobile pipe-external robotic crawler used to remotely strip and bag asbestos-containing lagging and insulation materials (ACLIM) from various diameter pipes in (primarily) industrial installations. Steam and process lines within the DOE weapons complex warrant the use of a remote device due to the high labor costs and high level of radioactive contamination, making manual removal extremely costly and highly inefficient. Currently targeted facilities for demonstration and remediation are Fernald in Ohio and Oak Ridge in Tennessee.

## **II. INTRODUCTION**

Asbestos insulation abatement has been, and still is, a big problem in renovation and dismantlement [3], since EPA and OSHA regulations are strict on removal procedures and worker safety [4], due to the carcinogenic nature of the insulation product (despite ongoing disputes) [5].

The Department of Energy (DoE) owns many chemical processing plants across the US, which are scheduled for dismantlement. Most of their steam and process lines have been insulated with ACLIM and hence warrant special attention, especially due to the high potential of contamination with contaminated fluids and particles. Hence, these lines within the DOE weapons complex warrant the use of a mechanical and remote device due to the high costs of abatement, making manual removal and disposal extremely costly and highly inefficient.

The DoE has funded a two-phase program at CMU to develop an automated system to strip insulation from their process pipes. The two-phase program has progressed past Phase I with a proof-of-concept prototype development and testing scope, and is currently in Phase II. As part of the current scope, a complete regulatory, market and cost/benefit study has been completed. Current efforts are targeted towards the design and implementation of a prototype system to abate steam and process lines in the 4 to 8-inch diameter



**Figure 1: *BOA* Proof of Concept Prototype Robot**

range at a DoE facility by March/April 1997. In the first-phase effort completed in December 1994, we developed and tested a proof-of-concept prototype system using preliminary locomotion and removal systems, with fiberglass insulation as a surrogate material (see Figure 1).

### III. PROBLEM STATEMENT

The main challenges in developing an automated asbestos abatement system lie in the areas of process, operations and regulations ([1],[2],[11]). One has to deal with insulation and lagging materials of almost all possible forms and consistencies, which make any material handling mechanism hard to design. Furthermore, the device must be able to work in existing facilities which were not designed for human abatement activities in terms of reach, access, etc., and even less for the use of a machine to perform the abatement job. And lastly, the entire operation has to meet the stringent regulations drafted and enforced by OSHA and EPA, which are mostly concerned with keeping fiber counts below acceptable levels, while enforcing that only allowable work practices be employed during the abatement process. And of course the last hurdle before a system could truly be termed successful, is that it has to be able to save the abatement contractor money, while doing the job faster, safer and better than a human asbestos worker could.

Representative ACLIM materials we are concerned with, include the lagging materials, such as aluminum, straps, screws and wires, and the insulation material, typically friable (turns to powder upon touch), or as hard as CalSil. A pictorial view of these materials is shown in Figure 2.

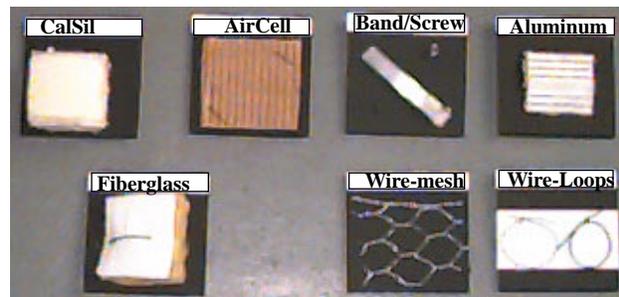


Figure 2: Samples of lagging & insulation material

### IV. PRELIMINARY RESULTS

It was determined that such a self-propelled, negative-pressure mini-containment system could meet EPA and OSHA mandated fiber-count levels during abatement operations, and that automated removal operations on piping could achieve a high removal rate. Using a mechanical cutting method (circular diamond-grit coated blade), we were able to achieve a net abatement rate of 4 ft./hr., which we knew we had to improve on to make the system more cost-effective. Compressing the material off the pipe once cut, was not sufficient to guarantee removal 100% of the time without some form of human assistance. This result lead us to the realization that a truly reliable and omni-directional cutting system was needed. The use of fiberglass as a surrogate was changed to Calcium Silicate (Calsil), since it was termed more akin to asbestos-containing material (ACM) in the field. This change made in-situ compression of the ACLIM unrealistic and the need for water-assisted/misted cutting and size reduction necessary, further aiding to reduce loose fiber emanation.

Based on these main and other secondary results, the DoE review panel decided to continue the project into Phase II. A revised statement of work for Phase II called for improvements and refinement to the design of the robotic removal head and locomotor system, further guided by a regulatory analysis and a market study and cost/benefit analysis to determine regulatory and performance requirements, market size and commercial potential of such systems for the DoE and within the abatement contractor industry.

## V. COST BENEFIT ANALYSIS

The overall study [5] clearly highlighted guidelines in the areas of regulatory compliance and certification, potential market sizes in the DoE and industry, as well as overall performance requirements and system-cost boundaries in order to be competitive and achieve substantial savings in the thermal insulation abatement market segment.

### A. Regulatory Analysis

As part of the regulatory analysis, we charted a ‘certification’ path for any alternative abatement method proposed to EPA and OSHA. Even though OSHA/EPA do not certify equipment for use in abatement jobs, they do specify system performance in terms of allowable exposure limits (which aids somewhat in system design), work practices (process of using abatement techniques and equipment) and approval processes (permitting, notification, etc.). From a design stand-point, we will have to ensure we meet the fiber-emissions level regulations, which currently lie at 0.1 fibers/cc - as spelled out in 40 CFR Part 61. These restrictions imply the use of static and dynamic seals, positive airflow at all times, proper wetting and fiber-sealing and a proper deployment procedure to avoid any fiber release. The ‘certification’ process that BOA will have to go through, involves the drafting of a technical performance report by an on-site industrial hygienist or project designer with P.E. license which is then submitted to the DC-office of OSHA for review and acceptance - a process spelled out in 29 CFR 1926.1101 (g) (6). Local, state and regional EPA and OSHA officials are kept abreast of the development and are invited to view the deployment and check for compliance on top of the required independent air monitoring. A full timeline and a list of deliverables and names within EPA and OSHA have been drafted for implementation during Phase II.

### B. Market Study

A thorough review of thermal insulation systems and the asbestos abatement industry within the DoE and industry was conducted. It was determined that the DoE has about 2 million linear feet of total piping (1.5M indoors, 0.5M outdoors) of medium bore-size (4 to 8 in. DIA.) in need of abatement, collected in the six major sites (Savannah River, Hanford, INEL, Oak Ridge, Rocky Flats, Fernald). A breakdown by site and indoors/outdoors is given in Table 1 below.

<b>DoE SITE</b>	<b>Outdoor</b>	<b>Indoor</b>	<b>TOTAL</b>
<b>Savannah Riv.</b>	110,000	562,000	672,000
<b>Hanford</b>	100,000	300,000	400,000
<b>INEL</b>	60,000	189,000	249,000
<b>Oak Ridge</b>	30,000	184,600	214,600
<b>Rocky Flats</b>	60,000	186,000	246,000
<b>Fernald</b>	70,000	48,700	118,700
<b>TOTAL</b>	430,000	1,460,300	1,890,300

**Table 1 :Medium Bore DoE piping breakdown**

The industrial market size was determined to be about 33.5 million linear feet each year over the next 10 years. We believe that a BOA-like system, attacking only a portion of that market (4 to 8 inch diameter piping) currently abated with glovebags (22%) and then only in more sizeable

installations where clearances are available for the robot to work on pipes, would be applicable to up to 0.5 million linear feet total within the DoE and about 1.5 million linear feet a year within the industrial market segment.

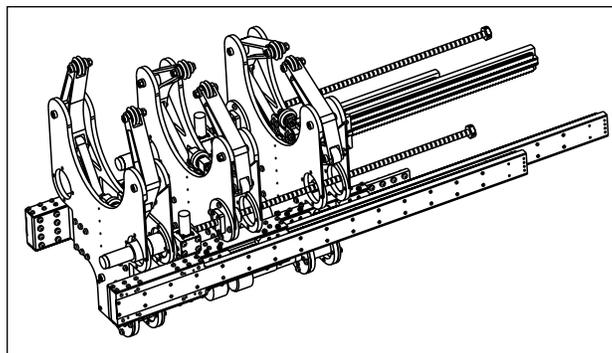
### C. Cost/Benefit Analysis

Based on the potential performance of a robot abating at a rate of 30 linear feet per hour, compared with about 3 to 6 feet in DoE/Industry, with associated per-foot abatement costs ranging between \$25 and \$150 for Industry/DoE, it was determined that substantial savings could be realized with the use of such a robot system. Overall abatement costs could decrease between 25% and 50%, depending on whether the system replaces a current glovebag or full-containment method. Overall savings were thus computed to lie between \$10 million and \$15 million for DoE, which does not even count savings due to reduced radiation exposure, work-crew reduction and insurance savings, overall worker safety and potential litigation cost savings. Potential unit sales to DoE (and/or its M&Os and subcontractors) and commercial asbestos abatement contractors were estimated to be between 150 and 300 units over the next 7 years, depending on the size of the contractor and job, as well as the final production cost of the system.

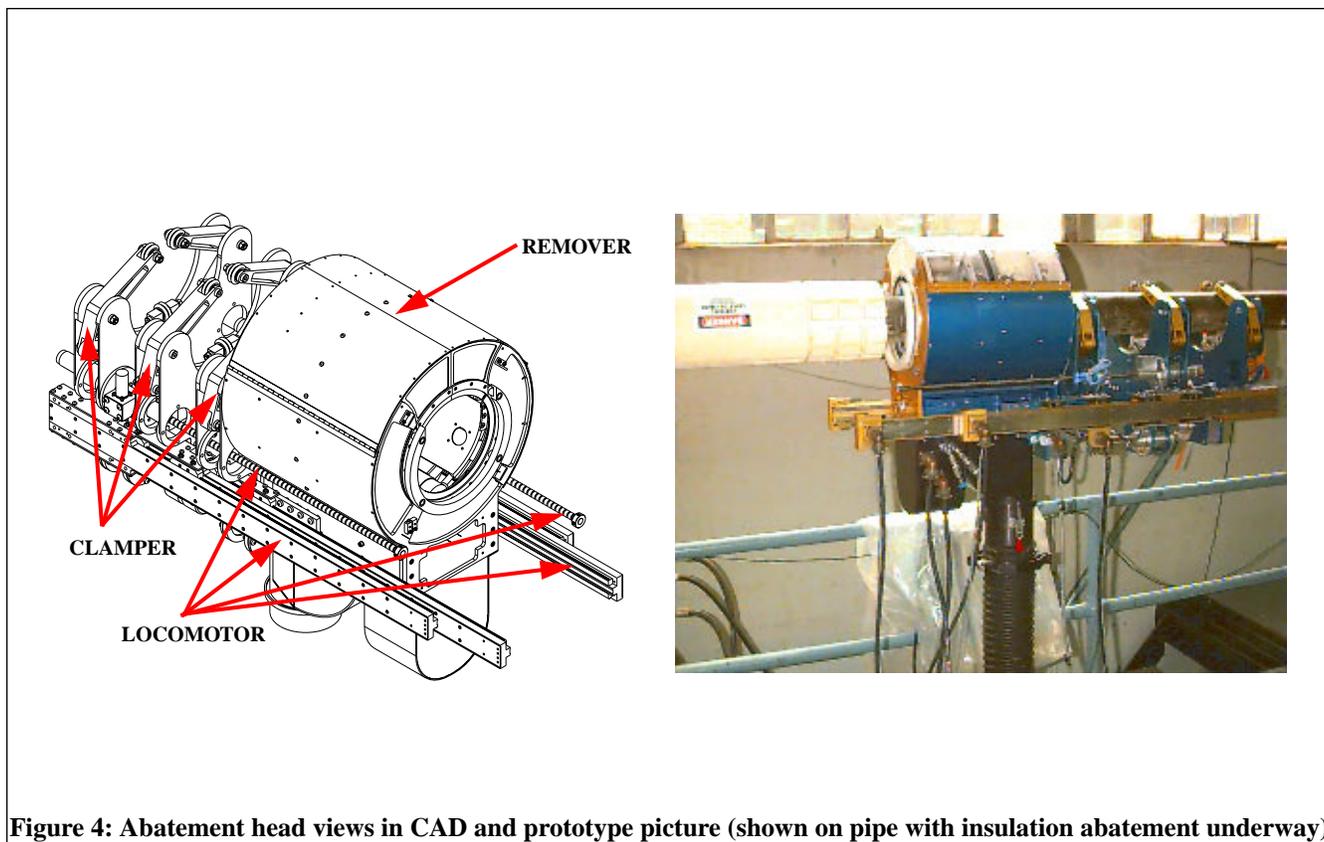
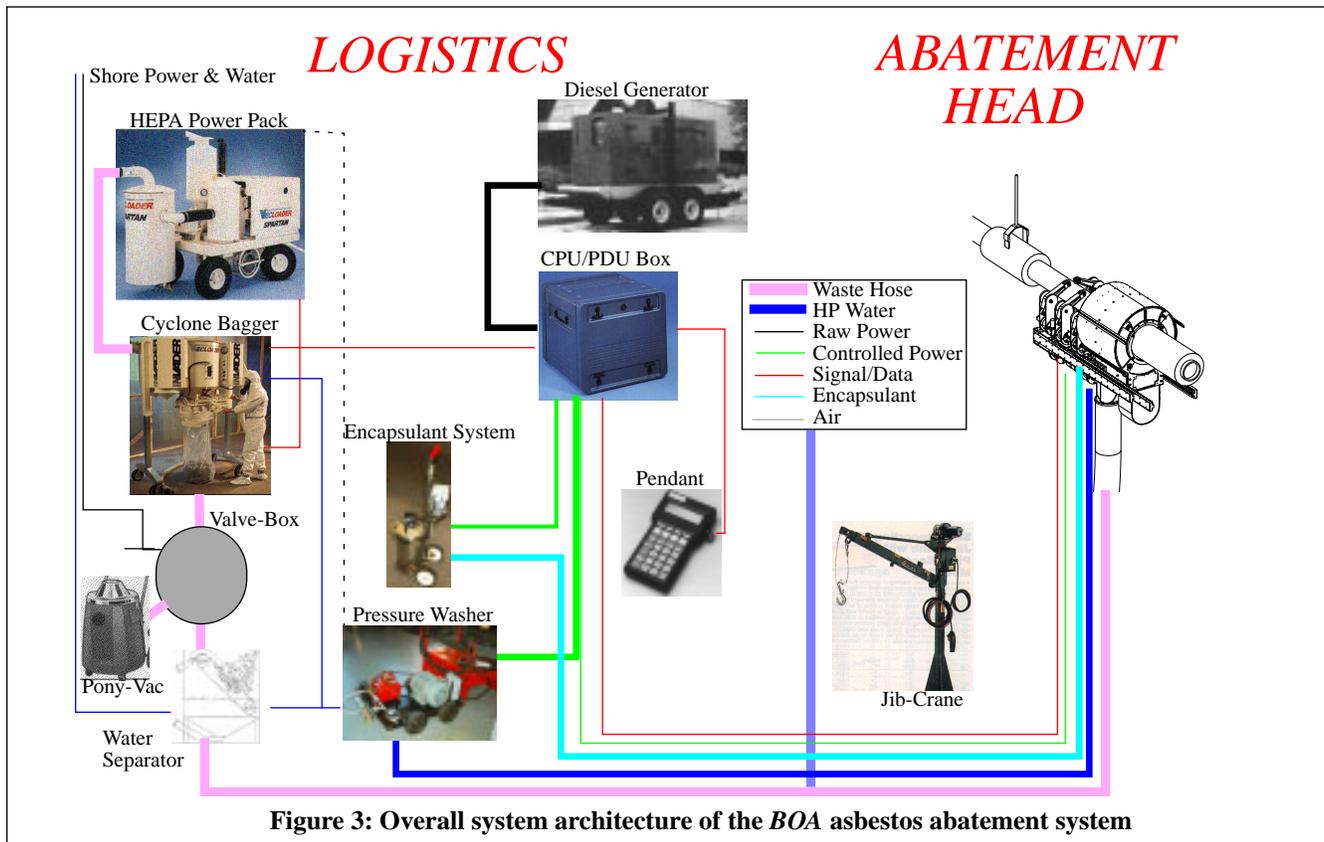
## VI. SYSTEM OVERVIEW

The overall system configuration of the *BOA* asbestos abatement system is shown in Figure 3 on the next page. The abatement head is located on a pipe, and tethered to the off-board logistics support and control units. Connections between the head and the logistics unit include power, control and feedback lines, water and encapsulant lines, as well as a 4-inch diameter vacuum hose. A jib-crane is used to emplace and remove *BOA* on and from the pipe upon start-up and around obstacles. The off-board logistics are comprised of a diesel-powered electric generator, a 1,000 cfm industrial HEPA-vacuum system, a cyclonic waste-bagging system, and a water-separator system for removing water from the waste-stream. A pressurized water pump and encapsulant system are used to cut the insulation and wet the removed sections to trap any loose fibers. A central controller box controls, coordinates and monitors all system parameters and interfaces to a human operator via a simple touch-pendant.

The crawler itself (also termed the abatement head), dubbed *BOA*, consists of a locomotor and remover section, where the locomotor is responsible for clamping and inching along the pipe, while the remover contains all the systems needed to remove the ACLIM from the pipe to the required cleanliness levels. A picture of the overall abatement head and the individual locomotor and remover are shown in Figure 4 on the next page in a CAD and photographic rendering.

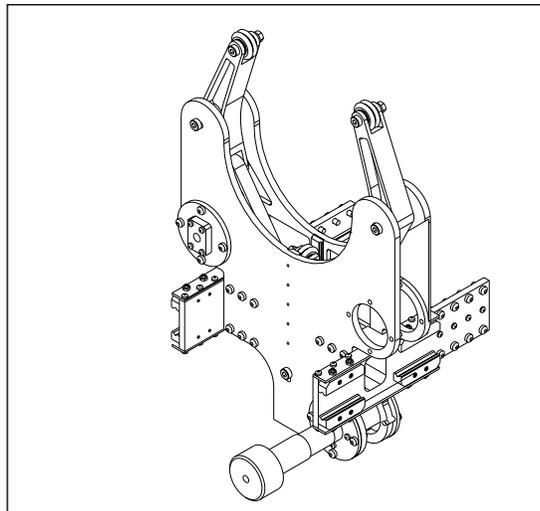


**Figure 5: Overview of locomotor system**

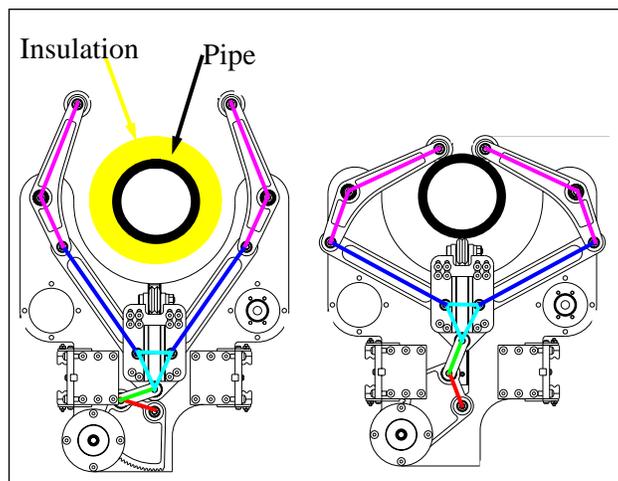


The abatement head is able to automatically crawl along the pipe and remove insulation via its remover section. The locomotor is based on a set of clamping units that are interconnected via the locomotor stages to allow the system to crawl in an inch-worm fashion. A perspective view of the locomotor section (with the attached clamer units), is shown in Figure 5.

The clamer is a simple four-bar linkage system operating on three-footed contact rollers to allow centered and misalignment during the clamping operation. By using three clamping units, we will guarantee stable walking and removal operations, since two clamps will always be attached to the pipe. Figure 6 shows the overall clamer configuration, while Figure 7 shows the open and closed configurations of a ‘dissected’ clamer.



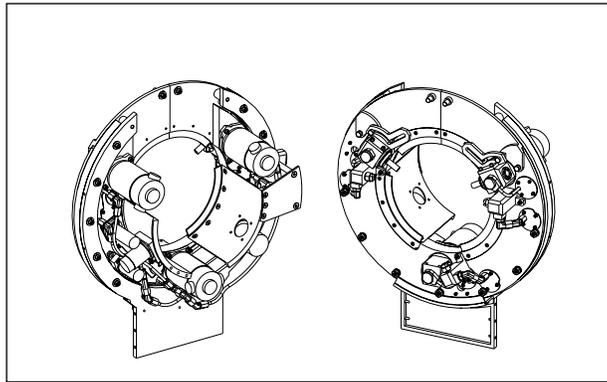
**Figure 6: Overview of clamer system**



**Figure 7: Clamer Overview and extreme positions**

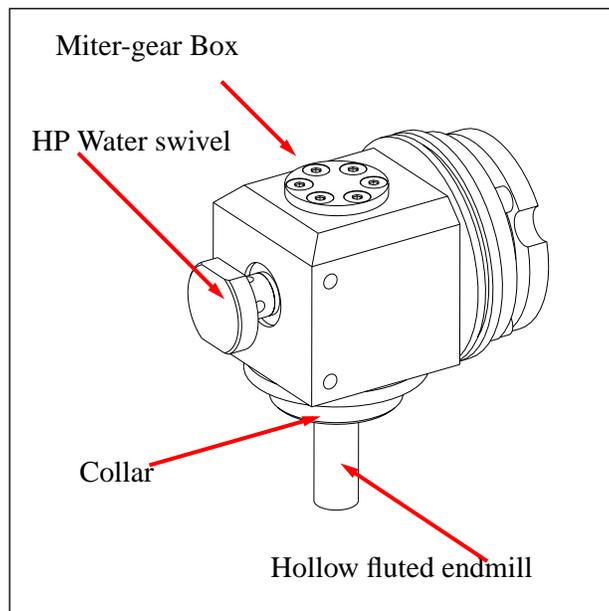
Note that we are using a simple three-point contact scheme, actuated through a gear-driven hybrid four-bar linkage mechanism. Orthogonally-placed v-groove rollers on the ends of the three contact points ensure that each clamer has a self-centering effect without losing the ability to stay clamped onto the pipe. The remover is based on a rotationally mounted set of three omnidirectional hybrid endmill/water-jet cutters that are used to dice the insulation into 2-inch chunks as the abatement head walks along the pipe. An inside view of the rotating cutter-head plate is shown in Figure 8. The cutter-head is a customized hybrid endmill/water-jet system which allows

the head to cut through all forms of metallic lagging and strapping, while being able to cut through insulation without damaging the pipe and without being susceptible to a variety of alignment and obstacle issues.



**Figure 8: Inside view of the rotating cutter-plate heads**

A perspective and view of the cutter-head is shown below in Figure 9.



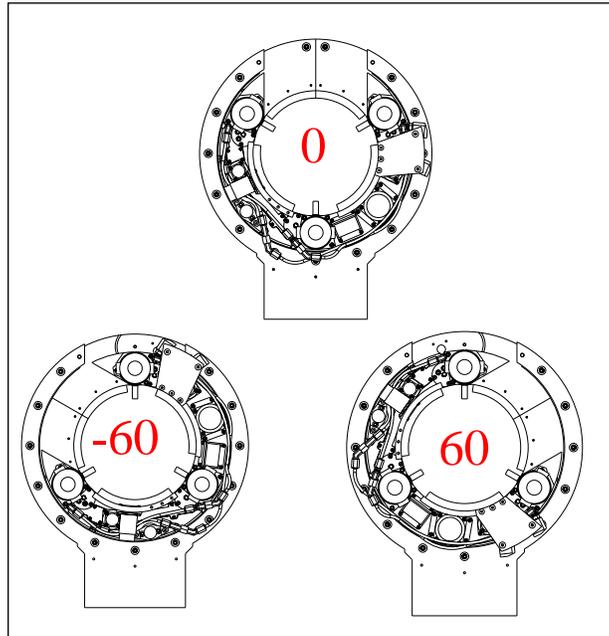
**Figure 9: Hybrid cutter-head system**

The cutter system performs a combination of circumferential cuts via the cutter-plate heads by rocking back and forth through a  $\pm 60^\circ$  angle, shown in Figure 10, and then combines with a set of forward and backward locomotion strokes to ‘dice’ out chunks of maximum size that can freely tumble out of the removal chamber and travel through the waste-hose uninhibited. Experiments to date have shown that cubes 2.5 inches on side, including aluminum lagging pieces of the same size, and even 24”- long bands (strap cut in only one spot) can all be conveyed through the waste-hose using the 1,000 cfm vacuum system.

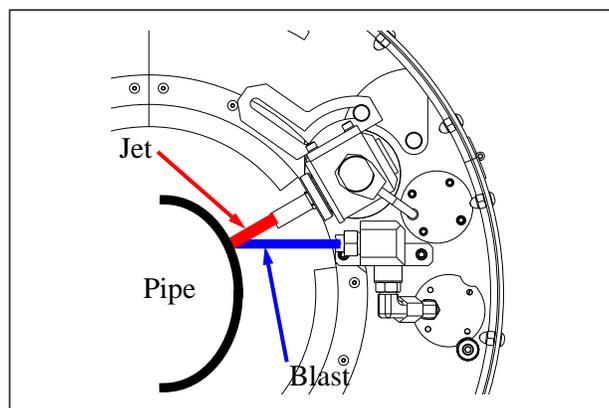
The cutting and nozzle-blasting actions are combined to dislodge the chunks from the pipe and clean the pipe (Figure 11). The removed insulation and cutter waste-water are vacuumed away from the system through the vacuum hose, which is attached to the bottom of the abatement head and leads the material away from the pipe and to the off-board water separation unit (which

recycles the water for cutting), and subsequently the cyclone bagger system.

BOA is currently sized to work on 4-inch diameter piping, but could easily be scaled to larger pipe-sizes<sup>1</sup>. Its productivity is predicted to be between 30 to 40 feet per hour. The abatement head is designed to get around hangers by itself, by stepping around/over them, but without removing the insulation immediately around the hanger. Furthermore, human interaction is needed at major obstacle locations such as valves, junctions and bends. A human is in general only needed to place BOA on the pipe and handle it around obstacles. Left-over small sections of insulation around hangers and obstacles can be readily and quickly abated using glovebags and a single asbestos worker that follows the robot along its path.



**Figure 10: Circumferential cutting sequence**



**Figure 11: Remover cutting and blasting jet systems**

Fiber-containment is achieved by sealing the entire system around the pipe, creating a high-velocity entrapment system around all seals (using the vacuum system as a waste-transport means

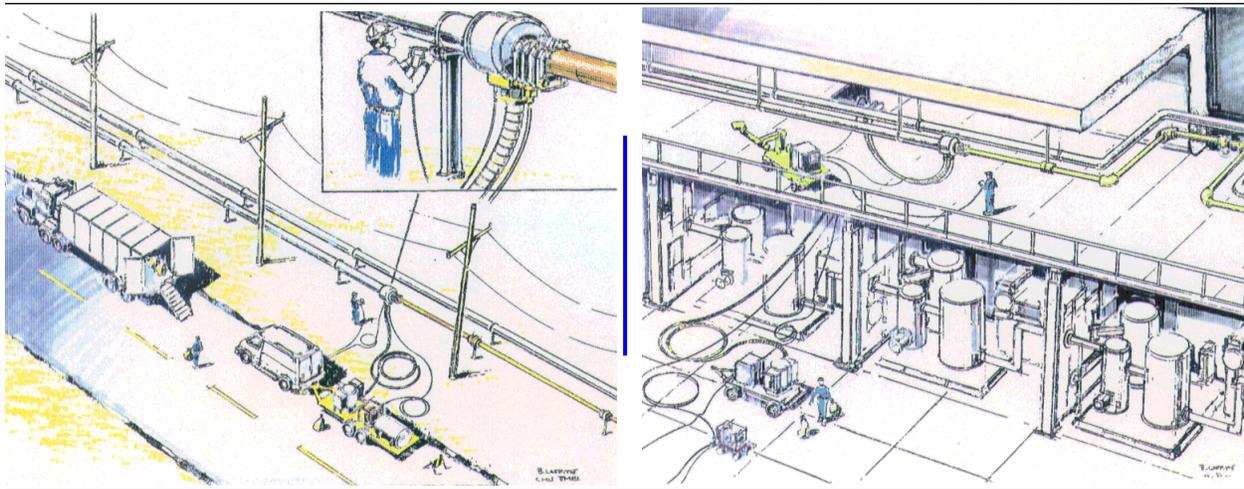
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1. smaller-bore piping is bagged and cut out of the network and disposed of with the insulation still on the pipe - a stationary floor-mounted BOA-like system could tackle this market as well!

and a vacuum means) and inside the removal module, wetting the insulation and sealing the exposed pipe, while monitoring air-quality around the system and thus obviating the need for a complete containment-area setup. This fact alone represent a major potential cost savings in overall abatement jobs due to the relative expense incurred in preparing the site for the asbestos abatement. This fact alone represent a major potential cost savings in overall abatement jobs due to the relative expense incurred in preparing the site for the asbestos abatement.

## VII. DEPLOYMENT ISSUES

Based on the study period at the beginning of Phase II, we also developed a new operational scenario reflecting the guidelines and lessons learned from the study itself. A good way to explain the scenario is to depict the two types of possible deployment scenarios, namely indoor and outdoor, as shown in Figure 12.



**Figure 12: Outdoor and Indoor deployment scenarios for the *BOA* system.**

The entire system is shipped to the site on a flat-bed towed-trailer, where all the logistics units are set up. Assuming no available on-site power, a diesel-generator is used to provide the power for all systems. The HEPA vacuum is set up 300 feet away from the abatement site, to minimize noise levels, and hoses and cables are run to connect the vacuum, electrical and water systems to each other. The water-separator is filled with water, as it serves as the reservoir for the pressurized water pump used for cutting and blasting the pipe. Once the control box is hooked up, the human operator performs a checkout procedure of the entire system, including the robot located in its storage/transport container. Upon successful completion of the start-up, the jib-crane used as the positioner, is emplaced onto BOA, and the complete abatement head is lifted off the transport pipe and brought to the section pipe that has previously been cleared to begin abatement. Once the head is firmly attached to the pipe and the positioner is removed, all systems are automatically turned on and the fully automatic abatement cycle begins.

During normal operations, one would have one operator with the pendant close to the on-pipe crawler monitoring it and overseeing its operations, while a second operator would be needed at the bagging station, as the waste material arriving from the abatement head needs to be batch-removed out of the cyclone separator every 10 minutes. A backup HEPA system is ready to be energized in case of major HEPA-Vac failure as well as during the bag-out cycle. The entire system has also been designed to be transportable to work on different floors in industrial buildings so that even extremely-high piping networks can be abated. In general, depending on whether pipes are up high or down low, the use of a JLG might be required, and our positioner and control pendant have been designed to work on different platforms and at remote locations.

## VIII. COMPETING TECHNOLOGIES

The BOA system is unique in that it represents a new class of abatement technology that is currently not available, namely a self-locomoting negative pressure mini-enclosure for automated pipe-insulation abatement. Insulation abatement contractors consist of a re-usable glovebag and a remoted vacuum filtering and bagging system as shown in Figure 13.



**Figure 13: 'Competing' Technologies**

## IX. PROJECT STATUS

A field-test demonstration of the BOA system at Oak Ridge was performed outside and in the back of Bldg. K-1210 on the old K-25 site (now ETTP) in Oak Ridge, TN on August 28th, 1997. The overall system had spent the prior 10 days being transported and set up on site, as well as being used to train on-site K-25 asbestos workers on how to use it. The system operated on a 100-foot run of CalSil-insulated (asbestos surrogate) 4-inch piping hung from hangers, and lagged with partial aluminum lagging and screws/bands. The system was demonstrated to a group of industry, site and DoE representatives. During the short 45-minute demonstration we ran the system on a 20 foot section of piping, including a hanger with insulation, wires, aluminum lagging, screws and bands. We showed how the system is able to remove insulation and wires using a cutting/blasting method, and reducing the insulation into 2-inch sized insulation pieces. In addition, we demonstrated an automated hanger-pass, as well as continued abatement of aluminum lagging, including bands, wires and screws. Single-operator operation and off-board bagging and autonomous system operation were also demonstrated. The entire demonstration run was operated by K-25 personnel without any assistance of CMU personnel. No emissions exceeding the allowable fiber-count limits established by OSHA were recorded during the field-

trial at K-25, whether at the pipe-end or the off-board bagging site. A picture of the final BOA abatement head system is shown in Figure 14.



**Figure 14: BOA abatement head working on outdoor CalSil insulated pipe at K-25**

During and after the demonstration it was suggested, that the system was a believable and impressive solution for automated asbestos abatement, which should now see some minor improvements to increase its ruggedness and service intervals, be modified to work on a 3-inch pipe-run, of which Oak Ridge seems to have plenty, and it should be tested on asbestos-containing insulation to get final air-quality data to convince regulators and commercial interests of its capabilities as a real tool. Towards that end, CMU is working in conjunction with FETC, in order to explore the possibilities of readying the system for an asbestos-insulation abatement field-test at Oak Ridge in the spring of 1998, before it can be seriously considered for a large-scale demonstration project at Oak Ridge (possibly Y-12).

## **X. ACKNOWLEDGMENTS**

We would like to acknowledge the assistance of the FETC COR, Vijendra Kothari, and Dr. Linton Yarbrough at DoE HQ and Dr. William Hamel at UT Knoxville and ORNL-RPSD for their assistance during the current project. Furthermore, we wish to acknowledge participation from many people at various sites for their assistance in gathering the data required for our study and their support in finalizing the field trial sites at Oak Ridge. Furthermore, the CMU-PI on the project would also like to acknowledge the hard work and inspirational effort put in by the CMU team members. Carnegie Mellon University will develop the system and collaborate with an industrial partner to commercialize the technology at the conclusion of the program in FY'98.

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