DOE/MC/30362 -- 5114
(DE96004342)

BOA: Asbestos Pipe-Insulation Removal Robot System Phase II

Topical Report
January - June 1995

Hagen Schempf
John E. Bares

June 1995

Work Performed Under Contract No.: DE-AR21-93MC30362

For

U.S. Department of Energy
Office of Environmental Management
Office of Technology Development
Washington, DC

U.S. Department of Energy
Office of Fossil Energy
Morgantown Energy Technology Center
Morgantown, West Virginia

By
The Robotics Institute
Pittsburgh, Pennsylvania

DISCLAIMER

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PHASE II

USDOE

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June 1995

I. Executive Summary

This report explored the regulatory impact and cost-benefit of a robotic thermal asbestos pipe-insulation removal system over the current manual abatement work practice. We are currently in the second phase of a two-phase program to develop a robotic asbestos abatement system, comprised of a ground-based support system (including vacuum, fluid delivery, computing/electronics/power, and other subsystems) and several on-pipe removal units, each sized to handle pipes within a given diameter range. The intent of this study was to (i) aid in developing design and operational criteria for the overall system to maximize cost-efficiency, and (ii) to determine the commercial potential of a robotic pipe-insulation abatement system.

• Regulatory Analysis

To ensure that the BOA system will become an acceptable alternative asbestos abatement technology/method, it was necessary to review the applicable regulations in the field of asbestos abatement. The goals of this regulatory analysis were to (i) review all pertinent regulations, (ii) determine key technical design criteria for an automated abatement system to maintain compliance with these regulations, (iii) establish points of contact (POCs) within all the relevant regulatory and enforcement agencies, and (iv) establish a certification path and timeline proposed for regulatory acceptance of the BOA system.

•Agencies and Regulations

This analysis focussed on all federal, regional, state and local agencies and their regulations, highlighting the fact that at the federal, regional and state levels, the Environmental Protection Agency (EPA) and the Occupational Safety and Health Administration (OSHA) are the key regulatory and enforcement bodies. OSHA's mission is one of worker safety and protection, whereas, EPA's is one of protection of the environment and the general public. As such, OSHA regulates work practices and engineering control methods to limit fiber emissions, while the EPA dictates the general approaches to avoid fiber releases in the first place. OSHA has developed a detailed set of guidelines as part of their regulations (29 CFR Part 1926.1101), detailing work practices, materials to be used, permissible fiber counts and regulations pertaining to alternative abatement/control methods. EPA has developed standards (40 CFR Part 61), which dictate what jobs require notification and approval, require proper wetting and careful handling during removal, transport and disposal. Many states and/or counties have enacted tougher laws, and enforce these regulations at the local level, rather than leaving it to the regional or federal regulators.

In addition, should the asbestos to be abated be contaimnated with radiation products, the material is considered mixed waste. Based on the levels of radiation, additional regulations pertaining to the handling of radioactive materials, as defined and regulated by the NRC, come into play. For most of the situations covered within this report, where more than 85% of DoE contaminated asbestos lies at levels less well below 5 mRem/hr., the asbestos protective gear and work practices are more stringent than those required for radiation protection. Hence regulations imposed by the NRC for dealing with radioactively contaminated products have not been explored in further detail in this study. Further work on this topic will be needed, should asbestos abatement in highly contaminated areas become more prevalent within the DoE complex.

•Regulatory Impact (Notification, Certification, Technical Ramifications)

Upon review of the regulations, a plan for notification, permitting and licensing at the local, state, and federal level was extracted and detailed for abatement jobs that would take place either in Pittsburgh (@ CMU), Fernald, Ohio, or Oak Ridge, Tennessee (our three primary demonstration and field test sites, although the pattern is similar for other sites and could be developed if necessary). All notification and permitting is handled through the regional, state and/or local EPA offices or similar agencies. OSHA in turn, through its office of Technical Support in Washington, DC, provides for the use of alternative abatement methods by requiring a written evaluation of the method being proposed as an alternative abatement solution from either an industrial hygienist or a project designer with a professional engineers license on site (i.e. within a DoE site). It is possible that once a track-record (statistically representative) is established, continual filing of these evaluations to OSHA might be reduced or simply eliminated. Other than these requirements, DoE might have other internal filing/notification/permitting requirements we are not aware of, but based on our analysis of previous DoE jobs and abatement documents, we believe there to be no additional requirements. An interesting test case involving a company seeking certification of an alternate abatement control method was analyzed and it was discovered that their approach is similar to the one we are proposing in terms of breadth (agencies and POCs) and depth (extent of involvement of agencies and their POCs).

In terms of technical implications, we discovered no new regulations that we were not already aware of during the design of BOA I. The key phrase is still: 'containment, containment, containment'. Since permissible fiber levels are now lowered to 0.1 fibers/cc, we will need to improve and ruggedize any static or dynamic seal on the next version of BOA, while improving the degree and coverage of wetting of the material.

•Strategy, Action Items and Timeline

A strategy was developed to ensure that all agencies and the identified POCs are kept informed, continually consulted, and queried for feedback. We propose to continue providing information of our current Phase I effort (by way of the completed Topical Report and the composite video of BOA I) to the list of POCs at the federal, regional, state and local level of the regulatory agencies mentioned above. In addition, we will provide a copy of this regulatory analysis to the federal, regional, state and local regulatory representatives, once it is completed, reviewed by METC and approved for release by the DoE - an activity expected to be completed by July 1995. Upon conclusion of the design effort for BOA II, we will provide copies of the new design document and an operational scenario description for BOA to the same regulatory POCs for review - an activity expected to be completed by December 1995.

Upon selection of the field test site, we will commence more intense dialogues with the respective DoE representatives, their ES&H personnel, the local and regional regulatory representative and their federal counterparts in EPA and OSHA. We propose to collaborate with the DoE site in providing information to facilitate their submission of all notification, permitting and licensing forms to the respective agencies at all local, state, regional and federal levels. The entire CMU team will by that time have received permits and licenses to operate as asbestos workers and supervisors in Pennsylvania, Ohio and Tennessee. In addition, we will invite a (set of) representative(s) from the selected DoE site(s) to attend the acceptance demonstration at CMU in July 1996, after which we would ask him/her (them) to write the required alternative abatement method description and variance request to be filed by the DoE site with OSHA in Washington, DC. CMU will also file their required NEPA information package as well as a detailed field test plan should DoE decide to go ahead with the planned field test.

•Summary and Conclusions

Contrary to the original wide-spread disagreement on <u>how</u> to approach the certification of an alternative asbestos abatement system and/or method, this analysis has provided a clear road-map of how to comply with the legislative notification, licensing and permitting process. By reviewing the regulations and having discussions with agency representatives and companies with prior experience in this field, there no longer is any uncertainty as to the proper path to take, who to contact, what to submit, nor what regulations need to be complied with.

It is our belief that, based on the review of the regulations and discussions with selected POCs within the regulatory and enforcement agencies, the BOA system is a viable and certifiable alternative control method, as long as it meets the major operational, control and air cleanliness standards enforced by the EPA, OSHA, and all state and local regulatory agencies. BOA I satisfied most, if not all, of these requirements, and we hope to improve upon these and the overall applicability and ease of operations and ruggedness in the ongoing BOA II development effort.

• Cost-Benefit Study

The cost-benefit study was structured to include (i) a market assessment, (ii) details of the technical risks and opportunities, (iii) a cost-benefit model to ascertain realizable savings, (iv) prediction of overall savings, and (v) the commercial potential of robotic abatement systems within the DoE and the industrial market segments. Important findings within key areas of this cost-benefit study are summarized below:

•**Market Assessment**

The total asbestos abatement market is estimated at around $2.8 billion for 1995, with about 1,200 contractors vying for a share in an asymptotically stabilizing market. All application segments are continually shrinking, except for the government segment, whose market share and activity are growing, and expected to top 25% in 1995. In these segments, it is estimated that 31% of the market lies in thermal insulation, of which pipe-insulation is a large percentage (91%), resulting in a $790 million annual market for thermal pipe insulation abatement. Most of this market is focussed on renovation (60%) and demolition (18%), with the remainder represented by operations and maintenance. The six main application segments are office/commercial, industrial, utilities, government, schools and residential, of which only the industrial and government (DoE) segments were determined to be applicable to robotic abatement.

The main two market segments that the study was focussed on, were those of the government sector, namely DoE exclusively, and the industrial sector. Both the office/commercial and school and residential segments were ommitted due to the presence of mostly smaller piping and in extremely tight and hard to reach configurations. The utility segment, namely the commercial and nuclear power plants, were found to also not be applicable to a BOA-like system, since the age of their piping networks is less than others (younger than 20 years), leaving little pre-1975 asbestos-clad piping available for abatement (ACM materials were banned thereafter), while having extremenly tightly cluttered pipe networks which would greatly reduce the applicability of BOA.

Data on the market-size for DoE was acquired from site visits, contractor reports, and from DoE site information, while industrial segment information was obtained from an asbestos abatement industry report and personal asbestos contractor surveys. Several scaling factors were used to determine the total linear footage where an automated abatement system could be used within the both the DoE and industrial market segments, including: (i) the percentage of pipe that is of a size technically accessible to BOA (4"- 8" OD) - typically about 40% of the pipe at a given site, and (ii) the percentage of piping within this pipe-size range on which a BOA system is actually applicable (accounting for obstacles, hangers, minimal clearance, etc.) - typically between 25%-indoors to 75%-outdoors. To account for not being able to visit a statistically significant number of industrial sites to see the pipes ourselves (as was done for the DOE), the industrial market was further scaled by the share of piping that is currently being abated using the glovebagging technique (since we estimate that the BOA system would be most applicable in areas where glovebagging would be the preferred manual abatement technique) - typically about 20% to 25%. The BOA-applicable piping footage was thus determined to be around 300,000 total linear feet within the DoE, and 1,500,000 linear feet a year (over the next 25 years) within the industrial market segment.

•**Technical Risk and Opportunities**

Despite limitations in terms of access to pipes in 'cluttered' conditions and regulatory and operational requirements, a robotic abatement system was found to be technically feasible and highly competitive with current technologies and work practices within both the DoE and Industrial market segments. Major benefits of the robotic abatement system are its increased abatement productivity, added safety for workers, and the overall repeatable quality of work it will be able to achieve. It was determined that the robot system can compete against manual glovebagging practices in most cases, and against full-containment work practices in locations where glovebagging is prohibited. The robot system will be classified as a negative-pressure travelling containment system which is akin to a glovebag, yet safer than a glovebag and more like an automated mini-containment. Key factors that determine the successful operation and use of such a robot system include the pipe-size range abatable by the system, its overall size and weight (clearance and handling), and its overall abatement productivity. Operational characteristics, such as deployment, negotiation of obstacles and hangers, and the approach used to abate, convey and bag the waste stream are also important.

- **Cost-Benefit Model & Case Studies**

  Based on a detailed understanding of manual abatement methods and costs, we estimate that a robotic abatement system can reduce overall insulation removal time, reduce the need for construction of enclosures, and significantly reduce the time spent on set-up and dismantlement in full-containment scenarios.

  To estimate relative savings realized by a robotic abatement system vs. manual full-containment and glovebag removal, we developed a working model (spreadsheet) that predicts savings expressed in terms of labor-hours saved and then normalizes these to a per-linear-foot figure. This model conservatively assumes that there is no reduction in set-up or clean-up time. The model was validated using DoE and industrial contractor job cost data and estimates, and then applied to several DoE and industrial site case studies to understand the model's sensitivity to variations in manual practices, robot features, and site characteristics.

  Based on a parameter sensitivity analysis, it was determined that the main economic driver in the cost-benefit analysis was human vs. robotic abatement productivity, while wages and site characteristics (hangers and obstacles) are of secondary importance. Basic savings figures are also found to be sensitive to the levels of radiation present at DoE sites, but this does not seem to be a major economic driver in the cost-benefit analysis of the BOA system.

- **Predicted Savings**

  Using this cost-benefit model, we predict savings to the DoE of about $25 to $30 per linear foot if competing with outdoor/indoor manual glovebagging work practices, and about $30 to $55 per linear foot if competing with outdoor/indoor full-containment approaches. Savings within industrial settings were found to lie between $3 and $4 per linear foot (the difference is mainly due to increased worker productivity and lower labor rates within the commercial segment). Overall, the model predicts savings of roughly 25% to 30% of full glovebagging job costs, and about 40% to 50% of full-containment job costs within DoE, and a flat 30% of full job-costs within the industrial market segment.

  Based on the linear footage applicable to a robotic abatement system in the 4" to 8" range, and the cost savings for indoor and outdoor competing glovebag and full-containment methods, **we predict that the DoE will conservatively save between $9.1 and $13.7 million** over the life of its pipe-asbestos insulation abatement program, possibly even **as much as $33 million** if certain regulatory and exposure and insurance/litigation cists are considered. Using the conservative estimates contained in this report, **we expect that the DoE will see a return-on-investment (ROI) of between 340% and 500%** ($9.1M to $13.7M return on $2.7M total investment). The effective cost savings due to this technology development program is 4.5%, based on an estimated $203 million cost for human abatement of all of the DoE piping at six of its major sites (Hanford, Savannah River, Rocky Flats, INEL, Oak Ridge and Fernald) within the targeted pipe-range. This compares favorably with the DoE-wide goal (3 to 4%) in cost savings due to technology developments within DoE.

  Additional benefits of the technology include (i) increased worker safety, (ii) , total worker radiation exposure savings of at least 60 person-Rem within the DoE, (iii) guaranteed compliance with EPA and OSHA regulations and consistently high levels of abatement quality, and (iv) eventual reduction in insurance and bonding rates and long-term reduction in asbestos exposure lawsuits.

- **Commercial Potential**

  Besides representing a cost-effective solution to the DoE, development of a robotic abatement system has significant commercial potential. We estimate that five of the six main DoE sites have enough footage of pipe on which the BOA system could be used to justify buying a system, and two of the larger ones (Hanford and Savannah River) may have enough pipe to justify two systems per site. We predict the total need for the DoE to be between five and seven systems.

  The industrial market is roughly 20 times larger than the DoE market and has a projected market life of about 25 years. Potential first-time sales projections across both market segments are between 70 and 240 systems (sold in the first six years). Some contractors may repurchase BOA systems to replace those which have reached their useful life time. Given the normal difference between market size and actual sales, we anticipate that a company could conservatively expect to sell between 100 and 150 BOA systems in six years. Current information indicates that the selling price of the system must stay below $125,000.- to ensure sufficient payback. Commercial success depends most heavily on achieving maximum removal productivity rates and ensuring that BOA can be profitably built and sold within this $125,000.- range. Additional critical design goals to maximize BOA's cost-efficiency include:

- Minimize the annular space taken up by the body of the removal unit. - (Goal = 3" outside insulation OD)
- Minimize the amount of human intervention needed at hangers and/or obstacles. (Goal = 10 minutes or less for both. Optimally, if the need for human assistance at hangers is reduced, much of the costs associated with the construction of scaffolding will be eliminated.)
- Maximize the abatement productivity on straight, clear runs of pipe. - (Goal = at least 40 lf/hr on straight runs)
- Ensure ease of use and interchangeability of the removal units.
- Reduce the size and weight of the removal units. - (Goal = a system that is easily assembled from pieces that are each below the Recommended Weight Limit (RWL) for overhead lifting as defined by NIOSH), or devise a mechanically-aided emplacement system and plan.
- Minimize part count, complexity, and other aspects of the design to reduce production costs. - (Goal = $60,000/unit)
- **Conclusions and Recommendations**

The results of this study, in conjunction with preliminary technical feasibility estimates, indicate that BOA will be cost-effective for use in the Department of Energy's facilities, and that a total cost savings of approximately $9 to $14 million will be realized by the DoE if this system is developed. In addition, evaluation of the potential of the BOA system for use in the industrial market segment indicates that this system, if developed, will be a commercially viable product. **We therefore recommend that the development of the BOA pipe-insulation abatement system in Phase II be pursued.**

II. Abstract

This topical report details a regulatory analysis and a cost/benefit study for a robotic asbestos pipe-insulation removal robot system to be used within the DoE's weapon complex as part of their ER&WM program, as well as in industrial abatement. Both efforts can best be summarized as follows:

- **Regulatory Analysis**

This section explores the regulatory approach to ensuring that a robotic abatement system can be successfully certified and become an allowable alternative for pipe-insulation abatement within the DoE and industrial settings. The report focuses on an analysis of agencies and regulations, such as EPA and OSHA, which dictate laws regarding environmental protection and worker safety. It was determined that even though EPA is responsible for the protection of the environment and requires certain handling criteria and notification/permitting during/before abatement jobs, OSHA is the one that has to certify the system as an acceptable alternative to current human abatement work practices. Based on a review of all national regulatory bodies governing asbestos abatement, a plan for notification, permitting and licensing at the local, state, and regional (not federal) was extracted, and detailed for abatement jobs that would take place either in Pittsburgh-Pennsylvania, Fernald-Ohio, or Oak Ridge-Tennessee, since they are the main sites for this DoE-sponsored study. Besides all the currently required notification and permitting processes, a variance report has to be filed with the Washington, DC office of OSHA, and regional, state and local EPA and OSHA officials need to be notified and consulted on the impending abatement using the proposed alternative method (robotic abatement).

Based on this review of the regulations and the notification/permitting process, which was corroborated by the agency representatives themselves and a company representative having gone through this process, it was determined that the certification aspect would be straightforward in concept. The implementation of the notification process was paralleled to the actual system development process in terms of its design and demonstration, so that EPA and OSHA and site representatives could be kept informed of the system and its operations before a demonstration in a mock-up environment, before a full-scale demonstration within a DoE site is contemplated. Additionally, technical implications and performance requirements of the robotic abatement system were gleaned from the regulations and discussions with enforcement agencies, which can be loosely translated into: containment, containment, containment!

- **Cost/Benefit Analysis**

This section explores the cost/benefit of a robotic thermal asbestos pipe-insulation removal system over the current manual abatement work practice. A market study was performed and detailed the presence of a substantial market in pipe insulation. Albeit the continued shrinkage of the asbestos abatement market nationwide, substantial annual revenues in thermal insulation system abatement ($880 million), continued abatement in the industrial market segment and growths in the government market segment are promising for the application of a robotic abatement system. The government and industrial market segments were found to be the most promising for a technically feasible robotic device, while utility and office/residential segments were classified as out of reach for many reasons. This report focuses thus only on the industrial and government or DoE market segments.

A cost/benefit analysis was undertaken based on the knowledge of the overall industrial market segment size (based on a survey), and the DoE complex (based on site-visits and -data). A costing model was developed to ascertain the factors contributing to cost savings and case studies were used to develop reliable figures for dollars saved per linear foot of abatable piping. Overall savings for each market segment (industrial and DoE) were computed and then used to develop a commercialization plan for the robotic abatement system.

The robot system was found to have a substantial cost/benefit for both market segments, with relative job-cost savings ranging from 25% to 30% for indoor piping (comparison based on manual glovebagging technique), and as high as 40% to 50% for outdoor piping (comparison based on full-containment technique). A recommendation was made to develop a robot system to work on the 4" to 8" O.D. sized pipe-diameter range, which represents 40% of the overall piping market, representing a segment for which a technically viable system that meets all regulatory requirements, could be developed - a proof-of-concept system had already been demonstrated in prior work funded by the DoE.

Keywords: asbestos, robot, cost/benefit, thermal insulation, pipe, abatement, DoE, market, regulations, EPA, OSHA

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IV. Introduction

This report is intended to provide a summary of the Phase I activities for the development of ***BOA*: Asbestos Pipe-Insulation Removal Robot System**, funded under contract # DE-AR21-93MC30362. Towards that purpose, we provide the necessary background in this section to understand the focus and results of the current phase, while motivating the need for continued development.

1.0 Regulatory Analysis

The abatement of asbestos containing thermal insulation systems in commercial, nuclear and government facilities has been an on-going activity in the U.S. since the 70's, governed by a collection of regulations at the federal, state and local levels[1]. Current work practices and environmental standards for asbestos emissions set up by the EPA NIOSH and OSHA comprise the core of the regulatory backbone which drives the performance, cost and safety at any asbestos abatement job. Current work practices apply to human abatement approaches, and as such, besides focussing on clean air and water, also focus on the safety for the worker itself.

Since we are currently developing a robot system in order to improve upon the human abatement methods, we will need to understand the current regulations and sketch a path to be able to have the final system be accepted as a viable and legally accepted alternative to manual abatement. The goal of this document is to highlight the regulations that are the most important to the performance of any abatement job, and extrapolate from them (i) key design drivers that impact the overall design of the robot system and its deployment, and (ii) the approach one would need to take to be able to have the system and method accepted by the governing bodies as an acceptable alternative to the current human practices. Towards that end, the document will summarize the key regulations as set forth by different agencies, highlight the regulations with an impact on design and deployment of the eventual system, and chart the course over time to comply with regulations and achieve legal acceptance of the system as a tool usable in abatement scenarios.

2.0 Market Study and Cost-Benefit Analysis

In order to ascertain the potential commercial impact and justify/develop key technical design drivers, we were engaged to develop a cost/benefit analysis as part of our Phase II contract. The purpose of this section is to answer the '**Why** we are doing this study', and the '**What** are we doing in this study' questions at a somewhat general levels and provide a description of the document, its sections and their general content.

• WHY we are doing this study...

Asbestos control (abatement, management) is a highly regulated activity, which the entire government, public and private market sectors have to deal with in order to comply with the federal regulations imposed in the early 80's. Abating insulation is a highly labor-intensive, and hence costly, activity which potentially exposes humans to hazardous conditions and thus requires substantial safety measures, setup and takes a lot of time to carry out an abatement job. As such, this activity classifies as a potential benefactor for remote operations, due to its hazards, labor-intensity and highly regulated nature.

A robotic abatement system has been developed as a proof-of-concept in the first phase of this program, and we are now in the beginnings of developing a new and commercial prototype system to use in a real demonstration. As such, this system, should be targeted to certain applications and have certain features that allow it to be a cost-effective tool. In addition we need to prove that the system is not just cost-effective per linear foot of piping abated, but that the overall volume of potential piping it could abate is sufficient to ensure a commercial development success, as measured by the adoption

1. "The History of Regulating Hazardous Waste", by Travis Wagner, ECON, August 1992, pp. 24 - 32.

of the technology into the daily abatement market.

The need for a study is obvious, as we need to develop hard numbers for overall market size, targeted market segments, applicability of the robot system, and what the expected per-linear-foot savings of such a device could be. Sponsors and contracts will need to be told of their potentially realizable savings, return on investment, etc. The study contained within in this document attempts to address these issues and provide answers to (i) the designers for what is really important in the design of the system, (ii) the program sponsors (DoE) as to what savings could be realized if such a system was to be used in their sites, and (iii) the contractors that would be buying such a system to use on government and industrial job sites.

- **WHAT are we doing in this study...**

The first step in this study is to understand the overall market size, based on published reports, site-data, contractor information, etc. and segment the market based on this information into such categories as DoE, industrial, commercial, nuclear, etc. In addition, based on technical and job-site realities, it is clear that only a portion of that market is applicable, due to necessary clearances, cost-effectiveness of glovebagging over full-containment, scaleability of the removal system, etc.

A model needs to be developed to outline the savings per linear foot that a robotic abatement system could deliver over a human abatement scenario. Since absolute costs are hard to obtain due to the large variation in job scenarios, this is the only relative measure that is at all reliable. However, by having a reliable per-foot savings figure, even if distinguished between indoor and outdoor, one can extrapolate what the total savings could be. The model is hence based on the knowledge we have accumulated of how abatement jobs are costed, what affects them, talking to contractors, seeing abatement sites and ongoing jobs and reviewing job-cost data from prior abatement jobs.

We use the model and our site-visits to develop typical case studies, to generate a range of savings figures in $/ft. for the DoE and industrial markets, to develop a weighted average of actual overall savings per linear foot that is applicable to the footage a robot could be applied to across a site, market segment or contractor. Based on a detailed definition of the analysis approach and a careful definition of variables and other related constants, a projection of potential sales volume of robots to contractors and/or facility owners (i.e. DoE) can be made and the necessary financial and marketing plans drafted.

3.0 Report Structure

The remainder of the topical report is organized into two major sections, namely Chapter *V.: Regulatory Analysis*, which deals with the regulatory analysis for the acceptance of the BOA system as an alternative abatement method, and Chapter *VI.: Market Assessment*, which contains an overview of the DoE and industrail markets, a cost/benefit model assessment and a commercilization assessment with overall footage and savings predicted for DoE. Chapter *VII.: Appendices* contains all the appendices to back up data and conclusions in the document. The individual sections that form part of this document can thus be further summarized as follows:

- **Chapter V.: Regulatory Analysis**

Section 1.0: Regulatory Background

The necessary background is given to understand the legal, programmatic and technical issues that we need to concern ourselves during this project. A brief history of legislation and actions concerning asbestos is developed, the overall programmatic goals of using a robotic abatement system are re-stated, and the need for a regulatory analysis is highlighted in the areas of technical constraints and certification approach.

Section 2.0: Regulations

An overall summary of all applicable and pertinent regulations imposed or followed by EPA, OSHA, DoE and site contractors is given. We assume that all recommendations made by federal entities are implemented as laws by all state and local agencies. A brief summary highlights the main regulations that will impact design, operations and certification of the proposed robotic abatement system.

Section 3.0: Regulatory Impact

A more detailed analysis of the relevant regulations on the design, operation and certification of the robot system are given, in addition to currently proposed approaches or solutions to address them. In addition a preliminary list of topics relevant to the certification and actual deployment of the system will be drafted to shed light on the overall process of introducing a new technology into the marketplace and having it certified and deployed in a timely and legal manner.

Section 4.0: Course of Action

This chapter enumerates the individual actions and responsible parties to ensure that certification and on-site deployment at a DoE site are possible within the scope of this project. A timeline is furnished to prioritize each action and assign a due date to meet the overall field test date at the conclusion of our project.

- **Chapter VI.: Market Assessment**

Section 1.0: Market Assessment

The market assessment section focuses on specifying the overall size of the potential market broken down into various market segments. Furthermore, the market is segmented based on technical constraints imposed by the robot system and site conditions, as well as the level of asbestos insulation present based on age of the installations within a market segment. The market segments that are found to be of potential interest are then detailed further to ascertain the net footage of piping that is realistically abatable by an automated robotic system. The net result of this section is a detailed table of net footage for each market segment, that a robotic system could abate.

Section 2.0: Cost-Benefit Analysis

This section develops the model used to develop estimates of potential per linear foot savings of a robotic abatement system over that of human abatement. The model considers all factors and variables needed to describe a human and robotic removal job and uses different costing categories which are applicable to any market segment. The purpose is to provide believable savings figures for DoE and industrial markets, based on case studies and descriptive variables which would allow one to generate per-linear-foot savings figures (rather than absolute cost figures), which when used with the size of the market segments can aid in sizing the overall potential savings.

Section 3.0: Case Studies

Different case studies within the DoE and industrial market segments are selected to illustrate the validity of cost-savings figures developed through the cost/benefit model, and to predict the per-linear-foot savings for different cases. In all cases it is shown that the savings figures used in this report are all on the low-end and in real situations are bound to be higher. Pictorial renditions of the individual piping-scenarios are shown in Chapter *Appendix B -: Case Study Data and Images.*

Section 4.0: Commercialization Assessment

In this chapter we examine alternative models for completing the commercial development, establish projections for potential sales, and examine the value of BOA to a potential customer and to a potential commercialization entity. We conclude with several guidelines regarding objectives and roles for the further development of the technology.

Section 5.0: Overall Impact

The overall savings potential of a robotic abatement system is detailed for the two target market segments. Secondary benefits such as regulatory, safety, and quality of work issues are also presented.

Section 6.0: Conclusions and Recommendations

This section summarizes the key points relating to overall size of the applicable markets, the potential savings, and the implementation strategy to commercialize a robotic removal system. Finally, it presents our recommendations of how to proceed with the Phase II development of the BOA system, taking advantage of the results from this study.

Section 7.0: Additional Opportunities

Through this study, we have identified the potential need for an additional ground-based system to abate small-bore piping (< 4" O.D.) and separate insulation from piping for landfill burial or waste vitrification/processing. Additionally we speculate on the potential of fiberglass being regarded by regulatory agencies as a carcinogen which would not only increase the potential market share for robotic abatement systems, but also extend the life of the market significantly.

• **Chapter VII.: Appendices**

Appendix A -: Regulatory Appendix

A listing of all relevant federal, state, local, DoE and site contractor documents pertaining to asbestos abatement and all related activities is given.A list of all people within the relevant federal, state, local, DoE and site agencies and contractors is given.

Appendix B -: Cost-Benefit Model

This appendix details the cost/benefit model used to determine the per-footage savings for different DoE and Industrial case studies. Model structure, variables, equations and a sample calculation are included in this appendix.

Appendix C -: Case Study Data and Images

This appendix collects numeric and pictorial renderings of the individual DoE and industrial case studies used to develop average per-linear-foot savings for different market savings based on whether it is indoor or outdoor.

Appendix D -: Industrial Contractors Survey Forms & Results

This appendix provides a listing of all the industrial contractors surveyed as part of the market assessment, a copy of the survey form sent out to them for completion, and a summary table detailing the results of the survey.

Appendix E -: Contacts by Market Segment & Industry

This appendix lists the names, addresses and contact numbers by market segment, site and contractor for all people that were queried for input and comment on the data used in this study.

Appendix F -: List of References and Documents

This appendix provides a listing of all the documents and references used to extract or develop data reported in this study.

Appendix G -: Commercialization Assessment Data

This appendix provides details of the data used in the commercialization plan, as extracted and analyzed from an overall asbestos abatement market study.

V. Regulatory Analysis

1.0 Regulatory Background

In order to understand the source of all acquired information and to better illustrate the results of the study, the background to this work needs to be brought out. The legislative background that led to the establishment of all regulations, is chronologically detailed to enumerate and spell out jurisdictions of the agencies that have legislative and enforcement powers in the area of asbestos abatement. A brief justification for the use of robotic abatement systems is provided based on their capability to comply with current human worker-oriented regulations. The ultimate purpose of the background section will be to illustrate the impact of existing regulations on technical and operational aspects of the currently envisioned robotic abatement system, as well as the actual approach to ensure that the robot system and its operation can be certified at the federal, state and local levels.

1.1 Chronology of Legal Events

It is interesting to sketch the legislative birth and maturation of the currently existing asbestos-relevant legislation since even before its official beginning in 1970 with the Clean Air Act (Section 112) mandated by Congress. The intention will be to illustrate the current 'maze' of legislation based on a chronological discussion of the EPA's and OSHA's regulatory development process. In the end, it will also serve to illustrate the connection between agencies, their areas of jurisdiction and the necessary interfaces to those agencies currently regulating abatement in Doe, commercial nuclear and industrial settings.

SInce during and after World War II, the world saw a dramatic jump in the production of chemicals as part of petroleum derivatives, which itself had already been discovered in the mid 1880s. The post-war era saw a tremendous rise in the production and use of chemicals and products using those derivatives, with emphasis on the plastic and pesticide industry. It was mostly the shear volume of waste rather than the lack of knowledge of its adverse effects that really was the cause of most problems. For instance, the U.S. produced about 500,000 metric tons of 'hazardous' waste in 1946; by comparison, in 1984 that figure had risen to 3,000,000 (EPA estimate) - a six-fold increase! The results of this waste production and its subsequent mismanagement, were illustrated by contaminated water supplies, injuries to humans, and ecological degradation. Typically, the industry practices sanctioned by the government involved dumping in rivers and streams, in air and on the land, typically in unlined surface impoundments.

The environmental movement of the 60s, drove Congress to control the management of industrial waste. The Clean Water Act controlled discharges into the national waterways, while Clean Air Act controlled discharges into the air. In 1965 the Solid Waste Disposal Act was passed and required safeguards and encouraged environmentally sound methods for disposal of household, municipal, commercial and industrial wastes - the first step in controlling the sheer volume of waste generated by the nation. As such, the Clean Air Act forced the EPA to list asbestos as a carcinogen and hence classify it as an airborne hazard.

The legislative actions from the 60s and early 70s however, were found to not be sufficient to control those waste forms not covered by the Solid Waste Disposal Act. Hence, in the mid 70s, the Resource Conservation and Recovery Act (RCRA), enacted in 1976, had several clearly stated goals: to protect human health and the environment; to conserve energy and natural resources; and to reduce or eliminate the generation of hazardous waste as expeditiously as possible. Under RCRA, three distinct yet interrelated programs were developed: Subtitle D, Subtitle C and Subtitle I. Subtitle D and I (1984), encourage states to develop comprehensive nonhazardous solid waste management plans and to regulate underground nonhazardous (waste) storage tanks, respectively. The centerpiece of hazardous waste management is contained in Subtitle C of the RCRA. This piece of legislation clearly defines the responsible parties and how they are to manage hazardous wastes from the site where it was produced to the site where it is being stored - the birth of the 'cradle-to-grave' terminology. The main difference between Subtitles D and C, other than the distinction between hazardous vs. non-hazardous wastes, is that Subtitle D is currently structured as a voluntary state-grant program, while Subtitle C is a federally-run mandated regulatory program administered through the states.

One of the weaknesses of RCRA was that it did not address the management of hazardous and solid wastes encountered at inactive or abandoned sites. For those situations, Congress enacted the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA), also known as 'Superfund'. CERCLA contains stringent liability provisions under several sections (104, 106 and 107) covering the release of hazardous substances or pollutant or contaminants, irrespective of whether an owner has a site with hazardous or non-hazardous waste forms.

Since RCRA did not clearly establish recognizable bounds on the definition of hazardous waste, Congress tasked the EPA to further define and modify the definition by promulgating a regulatory definition of hazardous waste. Currently, the EPA continues this task (40 CFR 26.3 and 40 CFR Part 261) and is not expected to conclude it any time soon, since it is continually being hampered by litigation, changing industry trends, and periodic Congressional intervention. Asbestos clearly falls into the classification of hazardous waste, since it is a solid waste form or a combination of solid wastes which because of its quantity, concentration, or physical, chemical or infectious characteristics may:

- cause, or significantly contribute to, an increase in mortality or an increase in serious irreversible, or incapacitating reversible, illness; or
- pose a substantial present or potential hazard to human health or the environment when improperly treated, stored, transported, or disposed of, or otherwise managed.

Since RCRA's Subtitle C was meant to ensure that hazardous waste is handled in a manner that protects human health and the environment, the EPA has been continually issuing regulations regarding the identification, generation, transportation, treatment, storage and disposal of hazardous wastes.

Since asbestos has been classified as a carcinogen and hence an airborne hazardous air pollutant in the Clean Air Act of 1970, its legislative history very closely mirrors that of the general legislation enacted to broadly deal with the management of hazardous waste materials. A more asbestos-specific chronology of events is contained in Section 3.0 Regulations on page 5.

1.2 Robotic Abatement - Justification

One can glean from the regulations that are currently on the books, that air quality and worker safety are the primary concerns when it comes to the protection of the environment and the work-force. As a result of these regulations, the financial aspect of asbestos abatement has been heavily influenced. Cost factors are the main drivers that justify the development of any mechanical abatement system, which is at the heart of any cost/benefit analysis that would support the acceptance of such a system. Assuming that any design will always have to ensure that the fiber emissions levels are similar or below those during human abatement, and that currently accepted work practices are followed in order to protect any human worker in the area, the system will have to be able to show any one or all of the key attributes at the heart of any DoE development: better, safer, cheaper, faster.

A mechanical system is by its nature designed to do a job that is classified by a human to be tiresome and repetitive - TIS abatement falls into this class. By allowing a mechanical system to perform an abatement and thus reducing the number of people or their time exposure inside the hazardous area is certainly also a net plus when it comes to developing a safer alternative. The overall desire to make the system cheaper should be reflected in the overall capital and operational cost of the machine vs. the reduction in numbers and exposure of the labor force, increased abatement productivity and the net reduction in waste materials and hence disposal costs. Through the development of a mechanized system, reduced abatement time is possible, thus reducing overall costs for abatement, site monitoring and otherwise management and paperwork costs.

1.3 Regulatory Analysis - Benefits

The benefits in performing a regulatory analysis, lie in the net amount of useful information generated for the design and operation, certification and deployment phases of the project. Isolating the key regulatory constraints which any technical solution will have to abide by will be of benefit to the design of the machine. Certain established and accepted work practices will heavily influenced the operational scenario under which the robot will be deployed. Understanding the regulatory structure and reporting guidelines, aids in developing the right contacts and materials to ensure that the eventual design can be certified for use in real abatement scenarios. Each of these individual areas has been further detailed below. For the sake of discussion we have used a few key regulations and the main affected technical, operational and certification issues to illustrate the impact of regulations on the design, operation and certification of the system.

1.3.1 Technical and Operational Constraints

It is clear that the current regulations detailing permissible exposure and fiber-count levels will heavily influence the overall design in terms of sealing of the unit, use of vacuums systems and wetting/ encapsulant material during all abatement operations. Removal of ACM in TIS requires the constant wetting of the removed material which affects the use wetting agent with surfactant during all cutting, scraping and brushing operations. Additionally, cleanliness requirements will drive the need for an abrasive cleanup step, whether by mechanical brushing or high-pressure water spray to ensure the removal of all visible fibers from the pipe. Final air clearance samples will drive the use of encapsulant fluid to trap any microscopic fibers still on the pipe.

Operationally it becomes important to note that power and water will have to be separately provided, as all services to the abatement area will be shut down. In addition, the system will have to be self-starting, as all contact with the insulation is considered a disturbance. Should the robot not be able to do certain obstacles, those will have to be glove-bagged or bagged separately for human removal. Any waste fluids generated during the abatement will have to be collected, and if excessive will have to be filtered.

1.3.2 Certification Approach

In order to allow for system certification by EPA and OSHA, it is important to note that the federally proposed guidelines are all recommendations which are typically turned into regulations at the state level and possibly made even stricter at the local level. In either case, the minimum requirement for any alternate method of abatement, which is a category allowed by federal regulations, is that it meet all mandated EPA and OSHA rules. In addition, it is necessary for the local EPA representative in the respective region to view the process and recommend it be allowed to national EPA office by way of a letter. In addition, it is also possible to have either an industrial hygienist or project designer with professional engineering certificate to view and approve the process for local on-site use for certain size jobs.

Additionally, NEPA and field test plan information needs to supplied for the deployment at a selected DoE site, so that they can file all the necessary paperwork. This information bases itself heavily on the understanding, interpretation and compliance with existing EPA and OSHA (and possibly even NIOSH) regulations. Additional regulations, such as those imposed by the DoE and on-site contractors will also have to be reflected in the necessary reports.

2.0 Regulations

The regulations governing the abatement of asbestos insulation systems saw their birth with the passing of the Clean Air Act (Section 112) by Congress in 1970. Since then, a variety of federal regulatory agencies have continually improved and toughened the laws governing air/water cleanliness and work practices for worker safety. The most recent update occurred in August 1994, when OSHA issued a new set of regulations that reduced permissible exposure limits and further regulated asbestos abatement work practices.

This section is intended to provide a summary of the currently existing regulations imposed by federal, state and local agencies, highlighting the main issues arising from the currently proposed and implemented regulations which bear on the design, certification, deployment, and operation of a robotic asbestos abatement system.

2.1 Overview

Two federal government agencies cover asbestos work - the Environmental Protection Agency (EPA) and the Occupational Safety and Health Administration (OSHA). The EPA is responsible for researching, drafting recommendations and standards (which really carry the same weight as laws), and also enforcing the laws protecting the environment in general. OSHA is part of the Department of Labor and is responsible for the same categories as the EPA, except that their focus is the safety and protection of the worker. An additional agency, the National Institute for Occupational Safety and Health (NIOSH), researches worker safety and health, and reports its findings to OSHA and recommends health and safety standards to OSHA, including the certification procedures for respirators. Each of these agencies and their relevant regulations considered in this analysis (see *Appendix A: Regulations and Notification Forms Listings on page 24*) are detailed further below.

2.1.1 Environmental Protection Agency - EPA

The Clean Air Act of 1970 (Section 112) directed the EPA to develop emission standards for hazardous air pollutants, including asbestos. The National Emission Standards for Hazardous Air Pollutants (NESHAP) was issued under this act. This law includes regulations pertaining to demolition and renovation of buildings containing friable asbestos. The major aspects of the law are:

- Notification of EPA of any demolition/renovation of buildings containing asbestos
- Work practices for asbestos removal, including no visible emissions to the outside air
- Waste disposal requirements

Under NESHAP, any abatement job of more than 160 ft2, or 260 linear feet of pipe was considered a large job and required abiding to all NESHAP rules such as: Asbestos must be kept wet until it is sealed in a leakproof container, no asbestos can be dropped from higher than 50 feet, and that the EPA must be notified before any job is begun.

In October 1986, the Asbestos Hazard Emergency Response Act (AHERA) was signed into law. This legislation requires schools to survey and 'manage' their asbestos. As part of AHERA, EPA defined asbestos-critical levels to include those that contain more than 1% asbestos, spelled out five control methods (enclosure, encapsulation, repair, removal and an operations and maintenance plan), specified the final clearance air sampling methods (aggressive air sampling and inspection via Transmission Electron Microscope - TEM), and developed a training program for all people dealing with asbestos to result in a nationally accredited license. In essence what occurred is that most, if not all, schools have wound up fully replacing their asbestos insulation, resulting in a boom in the abatement markets. In addition, EPA has put in place a Ban-and-Phase-out-Rule beginning in 1990 and ending in 1997, which bans 94% of all asbestos containing products, including: floor- and ceiling tiles, brake shoes, clutch facings and any other material containing any asbestos (previously the limit was set at 1% asbestos content). Furthermore, in order to cover those workers in certain states and localities which are not protected by OSHA, EPA passed the Worker-Protection-Rule, which gives them the same protection as everyone else; i.e. to the national OSHA levels.

2.1.2 National Institute for Occupational Safety and Health - NIOSH

NIOSH recommended to OSHA the currently accepted regulations governing the need, use and handling of all respiratory protection systems. Under the current laws, any respirator must be approved by two agencies: the Mine Safety and Health Administration (MSHA) and NIOSH. Under these laws, the employer is required to set up a respiratory protection program, keep written procedures, offer medical exams, train you on the use of respirators, and issue you a respirator and certify that the respirator fits you.

2.1.3 Occupational Safety and Health Administration - OSHA

The Department of Labor, through OSHA, started a national job safety and health protection program based on the Occupational Safety and Health Act of 1970, providing for job safety and health protection for workers on the job. The legislation deals with employee rights and employer duties, processes for on-site inspection, dealing with complaints, issuance of citation and levying of penalties. Specifically for asbestos, OSHA has two key regulations that cover dealing with asbestos in general: (i) the Construction Industry Asbestos Standard, which contains regulations covering abatement, and (ii) the OSHA Respirator Standard.

The OSHA Asbestos Standard sets the permissible exposure limit of asbestos in the air, currently at 0.1 fibers per cubic centimeter (f/cc), in addition to requirements in the areas of (i) work practices, (ii) respirators, (iii) protective suits, (iv) decon units, (v) negative air pressure, (vi) air sampling, (vii) record keeping for air sampling, (viii) medical exams, and (ix) record keeping for medical exams. The OSHA Respirator Standard (29 CFR 1910.134) refers to the NIOSH respirator standards and issued the 10-point 'worker's respiratory bill of rights', which turned the NIOSH recommendation into law. Other OSHA-enforced laws pertain to the right-to-know what types of hazards are present in the workplace and how your employer protects the worker, as well the non-discrimination act, which states that an employer may not fire you for fighting for your health and safety on the job.

2.1.4 Nuclear Regulatory Commission - NRC

The NRC is supposed to control all aspects of nuclear material within the US. Its jurisdiction supposedly also encompasses the regulation of nuclear waste forms. In our case that would include radiation-contaminated ACM, which in itself is then defined as a mixed waste form. Since handling and disposal are the main issues, one has to understand the regulatory differences between pure asbestos and purely radiation contaminated materials. There are very clear work practices and regulations covering the handling and disposal of radiation waste-forms, which are very well known within the DoE. Additionally, there is an equivalent set of regulations for work practices, handling and disposal of asbestos waste forms as regulated by EPA and OSHA. In both cases, the tougher regulations are the ones that should be followed, should one need to deal with mixed waste forms. Practices, protective gear and handling guidelines for asbestos exceed those for irradiated materials with less than 5 mRem/hr. - the only difference lies mainly in what monitoring equipment is used during any job (i.e. air monitors rather than radiation counters)[1]. Since more than 85% of the asbestos found within DoE is not radiation contaminated, and then only a minor percentage of the radiation contaminated piping has R-levels higher than 5 mRem/hr., it would seem that following the regulations imposed by EPA, OSHA and DoE for asbestos abatement, would thus be a conservative approaach as long as additional radiation monitoring was part of all procedures. further corroborate our cocnlusions we requested information from the NRC regarding the work practices, handling and disposal of mixed radiation-contaminated asbestos insulation, but by the conclusion of this study had not yet received the promised information, and were thus unable to summarize and comment on the specifics of their regulatory constraints. We perceive this to not be a major issue due to arguments made above and the possibility of addressing this problem later in the development program should we be faced with such situations.

1. Based on discussions with Fernald, K-25 and Hanford on-site representatives during our facility tours

2.2 Federal

Highlights of the most current regulations on the books are summarized in this section, and grouped according to the issuing/governing federal agency. The focus will be on the EPA and OSHA, except that we have included the Department of Energy (DOE) since their regulations may draw upon, modify or even expand on existing federal regulations.

2.2.1 Environmental Protection Agency (EPA)

The EPA regulation that covers asbestos abatement activities is **40 CFR Part 61 - National Emissions Standards for Hazardous Air Pollutants (NESHAP), Subpart M - National Emission Standards for Asbestos**, dated Tuesday, November 20, 1990.

The main highlights of this regulation can be summarized as follows, with section numbers, titles, and subsections corresponding to those in the regulation attached in the appendix:

- **61.141 Definitions**

"Adequately Wet" means sufficiently mix or penetrate with liquid to prevent the release of particulates. If visible emissions are observed coming from the asbestos-containing material, then that material has not been adequately wetted. However, the absence of visible emissions is not sufficient evidence of being adequately wet.

"RACM" means Regulated Asbestos-Containing Material

- **61.145 Standard for demolition and renovation**

(a) Applicability

(1) and (4) If the sum total of all RACM to be removed or stripped during either a planned renovation or demolition operation is greater than 260 linear feet (80 linear meters), all requirements of paragraphs (b) and (c) apply.

(2) If the sum total of all RACM to be removed or stripped during a planned *demolition* operation is less than 260 linear feet (80 linear meters), only the notification requirements in paragraphs (b)(1), (2), (3), and (4)(i) through (vii) and (4)(ix) and (xvi) that follow apply.

(4) If the sum total of all ACM to be removed or stripped during a planned *renovation* operation is less than 260 linear feet (80 linear meters), paragraphs (b) and (c) that follow do not apply.

NOTE Since there is ongoing renovation and demolition operations at the DoE sites and the yearly total amount of removed insulation is greater than 260 linear feet, it will be necessary for us to notify the local, state, and federal regulatory bodies as described below regardless of the amount of RACM removed during the actual demonstration at the DoE site(s).

(b) Notification requirements

(1) Provide the Administrator with written notice of intention to demolish or renovate.

(2) Update the notice, as necessary, including when the amount of asbestos affected changes by at least 20 percent.

(3) Postmark or deliver the notice at least 10 working days before the asbestos stripping or removal work begins.

(4) Refer to the copy of this section in 40 CFR Part 61.145 in the appendix to determine what must be included in this notification.

(5) The information required in paragraph (b)(4) of this section must be reported (to the Regional EPA office) using a form similar to that shown in Figure 3 of 40 CFR Part 61 (presented in the appendix.)

NOTE As described later in this chapter, the states each have their own notification forms that must be filled out and submitted to their respective regulatory agencies. A copy of this completed form may be sent to the Regional EPA office to satisfy the above reporting requirement.

(c) Procedures for asbestos emission control

(2) When a facility component that contains, is covered with, or is coated with RACM is being taken out of the facility as a unit or in sections:

(i) Adequately wet all RACM exposed during the cutting or disjoining operations; and.

(ii) Carefully lower the material to the ground and floor, not dropping, throwing, sliding, or otherwise damaging or disturbing the material.

(3) When RACM is stripped from a facility component while it remains in place in the facility, adequately wet the RACM during the stripping operation.

(6) For all RACM, including material that has been removed or stripped:

(i) Adequately wet the material and ensure that it remains wet until collected and contained or treated in preparation for disposal.

(ii) Carefully lower the material to the ground and floor, not dropping, throwing, sliding, or otherwise damaging or disturbing the material.

(iii) Transport the material to the ground via leak-tight chutes or containers if it has been removed or stripped more than 50 feet above ground level and was not removed as units or in sections.

• **61.150 Standard for waste disposal for manufacturing, fabricating, demolition, renovation, and spraying operations.**

(a) Discharge no visible emissions to the outside air during the collection, processing, packaging, or transporting of any asbestos-containing waste material generated by the source, or use one of the emission control and waste treatment methods specified in paragraphs (a) (1) through (4) of this section.

(1) Adequately wet asbestos-containing waste material as follows:

(i) Mix control device asbestos waste to form a slurry; adequately wet other asbestos-containing waste material; and

(ii) Discharge no visible emissions to the outside air from collection, mixing, wetting, and handling operations.

(iii) After wetting, seal all asbestos-containing waste material in leak-tight containers while wet.

2.2.2 Occupational Safety & Health Administration (OSHA)

The OSHA regulation that covers Asbestos abatement is **29 CFR Part 1926.1101 - Occupational Exposure to Asbestos,** dated Wednesday, August 10, 1994.

The main highlights of this regulation can be summarized as follows, with section numbers, titles, and subsections corresponding to those in the regulation attached in the appendix:

• **1926.1101** Asbestos

(a) Scope and application. Regulates asbestos exposure in all work as defined in 29 CFR 1910.12(b), including but not limited to the following:

(1) Demolition or salvage of structures where asbestos is present;

(2) Removal or encapsulation of materials containing asbestos;

(3) Construction, alteration, repair, maintenance, or renovation of structures, substrates, or portions thereof, that contain asbestos;

(b) Definitions.

"Class I asbestos work" means activities involving the removal of TSI and surfacing ACM and PACM

"Thermal system insulation (TSI)" means ACM applied to pipes, fittings, boilers, breeches, tanks, ducts or other structural component to prevent heat loss or gain.

(c) Permissible exposure limit (PELS)

(1) Time-weighted average (TWA). 0.1 f/cc of air as an eight (8)-hour time-weighted average.

(2) Excursion limit. 1.0 f/cc as averaged over a sampling period of thirty (30) minutes.

(g) Methods of compliance

(1) The employer shall use the following engineering controls and work practices in all operations in this section, regardless of the levels of exposure:

(i) Vacuum cleaners equipped with HEPA filters to collect all debris and dust containing ACM or PACM; and

(ii) Wet methods, or wetting agents, to control employee exposures during work; and

(iii) Prompt clean-up and disposal of wastes and debris contaminated with asbestos in leak-tight containers.

(3) Prohibitions. The following work practices and engineering controls shall <u>not</u> be used for asbestos work, regardless of measured levels of asbestos exposure or the results of initial exposure assessments:

(i) High-speed abrasive disc saws that are not equipped with point of cut ventilator or enclosures with HEPA filtered exhaust air.

(iii) Dry sweeping, shovelling or other dry clean-up of dust and debris containing ACM and PACM.

(6) Alternative control methods for Class I work. Class I work may be performed using a control method which is not referenced in this section if the following provisions are complied with:

(i) The control method shall enclose, contain or isolate the processes or source of airborne asbestos dust, or otherwise capture or restrict such dust before it enters the breathing zone of employees.

(ii) A certified industrial hygienist or licensed professional engineer who is also qualified as a project designer as defined in paragraph (b) of this section, shall evaluate the work area, the projected work practices and the engineering controls and shall certify in writing that the planned control method is adequate to reduce direct and indirect employee exposure to below the PELs under worst-case conditions of use, and that the planned control method will prevent asbestos contamination outside the regulated area, as measured by clearance sampling which meets with the requirements of EPA's Asbestos in Schools rule issued under AHERA, or perimeter monitoring which meets the criteria in paragraph (g)(4)(i)(B)(2) of this section.

(A) Where the TSI or surfacing material to be removed is 25 linear of 10 square feet or less, the evaluation required in paragraph (g)(6) of this section may be performed by a "competent person", and may omit consideration of perimeter or clearance monitoring otherwise required.

(B) The evaluation of employee exposure required in paragraph (g)(6) of this section, shall include and be based on sampling and analytical data representing employee exposure during the use of such method under worst-case conditions and by employees whose training and experience are equivalent to employees who are to perform the current job.

(iii) Before work which involves the removal of more than 25 linear or 10 square feet of thermal system insulation or surfacing material is begun using an alternative method which has been the subject of a paragraph (g)(6) required evaluation and certification, the employer shall send a copy of such evaluation and certification to the national office of OSHA, Office of Technical Support, Room N3653, 200 Constitution Ave., NW, Washington, DC 20210.

2.2.3 Department of Energy (DoE)

Aside from the federal regulations discussed above and the following state and local regulations, there are no additional regulatory or notification requirements put on asbestos abatement projects within the Fernald and Oak Ridge Department of Energy sites. Since these two sites serve as models for our study, we will assume this to be the case across all DoE sites. The validity of this assumption should be checked for all other sites, should the robot be deployed there for the field test - we are currently planning to deploy it either at Fernald or Oak Ridge. In either case, the agreement with DoE is that <u>any</u> additional regulatory permitting/licensing/notification will be taken care of by the site, and hence a detailed knowledge of said process is known to each site and will be implemented by said site(s).

2.3 State

2.3.1 Pennsylvania

2.3.1.1 Commonwealth of Pennsylvania Department of Labor and Industry

The Commonwealth of Pennsylvania Department of Labor and Industry, Bureau of Occupational and Industrial Safety regulates worker licensing and asbestos training, but does not regulate work practices or project notification requirements. Asbestos abatement workers are prohibited from performing, directly or indirectly, any asbestos abatement in the state of Pennsylvania without a valid license from the Department of Labor and Industry. Before we can perform any abatement activities within the state of Pennsylvania, we must be certified by the PA Department of Labor and Industry as either a worker, supervisor, or project designer. A copy of the *Commonwealth of Pennsylvania Department of Labor and Industry Application for Asbestos Occupation Certification* is presented in the appendix.

2.3.1.1 Commonwealth of Pennsylvania Department of Environmental Resources

The Commonwealth of Pennsylvania Department of Environmental Resources, Bureau of Air Quality Control governs all asbestos abatement work done within the Commonwealth of Pennsylvania that is not in Allegheny County or the City of Philadelphia. *A Commonwealth of Pennsylvania Asbestos Abatement and Demolition/Renovation Notification* form must be completed for each asbestos abatement job within the state lines, a copy of which must be sent to both the Department of Environmental Resources in Harrisburg and the EPA Region 3 headquarters in Philadelphia. For projects within either Allegheny County or the City of Philadelphia, this form must be submitted to the Allegheny County Health Department (ACHD) and EPA Region 3, and if the abatement project is large enough (> 131 linear feet) a permit application must accompany this notification to the ACHD (refer to Section 2.4.1.2 on page 15). Copies of these forms are presented in the appendix.

2.3.2 Ohio

2.3.2.1 Ohio Department of Health

Asbestos abatement contractors are prohibited from performing, directly or indirectly, any asbestos abatement in the state of Ohio without a valid license from the Ohio Department of Health. This agency regulates contractor and worker licensing and asbestos training, but does not regulate work practices or project notification requirements. Before we can perform any abatement activities within the state of Ohio, we must be certified by the Ohio Department of Health as either a worker, supervisor, or project designer. A copy of the *Ohio Department of Health Application for Certification* is located in the appendix.

2.3.2.2 Ohio Environmental Protection Agency

The requirements of the Ohio Environmental Protection Agency are very similar to those in the federal EPA regulations (40 CFR 61, Subpart M). With the exception of some modifications in wording, the technical portions of the regulations are identical. An *Ohio Environmental Protection Agency Notification of Demolition and Renovation* form must be completed and sent to both the Hamilton County Department of Environmental Services and EPA Region 5 in Chicago. A copy of this form is presented in the appendix.

2.3.3 Tennessee

At the time of this report (8/21/95), Tennessee is one of the few states in the U.S. that does not require asbestos worker certification and licensing for asbestos work done outside of school buildings. In 1986, Congress enacted the Asbestos Hazard Emergency Response Act (AHERA) which mandated a regulatory program to address asbestos hazards in schools. A part of AHERA dealt with the mandatory training and accreditation of persons who would perform certain types of asbestos-related work in schools. Subsequently, in 1990, Congress enacted the Asbestos School Hazard Abatement Reauthorization Act (ASHARA), which expanded these accreditation requirements to apply to persons who work with asbestos in public and commercial buildings as well as schools. Most other states have already adopted regulations to comply with ASHARA, but no official Tennessee law exists at this time (although a copy of the "proposed" law is presented in the appendix). The state of Tennessee has until July of 1995 to comply with this regulation. A Tennessee asbestos worker/supervisor application form similar to those for Pennsylvania and Ohio will be available at that time from the Tennessee Department of the Environment and Conservation.

The Tennessee Department of the Environment and Conservation, Air Pollution Control Division regulates asbestos abatement jobs within areas in Tennessee not covered by local regulatory agencies that are typically located in cities and areas of increased population density. Oak Ridge National Laboratory is not located within one of these high-population-density areas, and all asbestos work is therefor covered by the Rules and Regulations of the State of Tennessee, Chapter 1200-3-11: Hazardous Air Contaminants. Except for a few minor wording changes, these regulations are identical to those of the Federal EPA (40 CFR Part 61). A *Tennessee Division of Air Pollution Control Notification of Asbestos Demolition and Renovation* form must be completed and sent to the Tennessee Department of the Environment and Conservation, Air Pollution Control Division in Nashville as well as to EPA Region 4 in Atlanta. A copy of this form is presented in the appendix.

2.3.4 Summary

In general, state regulations are simply restatements of the federal EPA regulations listed above. State regulatory commissions such as the Commonwealth of Pennsylvania Department of Environmental Resources, Bureau of Air Quality Control (covers work done at CMU), the Ohio Department of Health and the Ohio Environmental Protection Agency (covers work done at Fernald), and the Tennessee Department of the Environment and Conservation, Air Pollution Control Division (covers work done at Oak Ridge) have notification and procedure requirements similar to that of the Federal EPA described previously. Each state has a form(s) that must be filled out and sent in prior to the start of any asbestos abatement work. Copies of these forms for the states of Ohio, Pennsylvania, and Tennessee are located in the appendix.

2.4 Local

2.4.1 Allegheny County

Allegheny County has its own set of regulations (ARTICLE XX - Rules and Regulations of the

Allegheny County Health Department, Bureau of Air Pollution Control (hereafter referred to as the "Bureau") - County Ordinance No. 16782, Chapter X - Toxic or Hazardous Air Pollutants, Section 1001 - Asbestos Abatement, dated July 1, 1989) that deal with asbestos abatement. These regulations are more strict than those in the Federal Register. The Allegheny County Department of Health enforces additional requirements on 1) applicability, 2) notification and permitting, 3) work area preparation, 4) clearance air sampling, and 5) final clearance inspection.

2.4.1.1 Applicability (Subsection 1001.03)

The provisions of Chapter X, Section 1001 apply to removal, demolition, or encapsulation jobs of at least 131 linear feet (40 linear meters) of pipe, as opposed to 260 linear feet in the federal EPA regulation. Demolition jobs of any facility containing less than 131 linear feet require notification only per subsection 1001.08B.

2.4.1.2 Licensing, Notification, and Permitting (Subsections 1001.06 and 1001.08)

Contractor license. Per subsection 1001.06, no person may perform asbestos abatement unless the person is licensed by the Bureau. An *Allegheny County Asbestos Abatement Contractor License Application* is presented in the appendix.

Notification. At least twenty (20) days prior to the beginning of the removal, demolition, or encapsulation of any ACM, written notice (using a *Commonwealth of Pennsylvania Asbestos Abatement and Demolition/Renovation Notification* form) must be submitted to the Bureau (and to EPA Region 3 in Philadelphia). Refer to subsection 1001.08B in the appendix for details of the requirements for this notice.

Permitting. A completed *Allegheny County Asbestos Abatement Notice/Permit Application*, a non-refundable application fee, and a detailed description of the decontamination enclosure system(s) to be used (including floor plans) must also be submitted to the Bureau no later than twenty (20) days prior to the beginning of any asbestos abatement project involving the removal or encapsulation of at least 131 linear feet of ACM. Details of the fee requirements, as well as a copy of the Asbestos Permit application, is presented in the appendix.

2.4.1.3 Work Area Preparation (Subsection 1001.10)

Critical barriers. All openings (including windows, doorways, ducts, etc.) to the work area must be sealed with minimum 6 mil plastic sheeting sealed with tape.

Floors and walls. All wall surfaces must be covered with minimum 6 mil plastic sheeting sealed with tape. Floors must be covered with a minimum of two layers of 6 mil plastic. Floor and wall plastic sheeting must overlap by at least 12 inches.

NOTE These regulations state that critical barriers, floors, and walls must be covered even when doing glovebag removal within Allegheny County, although alternative requirements may be approved by the ACHD Director - refer to section 2.4.1.6 on page 16

2.4.1.4 Clearance Air Sampling (Subsection 1001.15)

At least five(5) samples of air per the first 5000 square feet of work area plus one sample per each additional 5000 square feet of work area; or one (1) sample of air per room, whichever is greater, shall be collected and analyzed. The airborne concentrations of asbestiform fibers detected in each sample shall be less than 0.01 fibers per cubic centimeter of air. Further details of this requirement are in subsection 1001.15 in the appendix.

NOTE There are no such clearance levels for work done in Hamilton County, OH (Fernald) or

Anderson County, TN (Oak Ridge). In these counties and most other rural counties in the U.S., the "no visible emissions" and "adequately wet" requirements of the federal EPA and state agencies discussed earlier are the only regulations. Regardless of this fact, if BOA is to be used nationwide without exceptions and special variances, BOA should meet the clearance sample level of 0.01 fiber/cc. Note also that the AHERA rules are to soon be applied to all public buildings rather than just schools, which implies that all post-abatement inspection must include a clearance air sample - this law is expected to take effect by 1996.

2.4.1.5 Final Clearance Inspection (Subsection 1001.16)

A final clearance inspection by the Bureau is required after clean-up and clearance air sampling per subsections 1001.14 and 1001.15. Until the results of the Final Clearance Inspection are acceptable to the Bureau, the removal of any containment barriers and negative air systems, and the reopening of the work area to the public is prohibited. Such inspection shall be deemed acceptable when the results of the clearance air sample detect airborne concentrations of 0.01 fibers/cc and no asbestos-containing waste material or visible residue remain on any surface or object in the work area.

2.4.1.6 Alternative Methods (Subsection 1001.18)

On a case-by-case basis, the Director (of the Allegheny County Health Department, Bureau of Environmental Health, currently Wilder D. Bancroft) may approve an alternative procedure to those described in Section 1001, provided that the request is submitted in writing, and demonstrates that the proposed alternative procedure is equivalent, in terms of asbestos control, to the requirements of Section 1001. Subsection 1001.12H specifically states that when the glovebag technique is to be utilized, the Director may approve alternative requirements which are proposed in the *Asbestos Abatement Notice/Permit Application* for work area preparation, decontamination enclosure systems, removal procedures, clean-up procedures, and clearance air sampling.

2.4.2 Hamilton County, OH (Fernald)

The Hamilton County Department of Environmental Services serves as the local governing body for the Ohio Environmental Protection Agency. They do not impose any additional requirements, but rather act as the local Ohio EPA law enforcement agency. Notifications (*Ohio Environmental Protection Agency Notification of Demolition and Renovation* forms) for all proposed asbestos abatement work within Hamilton County limits are sent to their office.

2.4.3 Anderson County, TN (Oak Ridge)

Asbestos abatement projects at Oak Ridge National Laboratory are not governed by any additional local regulatory bodies (i.e. no additional permitting nor notification requirements). All notification and permitting is done through the state regulatory commission (The Tennessee Department of the Environment and Conservation, Air Pollution Control Division). Refer to this section above for details on the requirements for the state of Tennessee.

3.0 Regulatory Impact

The impact of the reviewed regulations at the federal, regional, state and local levels can be synthesized into a set of steps to cover (i) the comprehensive list of regulatory paperwork required for certification, (ii) the strategy to pursue to achieve certification, (iii) the list of required notifications, permits, (iv) listing of crucial design drivers to ensure BOA is certifiable, and (v) the list of agency contacts to be kept informed along the development process. These topics are all covered in this section, in addition to an example of a product in the same industry that was subjected to a similar 'circuitous' certification process.

3.1 Regulatory Strategy and Goal

All appropriate regional and federal regulatory agencies and personnel (see Table 1:) should be preliminarily informed about the BOA project and kept involved as we progress. In some cases, this has been informally done through phone conversations and the exchange of video of the Phase I demonstration of BOA. In the near future, though, we should seek to formally involve these regulatory bodies. It has been suggested by both the local Department of Health (DoH) and OSHA representatives that we compose a letter and/or document describing the mechanics and operations of our system, as well as what impact it will have on both worker safety (OSHA) and the environment (EPA). Since the BOA system complies with the intent of the regulations (that is, it keep workers away from hazards (OSHA's focus) and minimized hazardous emissions to the environment (EPA's focus), but does not necessarily comply with the "letter of the law" set by the standards, this letter/document should ask the regulatory representatives what their interpretation of the standards is for BOA, and to tell us if they have any concerns about our approach. Our goal will be the receipt of a written verification that our understanding and approach to the regulatory requirements on BOA is correct, appropriate or even just '...within the regulatory guidelines...'.

FEDERAL	
OSHA	**EPA**
Ms. Carol Jones OSHA Health Standards Room N3718 200 Constitution Avenue, N.W. Washington, D.C. 20210 (202) 219-7174	Mr. Tom Ripp U.S. EPA - 2223A 401 M Street S.W. Washington, D.C. 20460 (202) 564-7003
REGIONAL[a]	
OSHA Region 3 **Pittsburgh, PA**	**EPA Region 3** **Pittsburgh, PA**
Mr. Jim Johnston Regional Administrator U.S. Department of Labor - OSHA Region 3 Gateway Building, Suite 2100 3535 Market Street Philadelphia, PA 19104 (215) 596-1201	Mr. John Daly Asbestos Coordinator (3HW-42) EPA Region 3 841 Chestnut Bldg. Philadelphia, PA 19107 (215) 597-1970

Table 1: Federal and Regional Regulatory Agencies and Contacts

OSHA Region 5 Fernald, OH	EPA Region 5 Fernald, OH
230 S. Dearborn St. 32nd Floor, Rm. 3244 Chicago, IL 60604 (312) 353-2220	Asbestos Coordinator (T-SPTB-7) 230 S. Dearborn St. Chicago, IL 60604 (312) 886-6003
OSHA Region 4 Oak Ridge, TN	**EPA Region 4 Oak Ridge, TN**
1375 Peachtree St., NE Suite 587 Atlanta, GA 30367 (404) 347-3573	Asbestos Coordinator (P&TSB) 345 Courtland St., NE Atlanta, GA 30365 (404) 347-5053

Table 1: Federal and Regional Regulatory Agencies and Contacts

a. Notification to EPA and OSHA is sufficient through the region in which the development is ongoing; i.e. Region 3. Other regional offices accept the development region leading the interfacing and notification. Other regional offices need only be kept informed towards the conclusion of the development.

In addition, it will be advisable to also keep the state and local EPA and OSHA representatives/ agencies involved, by informing them of the current project, its status, and by supplying them a copy of the report describing the system in detail (i.e. a design document), as well as its mode of operation. The currently identified representatives in individual agencies based on the state and the locality, are listed below in Table 2:

STATE	
Oak Ridge, TN - Dept. of Env. & Cons.	**Others[a] Pittsburgh, PA - Dept. of Env. Resources Fernald, OH - Dept. of Env. Resources**
Mr. Jackie Waynick Tennessee Department of Environment and Conservation Air Pollution Control Division 9th Floor, L & C Annex 401 Church Street Nashville, TN 37243-1531 (615) 532-0570	see note
LOCAL	
Pittsburgh, PA - Health Dept.	**Fernald, OH - Env. Services**

Table 2: State and Local Regulatory Agencies and Contacts

Mr. Jim Stanko Allegheny County Health Department Building 7 - Asbestos Section 301 39th Street Pittsburgh, PA 15201 (412) 578-8133	Mr. Bradley Miller Hamilton County Environmental Services 1632 Central Parkway Cincinnati, OH 45210 (513) 651-9437

Table 2: State and Local Regulatory Agencies and Contacts

a. Pittsburgh, PA and Fernald, OH reside in a part of their respective states where local authorities retain jurisdiction over any asbestos abatement project. The relevant state offices will receive copies of any notifications from the local agencies/offices. Typically only the permitting needs to be accomplished through the state-wide offices. Hence the contact points for Pittsburgh and Fernald are purely at the local level and are thus listed.

3.2 Summary

The primary focus of the regulatory agencies described above is fundamentally the same: to limit the emission of asbestos fibers into the air and the exposure of humans. OSHA's standpoint is one of worker safety, whereas, EPA's is one of protection of the environment and the general public, but their goals are basically identical. A bullet summary of the technical ramifications of the regulations with respect to the design and operations of BOA are presented in this section, as are the notification requirements for abatement jobs utilizing this system. It will be necessary for us to involve the local regulatory representatives in this project as we approach a time when we will actually use the BOA system to remove asbestos insulation. In addition, it will be wise for us to keep the regional and federal representatives informed as well (refer to Section 3.1, Table 1: and Table 2:).

3.2.1 Regulatory Overhead

Specific regulatory and notification requirements will have to be handled on a case-by-case basis. The two agencies with jurisdiction in asbestos abatement are OSHA and the EPA.

- **OSHA**

  OSHA has an important 'alternative method' requirement for each abatement project, which is to provide written evaluation (see 29 CFR 1926.1101 (g)(6)) (of the overall system, the containment method and operational scenario) by a certified industrial hygienist or licensed professional engineer who is also qualified as a project designer to OSHA.

  Additionally, we will continue to keep all relevant OSHA POCs informed along the way.

- **EPA**

  For each abatement project, we will have to provide proof of asbestos worker/supervisor certification to the states, and written notification and a site-specific description of our system and emission-control method to the various regional, state, and local regulatory bodies using the appropriate forms described above. Note that no federal notification is required.

  Additionally, we will continue to keep all relevant OSHA POCs informed along the way.

3.2.2 Notification Process

The main requirements arising from the regulations discussed previously which bear on the notification requirements of a robotic asbestos abatement system are as follows:

- State asbestos worker/supervisor application sent with certificate of completion of approved training course and fee to appropriate state regulatory agency (various state forms - see above)
- Asbestos abatement notification form sent to appropriate regulatory agency (various state

forms - see above)

- Copy of above notification form sent to Regional EPA office for site where abatement project is going to take place (40 CFR Part 61, Section 61.145 (b)(5))
- Local asbestos abatement notice/permit application form sent to appropriate local regulatory agency (if needed - see above)
- Alternative methods evaluation document sent to OSHA Office of Technical Support (29 CFR 1926.1101, Section (g)(6))

A tabular representation of the notification process for Pittsburgh, Fernald and Oak Ridge, the required forms and the respective recipient agencies is given in Table 3: on page 21. A similar table could be developed for any other sites within the DoE complex, but has not been to date, since we expect to perform our field test at either one of these sites. No regulations, permits or other constraints that we know of would preclude this analysis from applying to any of those other DoE sites located in other states or counties not specifically mentioned in this analysis.

3.2.3 System Design and Operational Criteria

The main issues arising from the regulations discussed previously which bear on the design and operational specifications of a robotic asbestos abatement system are as follows:

- Adequately wet the material and ensure that it remains wet until collected and contained or treated in preparation for disposal (40 CFR 61.145 - NESHAPS)
- Discharge no visible emissions to the outside air (40 CFR 61.145 - NESHAPS)
- Carefully lower the material to the ground and floor, not dropping, throwing, sliding, or otherwise damaging or disturbing the material (40 CFR 61.145 - NESHAPS)
- Permissible exposure limit (PELS): (29 CFR 1926.1101 - OSHA)
  (1) Time-weighted average (TWA). 0.1 f/cc of air as an eight (8)-hour time-weighted average.
  (2) Excursion limit. 1.0 f/cc as averaged over a sampling period of thirty (30) minutes.
- Must use vacuum cleaners equipped with HEPA filters to collect all debris and dust containing ACM or PACM (29 CFR 1926.1101 - OSHA)
- Clearance air sample must be below 0.01 f/cc before critical barriers can be removed (Allegheny County Ordinance 16782, Section 1001)
- Ensure proper sealing during all phases of operation to avoid the need for critical barriers.

3.2.4 Informational Guidelines

As discussed in Section 3.1 on page 17, we propose to keep all local, state, regional and federal agencies and their respective representatives informed as to the progress of our project. Key information to be supplied to them will be (i) a letter and a copy of the Phase I results (mailed out before April 1, 1995), a letter and a copy of the revised BOA concept (mailed out by July 1, 1995), and a full design document and an operational scenario description based on the detailed design effort of the Phase II BOA system (mailed out before January 1, 1996).

Note that the design document and the operational scenario description will form the basis of any further notification and licensing activities to all the local, regional and federal EPA and OSHA representatives, as well as being the basis upon which the OSHA-reporting requirement will be formed.

Location of Abatement Project	Federal Notification Requirements	State Notification Requirements	Local Notification Requirements
Allegheny Co., PA (Guideline for CMU)	EPA Region 3, Asbestos Coordinator (Philadelphia) *Commonwealth of PA Asbestos Abatement and Demolition/Renovation Notification* OSHA Office of Technical Support Written evaluation and certification by certified industrial hygienist or project designer with P.E. (see 29 CFR 1926.1101 (g)(6))	Commonwealth of PA Dept. of Labor and Industry, Bureau of Occupation & Industrial Safety *Commonwealth of PA Dept. of Labor and Industry Application for Asbestos Occupation Certification*	Allegheny County Health Department *Commonwealth of PA Asbestos Abatement and Demolition/Renovation Notification* *Allegheny County Asbestos Abatement Contractor License Application* *Allegheny County Asbestos Abatement Notice/Permit Application* (if abatement job > 131 linear feet)
Hamilton Co., OH (Fernald)	EPA Region 5, Asbestos Coordinator (Chicago) *Ohio EPA Notification of Demolition and Renovation* OSHA Office of Technical Support Written evaluation and certification by certified industrial hygienist or project designer with P.E. (see 29 CFR 1926.1101 (g)(6))	Ohio Department of Health *Ohio Department of Health Application for Certification*	Hamilton Co. Department of Environmental Resources *Ohio EPA Notification of Demolition and Renovation*
Anderson Co., TN (Oak Ridge)	EPA Region 4, Asbestos Coordinator (Atlanta) *Tennessee Division of Air Pollution Control Notification of Asbestos Demolition and Renovation* OSHA Office of Technical Support Written evaluation and certification by certified industrial hygienist or project designer with P.E. (see 29 CFR 1926.1101 (g)(6))	Tennessee Department of Environment and Conservation *Tennessee Division of Air Pollution Control Notification of Asbestos Demolition and Renovation*	

Table 3: Summary of Notification Requirements

3.2.5 Certification Example

It becomes noteworthy to mention and detail an example of another asbestos-abatement related invention that was developed into a product which was then put through the paces to have it accepted as an alternate method. The example was drawn from a personal relation ship with an asbestos abatement contractor currently subcontracted under a separate DoE contract related to asbestos recycling or processing.

DSI Industries Consolidated, Inc. had developed a new type of wetting agents as part of their ABCOV (Asbestos Conversion) method, which chemically converts asbestos to a non-carcinogenic compound. Their certification approach entailed enrolling the local and regional EPA representatives, a representative from NESHAP and a representative from EPA's research office in North Carolina by keeping them up-to-date on their progress, and then inviting them to their multiple field-demonstrations and making independently performed lab-data available for their perusal. This approach eventually led to a letter of allowance from the regional EPA office, enabling them to use their techniques under certain established guidelines.

Through discussions with DSI, CMU recommends that a similar approach be pursued for our certification. Contacts need to be made with the local state and regional EPA representative, including a brief description and a video of the current method. Since the national EPA does not endorse any new technologies, but rather issues variances through their local and regional representatives, it is imperative to work closely with them in order to get a variance should it be required. In essence what will be required, is that a (set of) letters be drafted by the DoE (whether headquarters, research or site representative is unclear, but the more or the higher-up the better) stating their interest in applying this technology, as well as a letter by the DoE site contractor who would be applying the technology, and sent said letter to the local, regional and national offices. Actions will then be taken by the local and regional EPA representatives, who in turn will recommend that the variance be granted. The variance or allowance would be in the form of a letter from the regional EPA office to the local DoE site contractor. Based on the previous experience gathered by DSI, we believe that the currently proposed certification approach is the best and most comprehensive to take.

4.0 Course of Action

This section provides a summary tabular representation of the recommended list of steps to take to ensure the certification and/or acceptance of the proposed BOA system for performing asbestos abatement within any industrial, commercial or government facility. The enumerated list also provides a more detailed description of the contents/activities involved with each of these actions, and is then supported with a gant-chart like representation that depicts the time line of when separate actions need to be started and when they are expected to be concluded.

4.1 Action List

The complete list of actions draws on the results of the analysis, and also includes additional steps that we are contractually obligated to perform as part of the BOA system development, namely the drafting of all NEPA documentation as well as a detailed test plan. An attempt has been made to somewhat describe the nature/content of each of these action-items to illustrate the scope and justify the length of time estimated for each action. The proposed numbering scheme carries over into the timeline representation for each of these actions in Section 4.2.

The categorized list of action items is as follows:

#	ACTION ITEM	DESCRIPTION
1.	**Overall Information**	Background Information sent to all relevant POCs in all federal, regional and local agencies.
1.1	Agency Background Information	Phase I Topical Report and a copy of the video sent out to all contacted representatives within the EPA, OSHA and local departments where we might demo.
1.2	Regulatory Strategy Information	The regulatory analysis will be sent to EPA and OSHA representatives at the local, state, regional and federal levels to receive support for our approach.
1.3	OSHA Background Notification	Design and Operational Report (DOR), drafted at the conclusion of the Phase II design effort, to be sent out to the federal OSHA and EPA contacts in Washington, DC (OSHA-Carol Jones, EPA-Tom Ripp).
1.4	EPA Background Notification	
2.	**EPA Interaction**	Notifications sent out to provide notification of impending abatement activity at a specified site.
2.1	EPA Regional Notification	Notification of jurisdictional EPA regional office using respective form and appending the DOR.
2.2	State EPA (or equivalent) Notification	Notification of jurisdictional EPA/Health Dept. state office using respective form and appending the DOR.
2.3	Local Environmental Department Notification	Notification of jurisdictional county office using respective form and appending the DOR.

#	ACTION ITEM	DESCRIPTION
3.	**OSHA Interactions**	Reports sent to OSHA describing the actual abatement site, control methods and work practices by an industrial hygienist or project designer with PE license.
3.1	Alternative Methods Evaluation Document	According to 29 CFR Part 1926.1101 (g) (6), provide a written document to the OSH-DC office.
3.2	Load-Handling Description	Description of the operational scenario outlining the loads and working conditions required from the workers.
4.	**Permitting & Licensing**	Application and Acquisition of all the necessary permits and licenses to be able to assist and perform the abatement at a specific site.
4.1	State Asbestos Worker/Supervisor Application	Application form with proof of training sent to state agency to receive license and work permits.
4.2	Local Asbestos Worker/Supervisor Application	Same as above, except from a local authority or department with jurisdiction (if local regs supercede state regs).
5.	**DoE Interactions**	Documentation required by the DoE from the contractor (CMU only in this case) before any proposed field test is executed.
5.1	NEPA Documentation	Summary document outlining all the environmental, personal and other health impacts that field test might have on the environment - in essence a more detailed discussion of engineering and monitoring/control methods as compared to the '*Alternative Methods Evaluation Document*' sent to OSHA.
5.2	Field Test Plan	Detailed description of the field test plan listing the operational scenario, involved logistics, DoE supply requirements, timeframes, personnel, etc. Report to be based on guidelines drafted by Energetics, Inc. for METC.

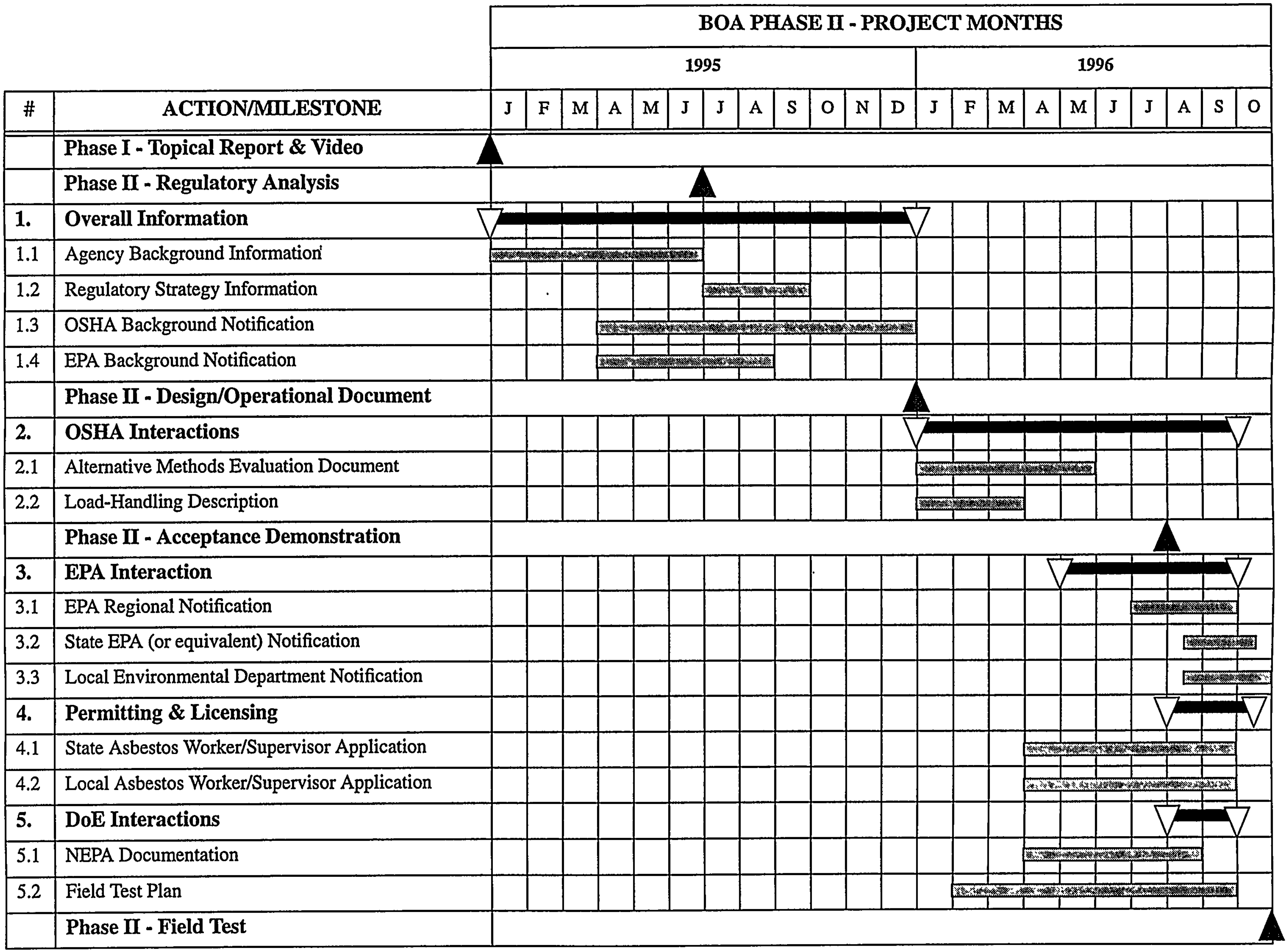
4.2 Timeline

The above list of action items has a temporal dependency as to when they should be executed, and what major programmatic events they coincide with. The main milestones that we currently intend to use by which to trigger the different actions are as follows:

MILESTONE	DESCRIPTION
Phase I Topical Report & Video	A Phase I Topical Report describing the system using diagrams and pictures. In addition a video stepping through the complete BOA system and its capabilities.

MILESTONE	DESCRIPTION
Systems Study	Documents completed describing the market-study, regulatory analysis and cost/benefit analysis.
Design & Operational Document	Description of the robot system design, including all detailed mechanical, electrical and fluid systems, as well as an operational description.
System Acceptance Demo (@ CMU)	Demonstration of BOA at CMU. Should DoE decide to go ahead, a deployment site will have been selected and all the necessary NEPA information and field test plans will need to be filed.

A pictorial rendition of all the action items, their relation to the overall project milestones, their relative duration and interdependencies are shown on the milestone/schedule chart on the next page.



BOA PHASE II - PROJECT MONTHS
1995
1996
#
ACTION/MILESTONE
J F M A M J J A S O N D J F M A M J J A S O
Phase I - Topical Report & Video
Phase II - Regulatory Analysis
1. Overall Information
1.1 Agency Background Information
1.2 Regulatory Strategy Information
1.3 OSHA Background Notification
1.4 EPA Background Notification
Phase II - Design/Operational Document
2. OSHA Interactions
2.1 Alternative Methods Evaluation Document
2.2 Load-Handling Description
Phase II - Acceptance Demonstration
3. EPA Interaction
3.1 EPA Regional Notification
3.2 State EPA (or equivalent) Notification
3.3 Local Environmental Department Notification
4. Permitting & Licensing
4.1 State Asbestos Worker/Supervisor Application
4.2 Local Asbestos Worker/Supervisor Application
5. DoE Interactions
5.1 NEPA Documentation
5.2 Field Test Plan
Phase II - Field Test

VI. Market Assessment

1.0 Market Assessment

This section characterizes the historical and potential growth of the asbestos abatement market, as well as major divisions within the market. The general characterization presented below brackets the total potential market for an automated pipe insulation abatement system. In conjunction with the evaluation of both the current state of the art for asbestos abatement and the risks and opportunities associated with the development of an automated system, this characterization is used to focus this development on the subsets of the market (herein "target markets" or "market segments") that demonstrate substantial sales potential as well as to determine the size of these potential markets.

1.1 Current Asbestos Abatement Market Situation

The current asbestos abatement services market is estimated at $70 billion over the next twenty to twenty-five years. Assuming a twenty-five year life for this industry, the average yearly revenue is projected at $2.8 billion. As of 1992, there were 1,600 asbestos abatement companies with a total of 2,090 locations.[1] While asbestos has not been used as a building material since the mid-1970's, it has been projected to be found in approximately 760,000 buildings.[2] As can be seen in and , the revenues and the number of contractors in the asbestos abatement industry are now experiencing a decline after a period of tremendous growth in the late 1980's. Many of these companies are now diversifying into other environmental industries (such as lead paint abatement).

Table 1.1: Asbestos Abatement Market Growth, 1987-1992

YEAR	MARKET SIZE (DOLLARS IN MILLIONS)	MARKET GROWTH (FROM PREVIOUS YR.)
1987	$1.9	216%
1988	$3.0	58%
1989	$3.9	30%
1990	$3.9	0
1991	$3.4	-13%
1992	$3.2	-6%

Source: The Jennings Group, Inc. - Exhibit 1, p. 10, Copyright 1993

Table 1.2: Estimated Number of Asbestos Contractors, 1989-1992

YEAR	COMPANIES	BRANCHES	TOTAL LOCATIONS	% CHANGE (FROM PREVIOUS YR.)
1989	2,230	425	2,655	NA
1990	2,050	510	2,560	-4%
1991	1,750	500	2,250	-12%
1992	1600	490	2,090	-7%

Source: The Jennings Group, Exhibit 5, p. 16, Copyright, 1993

1. The Jennings Group, Inc., Asbestos Abatement Contracting Industry 1993, May 1993
2. Paul Tarricone, "The Asbestos Agenda", Civil Engineering, vol. 59, Oct. 1989, p. 48-51

There are six major market segments (see Table 1.3:) defined by the type of building in which the asbestos containing materials (ACM) are found. The Government market is the only segment which has been experiencing significant growth in the last few years. The Office/Commercial and Industrial market segments have the greatest total revenue of all market segments, composing respectively 28% and 25% of the total market in 1992. The Office/Commercial segment is comprised of office and commercial buildings such as malls and grocery stores. Manufacturing, processing, refining and other fabrication sites are part of the Industrial segment. There is a separate category for Utilities which is also experiencing a decline in recent years. Table 1.3: presents gross revenue data on these market segments from 1990 through 1992.

Table 1.3: Asbestos Abatement Contracting Market Segments, 1990-1992
(dollars in millions)

MARKET SEGMENT	1990		1991		1992	
	$	%	$	%	$	%
Office/Commercial	1,250	32%	1,020	30%	895	28%
Industrial	1,050	27%	885	26%	800	25%
Utility	390	10%	305	9%	225	7%
Government	310	8%	475	14%	575	18%
Schools	665	17%	510	15%	480	15%
Residential	155	4%	135	4%	160	5%
Other	80	2%	70	2%	65	2%
TOTAL	**3,900**	**100%**	**3,400**	**100%**	**3,200**	**100%**

Source: The Jennings Group, Inc., Exhibit 2, p. 12, Copyright 1993

The market is also defined by the type of asbestos-containing materials present. There are three major types of ACM: (i) spray-on asbestos, used mostly on ceilings and around air ducts, (ii) thermal asbestos, used on pipes and boilers, and (iii) vinyl asbestos tile, used on floors. Most of the asbestos removed in 1992 was spray-on with thermal close behind.

Table 1.4: 1992 Asbestos Market by Type of ACM Removed

	DOLLARS (IN MILLIONS)	% OF MARKET
Spray-on	$1,250	39%
Thermal	$990	31%
Vinyl asbestos tile (VAT)	$385	12%
Other	$575	18%
TOTAL	**$3,200**	**100%**

Source: The Jennings Group, Inc., Exhibit 4, p. 14, Copyright 1993

The last significant breakdown of the asbestos abatement industry is by type of work. Renovation is the predominant impetus which forces the removal of asbestos at sites. Demolition of buildings is a distant second reason. There has recently been a policy change which is now encouraging Operations and Maintenance (O&M) work and recognizes it as the preferred method of dealing with asbestos. O&M-type regulations require that all ACM-suspect locations be surveyed and that all the asbestos is maintained in place. Asbestos only poses a potential health concern when it is broken down into fibers which can be inhaled or ingested. While in 1992 O&M work only represented 10% of the asbestos work, this percentage is expected to increase in the future.

Table 1.5: 1992 Asbestos Market by Type of Work

	DOLLARS (IN MILLIONS)	% OF MARKET
Renovation	$1,920	60%
Demolition	$575	18%
O&M	$320	10%
Other work	$385	12%
TOTAL	**$3,200**	**100%**

Source: The Jennings Group, Inc., Exhibit 3, p. 13, Copyright 1993

1.2 Technological State of the Art

1.2.1 Manual Abatement Techniques

Manual abatement of asbestos-containing materials from pipes is a highly regulated activity. The specific regulations regarding what methods are allowable under what circumstances vary from state to state, and sometimes from county to county, but in general, there are two main pipe-insulation abatement techniques that are standard and allowable.

• Full- or Mini-Containment

For large scale abatement projects (i.e., several hundred feet of pipe), the most common abatement method is "Full Containment" which means creating a walk-in negative-pressure enclosure around the work area and performing all work within this enclosure. "Mini-Containment" is virtually the same as Full Containment except that the enclosure is smaller. Both methods involve:

- putting plastic sheeting over all walls, floors, and exposed surfaces,
- drawing a vacuum on the work area with large HEPA vacuums,
- going in and stripping insulation off the pipes,
- cleaning all surfaces after removal,
- spraying a lock-down compound on all surfaces, and
- passing a final air sample clearance test prior to the shut down of the vacuums and removal of the enclosure.

Containments are the preferred abatement method in areas where pipes are grouped tightly together or where construction of a negative-pressure enclosure is feasible and more cost-effective. In addition, in many states, the construction of negative-pressure containment areas is required by law for abatement of over a certain length of pipe.

• **Glovebagging**

Glovebag removal is a technique typically used for repair or small-scale abatement projects, although it is used in many large-scale abatement projects if the construction of an enclosure is not feasible and the regulations allow their use. This is typically true for pipes that are suspended from ceilings in large rooms or in wide open spaces within large buildings since, in these large areas, it is sometimes difficult to build a mini-containment area and it is impractical to draw a vacuum on the entire building or room. Gross removal by glovebags, if not prohibited by specific state or local regulations, is frequently done in industrial settings or other areas where there are pipes within large, open rooms.

• **Other Techniques**

Regulations allow several other methods for removing pipe insulation, but they are not nearly as common as the two techniques discussed above. These other methods include negative-pressure glovebags and glove boxes, and a water spray containment method. Both of these methods are used infrequently and are much slower than typical glovebag removal. Although these techniques are sometimes mandated by the DoE, we will be focussing on evaluating the cost-benefit of BOA versus the standard glovebagging method described above. If sizeable cost-benefit can be shown versus the easier and faster (and therefor cheaper) glovebagging technique, it follows that it will be cost-beneficial with respect to the other more time-consuming and costly techniques.

1.2.2 'Robotic' or Semi-Automated Abatement Systems

1.2.2.1 Current State of the Art

A thorough U.S. and international patent search addressing robotic or semi-automated pipe insulation abatement systems has been completed. Although there are many existing patents that cover the automated removal of coatings from the external surface of pipes, no patents were located that dealt with the removal of "thermal insulation" (herein defined as asbestos, calcium-silicate, fiberglass, or other insulating material that has a thickness greater than 1/4"). Many of the coating removal systems used water, sand, or other blast media to remove coating from pipe. Still others used mechanical means such as cutters and brushes to accomplish this task. These mechanisms are similar to those proposed for BOA, but they only apply to removal of coatings of a thickness less than or equal to 1/4". In summary, no applicable or conflicting systems were found in patents that may interfere with, or support, the development of a robotic pipe insulation abatement system as demonstrated in Phase I.

1.2.2.2 Competitive Commercial Products

Based on an extensive search of the asbestos abatement equipment manufacturer market, only two types of equipment were found that are offered as 'mechanical automation' alternatives for different types of abatement scenarios. Although not directly comparable to the BOA system, they are worth mentioning here. The first is a negative pressure containment box developed by Aerospace America, Inc. This product replaces the disposable glovebags with a reusable hard-shell emplaceable enclosure within which manual glovebag work is performed. It retails for about $500 (compared to $5 per glovebag for cold pipe only), and sales volume has been very encouraging (~ 2,000 units to date). The second unit is a VEC-Loader, built by VEC, Inc., and is used to vacuum asbestos from the inside of full-containment areas and bag it remotely. It is only really meant for cleanup, but could be a piece of technology that has an impact on the BOA system. It retails for about $90,000 and as many as 250 units have been sold over the last 5 years. Pictures of the two units are shown in Figure 1-1. In the field of automated pipe insulation removal systems, BOA defines the state-of-the-art to date. If desired, patent protection should be possible since no other patents dealing with the removal of pipe insulation (> 1/4" thick) have been found. A patent generally describing an automated mechanism that removes thermal insulation from pipes without human intervention is thus novel and of potential benefit to the commercial partner. Should the market-size and the commercialization warrant pursuing patent protection over other means (licensing, trade secret, copyrighting, etc.), a general patent should be obtainable.

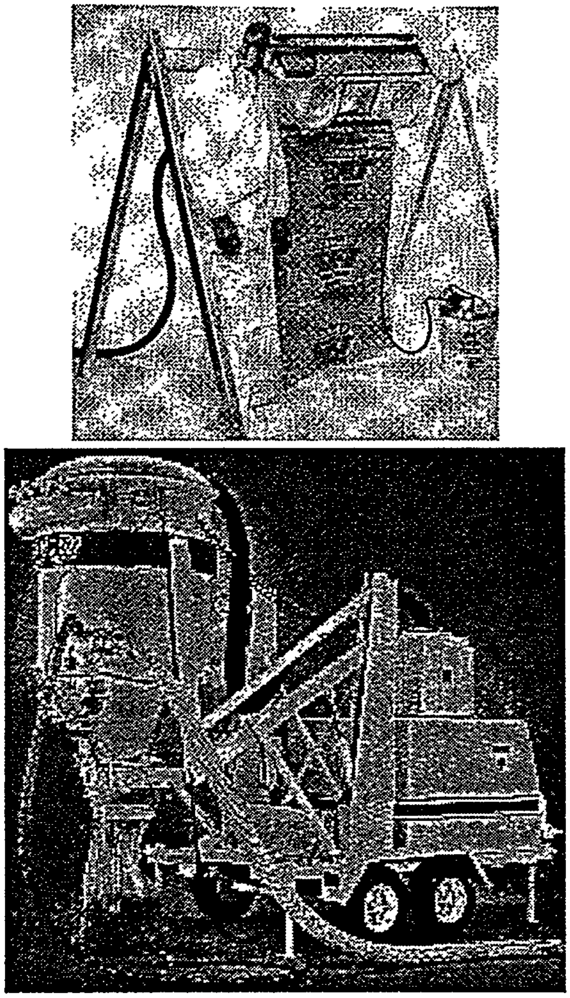


Figure 1-1 : Commercial asbestos abatement support equipment: glovebox and VEC-Loader

1.3 Risks and Opportunities

As with the development of any new product, there are certain risks and opportunities that affect its introduction into the market. A perceived opportunity is usually the reason why an idea is pursued in the first place, while risks are the obstacles in the development, use, or commercialization of a product that could negate its predicted benefit, and therefor hinder its success in the market. The following sections identify the main risks and opportunities involved in the development and possible commercialization of an automated asbestos pipe insulation abatement system.

1.3.1 Facility Characteristics that Affect Abatement Method and Applicability of BOA

Upon inspection of facilities that contain ACM-covered piping, it is obvious that a robotic/automated abatement system, regardless of complexity could not be cost-effective at removing insulation from all pipes. There is simply too much variation and too many obstructions for a single unit or sets of units to operate on every inch of piping. Characteristics of pipe networks that adversely affect automated removal include:

• **'Spaghetti',**

pipes that are densely spaced, overlapping, and look almost tangled because they are so tightly packed together. There is such minimal clearance around these pipes, that a system that travels along the exterior of the pipe would have to virtually fit within the annular region of the insulation itself. Annular clearances of less than 1-2 inches are common. 'Spaghetti' is mostly characteristic of small bore pipes (< 3" dia.), although it is characteristic of some larger pipes as well. Technical solutions applicable to these scenarios are too complex, costly and of doubtful potential to be pursued any further.

• **Frequent obstructions,**
such as other pipes or supports, bends, tees, valves, or flanges.

• **Small diameter pipes (< 3"),**
that may not reliably support the weight of BOA, especially in areas where there are long stretches between hangers/supports.

• **Extremely corroded pipes,**
which could collapse under the clamping force or weight of an automated system.

• **Pipes with extremely limited access,**
from the bottom, or pipes in remote locations that preclude access for installing BOA on the pipe.

Figure 1-2 contains a set of pictures showing (i) small bore 'spaghetti' piping, (ii) piping in the appropriate diameter range yet with frequent obstacles and minimal clearances, and (iii) high BOA-potential piping because of straight runs with infrequent obstacles.

Based on the above breakdown of characteristics that adversely affect automated abatement, we decided to focus on runs of pipe that could be cost-effectively manually abated using glovebags. That is to say, we are focussing on pipe runs that could be most economically abated using glovebags if no regulatory barriers existed hindering the use of this abatement method. Pipes that have the characteristics listed above, specifically 'spaghetti', are not typically 'fit' for glovebag removal. Because the pipes are so densely packed together, it is more efficient to construct a full- or mini-enclosure around the whole network of pipes in a given area, rather than try to glovebag each pipe run individually. Once an enclosure is built, manual abatement within this enclosure is very efficient. Unless BOA could be used to abate all of the pipes within a given area around which an enclosure would typically be constructed, and therefor negate the necessity for construction of the enclosure to begin with, there would be limited return on BOA's use in this environment.

The cost-benefit of an automated system is strongly based on the increase in removal rate of the robotic system versus manual removal, and the corresponding decrease in total labor. Automated removal, although faster than manual glovebag removal, is probably not much faster than manual removal within an enclosure. To obtain a conservative estimate we are assuming that, if the construction of a full-enclosure is the preferred method of removal, the use of a system such as BOA will not be cost-effective. The definition of applicable market size and cost-benefit analysis will thus focus on the amount of 'glovebaggable' runs of pipe.

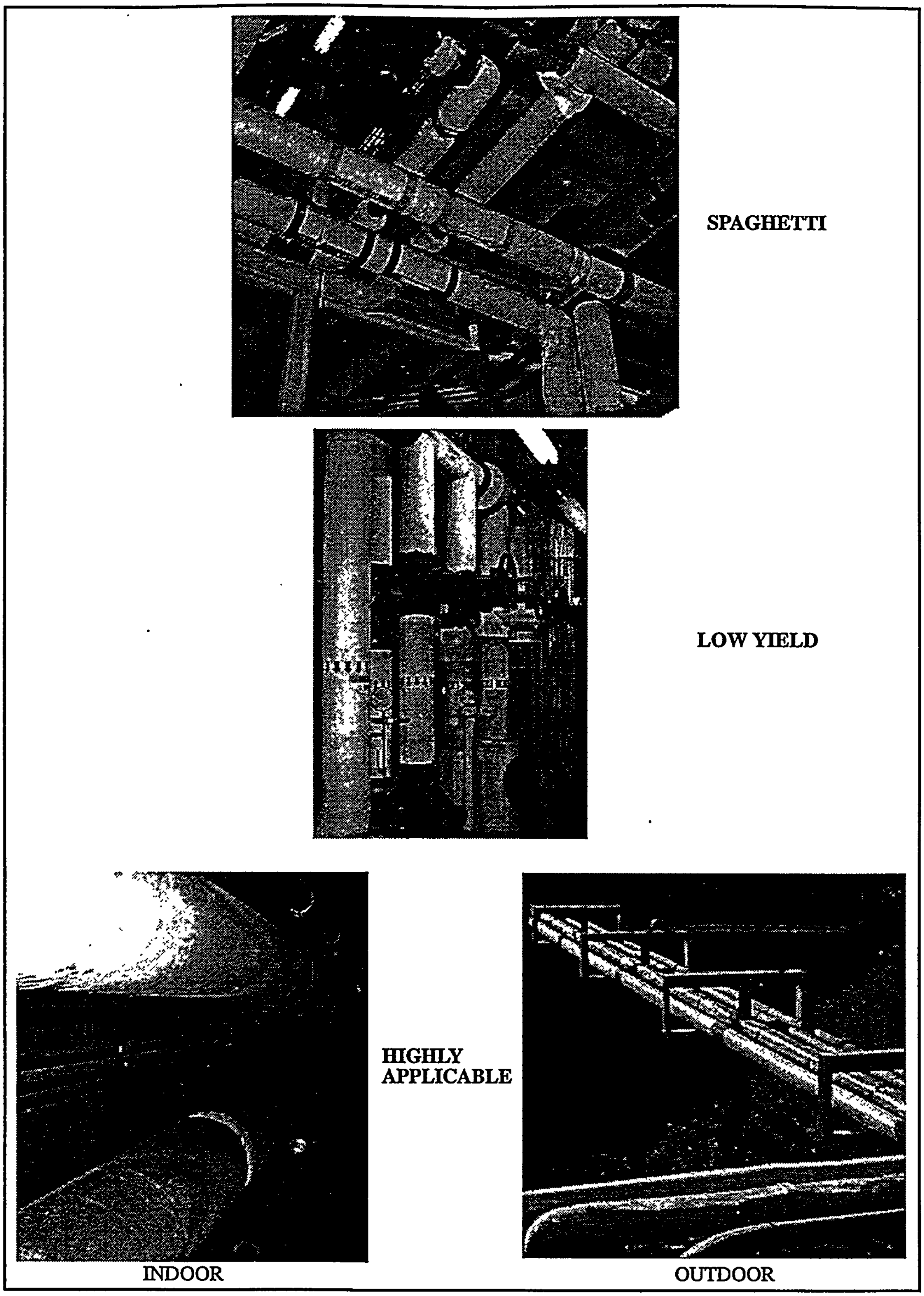


Figure 1-2 : Characteristic pipe runs which are inappropriate to BOA ('spaghetti'), in the proper size range yet too obstacle-ridden (low-yield), and ideal piping runs (highly applicable).

1.3.3 BOA Characteristics that Affect Applicability

The applicability of an automated pipe insulation mechanism is not only affected by the physical characteristics of the facilities in which the system is to be used, but also by the physical and performance characteristics of the system itself. The following is a list of the main system features or design consideration areas that are crucial in the development of a cost-effective and usable automated abatement system.

- **Physical Characteristics**

  - *Range of Pipe Diameter*
    Based on our survey of the DoE needs and a system feasibility analysis, we have determined that it is desirable to develop a system that can operate on pipes ranging from 4"-8" in nominal outside diameter (8"-12" insulation OD). We anticipate the development of a system comprising a single ground-based support system (vacuum, computer, power supply, etc.) coupled with multiple "removal heads" or "units" (currently estimated at three, i.e., 4", 6", and 8") that can each operate on pipes within a given range.

  - *Size/Clearance Needs*
    We anticipate that each "removal unit" will require an annular clearance of approximately 3"-6" around the pipe insulation it is designed to remove. For example, the 4" unit (that removes ~ 8" OD insulation) will have an overall outside diameter of approximately 14"-18", whereas the 8" unit (that removes ~ 12" OD insulation) will have an overall OD of approximately 18"- 24".

  - *Weight*
    Although exact weight estimates are not available, we anticipate that each BOA removal head will weigh more than the Recommended Weight Limit (RWL) for overhead lifting as defined by the Lifting Equation published by the National Institute for Occupational Safety & Health (NIOSH - 1991)[1]. It follows that an external mechanical lift will be required to install and remove BOA. If possible, each BOA removal head might also be split into several smaller assemblable sub-units, each within the manual weight limit.

  - *Removal Mechanisms/Media*
    A variety of cutting and removal mechanisms/media have been tested, and additional testing continues. We anticipate using a combination of cutting means to remove asbestos-containing lagging and insulation materials (ACLIM) from pipes. These may include (i) end-mill style mechanical cutters to cut aluminum and tar paper lagging as well as stainless steel wires and bands, combined with (ii) non-contact cutters and material removal means such as high pressure water jets.

    A concern regarding the use of high pressure water jets as a removal mechanism is its limited applicability on live steam lines. The use of cold water on live steam lines is a serious safety hazard due to the potential for cracking the pipe under thermal strain. We are currently evaluating alternative non-contact removal methods (such as CO_2 or hot water/steam blast) and whether or not there is enough abatement activity on live steam lines to justify a modification to the design of the system.

  - *Abatement Productivity*
    Preliminary testing of cutting and locomotion mechanisms has shown that a cutting rate of ~1 linear inch per second is reasonable through insulation lagged with aluminum sheathing and/or stainless steel bands and internally-buried wires. This translates to a predicted abatement productivity in the range of 20-60 linear feet of pipe per hour.

- **Operational Characteristics**

  - *Placement on and Removal from Pipe*
    As stated previously, we anticipate the BOA system will require additional mechanical assistance for placement on and removal from pipes. It is proposed at this time that this be accomplished with the use of a man-lift or pneumatic/hydraulic arm. Operational constraints regarding the

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1. Putz-Anderson, V. & Waters, T., Revisions in NIOSH guide to manual lifting, (1991)

access of this additional equipment to the pipes will be one of the drivers in the final design of this system.

- *Self-Starting*
An important operational characteristic of BOA is its ability to start on a run of pipe without the need for a section of pipe to be cleared manually. It is desirable for the unit to be able to 'self-start' on an insulated section of pipe. We have postulated that this may be possible if the unit is supported externally by some sort of mechanical lift. This would allow BOA to clear a section of pipe onto which it could attach itself, without having to hang or clamp onto an insulated pipe-section (possibly causing an uncontrolled fiber release). Since we predict there will be a need for mechanical assistance to lift BOA to the pipe, this external support means will already be present, and with slight modification/specialization, could be adapted to serve as BOA's self-starting support.

- *Hanger Abatement/Handling*
To ensure sufficient productivity, it is desirable for an automated system to have the ability to remove insulation from around a hanger. This poses several technical challenges since the necessary capabilities will vary according to what type of lagging and/or attachment method (wire, band clamps, etc.) is used to hold the insulation to the pipe. Even if there is no metal lagging on the outside of the insulation and no visible bands or wires (i.e., only painted plaster-tape (PPT) is visible), there is no assurance that there are not wires or bands under the PPT or imbedded in the insulation. It is therefor assumed in our cost-benefit analysis that there will be metal attachment means on all runs of pipe. Technical difficulties regarding removal of metal bands, wires, or lagging at hangers may cause a need for manual assistance at some hangers.

- *Obstacle Evading*
Another key operational factor is how BOA deals with obstacles that it cannot bypass without human assistance. Our surveys of several DoE facilities concluded that obstacles of this type (valves, flanges, elbows, tees, other non-hanger support means, etc.) occur typically every 20-50 feet. Our analysis shows that the time which humans must spend removing BOA from the pipe and placing it on the other side of the obstacle is an important factor and should be kept to a minimum. We are now predicting this time to be between 15 and 30 minutes.

- *Size and Weight of Support Equipment/Transport of Equipment to Actual Job Site*
Due to limited access to many of the pipe runs observed during site visits, it is a primary focus to make the system portable through doorways and ideally up stairwells.

- *Tether Size and Handling*
Tether size and its handling is typically a concern in congested areas such as abatement sites. We anticipate that BOA's tether(s) will include a power cable, water line(s), and vacuum hose(s). The diameter of the tether(s), will be minimized, and flexibility and abrasion-resistance will be optimized. Final tether size will depend on power and water flow requirements, vacuum ratings and waste conveyance method(s).

- *Waste Handling*
Currently, several methods of waste handling are being evaluated, including the "strip-and-bag method" (Phase I BOA design), as well as a process of dicing the insulation into small pieces and sucking them down a vacuum hose/disposal shoot. The amount of human assistance needed by BOA as it travels down a pipe should be minimized. This will reduce the amount of scaffolding needed and may significantly reduce the overall job cost.

1.3.4 Regulations

Asbestos abatement activities are governed by federal, state, and local regulations[1]. These regulations affect the method by which asbestos-containing materials (ACM) may be removed. The allowable manual abatement techniques, discussed in *1.2.1 Manual Abatement Techniques*, create limitations on the productivity of humans during asbestos removal. As discussed in *1.3.1 Facility Characteristics that Affect Abatement Method and Applicability of BOA*, BOA will typically be used on ACM-covered

1. "BOA: Asbestos Pipe-Insulation Removal System - Regulatory Analysis", 1995, METC Topical Report

pipes that could otherwise be abated using glovebags. The specific regulations that affect human abatement productivity using glovebags require the following steps:

- Glovebag Set-up
  - Put duct tape around pipe where glovebag will be attached.
  - Put all tools and materials inside glovebag.
  - Carefully attach and seal glovebag to pipe.
  - Attach a HEPA vacuum to glovebag.
  - Attach a low-pressure water sprayer to glovebag.
  - Smoke-test glovebag to test for leaks.
- Glovebag Removal
  - Wet asbestos with amended water.
  - Carefully cut and remove asbestos from pipe.
  - Brush off all asbestos stuck to pipe.
  - Rinse all asbestos off pipe and sides of bag.
  - Spray lock-down sealant to seal invisible fibers to pipe & bag.
  - Seal cut edge of insulation with encapsulant (paint).
- Glovebag Clean-up
  - Grab tools in hands and pull gloves inside out.
  - Evacuate air from bag with HEPA vacuum.
  - Twist gloves (with tools inside) and tape them shut. Cut gloves from bag.
  - Turn vacuum on again. Twist bottom of bag (containing removed asbestos) shut and put tape around the twist.
  - Put second waste bag under glovebag. With the vacuum on, carefully cut the glovebag off the pipe and lower into the waste bag.
  - Remove plastic-bag remainders from the pipe and place in the bag.
  - Use vacuum to evacuate air from waste bag.
  - Remove vacuum and water hoses and tape waste bag shut.
  - Fold over the top of the waste bag, and tape it down (gooseneck the bag).

Upon inspection of this list of requirements, it is obvious that manual glovebag removal is rather inefficient. In fact, not only is glovebagging a slow process, but regulations require that two people work on each glovebag and shower at the end of each shift or any time they leave the premises. Based on surveys of both DoE and general industry abatement contractors, a typical glovebag operation takes about 15-30 minutes (and sometimes up to 60 minutes) to complete and can be used to remove about 3 feet of pipe insulation (~3-6 feet/man-hour). Approximately 40% of this time is in set-up alone. A key element in the comparison between manual and robotic abatement is that the robotic system will act as a traveling containment area, minimizing set-up time at the pipe during operation. Unlike human abatement, there will be no slowdown for brushing removal of "baked-on" asbestos fibers since the automated system will clean the pipe to this level continuously.

The use of the glovebag abatement method for gross abatement of pipe insulation is prohibited in some states. In areas where the pipe insulation *could* be most cost-effectively abated using glovebags but must be abated under full-containment due to regulatory requirements, the cost savings of an automatic abatement system would be much greater than what we are estimating in this analysis. In many of these cases, approximately 40% of the total job cost (the typical percentage due to construction of the negative-pressure enclosure itself) could be saved by eliminating the need for the construction of a full- or mini-containment enclosure. This scenario is representative of open-area pipe abatement such as that on outdoor pipes or pipes centrally located in large buildings or warehouses. Again, the cost estimating strategy we are using is conservative.

1.3.5 Worker Safety and Litigation

Four types of diseases have been linked to breathing air contaminated with asbestos: asbestosis, pleural plaques, cancers, and mesothelioma. These diseases may result in a range of symptoms from mild discomfort to death. A study conducted at Mt. Sinai Hospital found that approximately 27.5 million people were exposed to asbestos between 1940-1980. Approximately 7.5 million of these individuals were involved in the building construction industry. The study found that the risk of contracting asbestos-related cancers varied widely by occupation type. The highest risk was found in the primary asbestos manufacturing workers and the insulation installation workers. Individuals in the building construction industry exposed to asbestos have a risk factor that is one fifth that of the primary manufacturing and insulation installation workers.[1]

It is estimated that between 125,000 and 250,000 asbestos-related personal liability lawsuits may be filed between 1992 and 2030. The associated damages and defense costs could potentially range between $38 and 60 billion.[2] Conservatively using the $38 billion litigation cost estimate over the 38 year time span (1992-2030), approximately $1 billion in lawsuits could be filed each year. It should be clarified that this study focused on the litigation costs for injuries acquired primarily during the manufacturing and installation of asbestos products. A category for injuries incurred during asbestos removal has not been separately studied. OSHA has recently imposed stricter regulations over the asbestos abatement industry; however, it is certain that some litigation will occur related to abatement-incurred injuries. Although no definitive costs can be determined at this time, an automated device could greatly reduce the worker liabilities and litigation costs. In addition, such technology may have a significant impact on the cost associated with various types of insurance covering asbestos workers, including medical, worker's compensation, short-term and long-term disability, and life insurance.

1.3.6 Quality of Work

A robotic system also has the potential to improve the quality of asbestos removal work when compared to manual abatement. In preparing for this study, we have become familiar with the asbestos abatement industry by taking an asbestos abatement supervisor training course, surveying abatement contractors, and interviewing asbestos abatement project managers at the main DoE sites across the country. From these resources, it has come to our attention that the asbestos abatement regulations are being 'bent' occasionally, and sometimes on a regular basis. This is not an issue in DoE facilities since there is usually strict supervision, but in the general asbestos abatement industry, abatement in strict accordance with the law is not typical. Since competition in the asbestos abatement industry has become so fierce, abatement contractors have felt the need to 'bend' the regulated work practices to stay competitive. Corners are frequently cut, resulting in a lower quality of asbestos abatement work. In addition, worker productivity typically drops significantly when there is any form of direct supervision. Productivity also drops at the end of the day due to fatigue. The end result is a decrease in the quality of work and an increase in overall job time, and therefore, overall job cost.

In contrast, with a robotic system, there is little need for supervision and the quality of work and regulatory compliance is consistent. An automated system that is designed to follow the regulations will work reliably at a constant rate. Along with cost savings from shorter job times, there is the security of knowing that the certified robotic system is consistently complying with the regulations. Such a capability will enhance the competitiveness of the abatement contractors using this automated abatement system.

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1. Nicholson, Selikoff, and Perkel, "Occupational Exposure to Asbestos: Population at Risk and Projected Mortality - 1980-2030", American Journal of Industrial Medicine, vol. 3, 1982, p. 259-311
2. Nejmeh, G.A., et al, "Charting the Asbestos Minefield," Shearson Lehman Brothers, Inc., Jan. 20, 1992

1.4 Target Markets

1.4.1 Overview of Market Segmentation

In the overall asbestos abatement market, we are targeting facilities with the following characteristics (i.e., where BOA is highly applicable):

- long, straight, obstruction-free runs of pipe
- large buildings which make full enclosure set-up difficult and very costly
- elevated pipe runs that would require the construction of scaffolding for manual abatement
- pipes that have clear access from below
- pipe diameters of 4"-8"

The sections that follow discuss whether facilities in the market segments previously identified possess these characteristics and are therefor target markets for the use of an automated pipe-insulation abatement system.

• Department of Energy

Having toured several DoE facilities (Fernald, Oak-Ridge's K25, and Hanford) and obtained information from other facilities, we have concluded that an automated abatement system will be applicable at these sites and that a significant savings in overall abatement costs could be realized within the DoE complex of nuclear facilities. Although each facility visited contains large amounts of ACM-covered pipe that could not realistically be removed with an automated system, there is a significant amount of pipes that possess the favorable characteristics listed above. This fact, in conjunction with the shear magnitude of the DoE's pipe asbestos problem, makes the DoE network of facilities a target market for an automated removal system such as BOA. A detailed analysis of this market segment will follow in *1.4.3 Detailed Market Assessment of the Industrial Segment.*

• Commercial Utilities

Given the prevalence of insulated piping in commercial power plants, the power/utility market warranted investigation. However, upon researching these facilities, it was found that a major portion of the plants (>50% of nuclear units) were built after the ban on asbestos and therefore asbestos removal is not relevant. In addition, since these plants tend to frequently inspect piping, much of the asbestos which may have been present in older plants has already been removed and replaced. The nature of piping in these facilities is also less amenable to BOA-style removal. Pipes tend to be densely packed and have many obstructions. For these reasons, commercial utilities have not been considered a primary target for the BOA system.

• Office/Commercial and Industrial

Similarly, the applicability of BOA to the industrial and office/commercial market segments was evaluated. As noted above, the robotic device is best suited to remove insulation from long, straight runs of pipe. Long, straight runs of pipe are more characteristic at industrial sites than in office and other commercial buildings. The office/commercial market therefore was not considered in any detail. The industrial market segment, however, is considered to be well-suited for abatement using a robotic or remote device like BOA.

In summary, the DoE and Industrial market segments show significant potential for BOA applicability and sales. To evaluate these market segments and to facilitate detailed market assessment and cost/ benefit analysis of BOA, we have quantified these markets according to their potential linear footage of existing asbestos that requires abatement. This is an important measure of market size. The driving benefit of BOA is that it can save labor costs. Since almost every job is different, the savings that BOA generates needs to be 'normalized' w.r.t. job size (i.e. pipe-length) so that is can be compared to manual methods.

In the sections to follow, we present our general approach to this market assessment, then detail our assessment of the total linear feet of asbestos abatement available in each of the target markets, refining these figures based on known restrictions which may limit the use of BOA.

1.4.2 Market Analysis Approach

This section outlines the general approach we used in the study of the two main market segments. A parallel approach was taken for analyzing the potential of a robotic system within both the Department of Energy's (DoE) nuclear facilities complex and the industrial market. This section presents how we determined for both industries: (i) overall market size in linear feet [LF], (ii) share of the market [LF] in which BOA is applicable, and (iii) typical $/LF saved. Indoor and outdoor piping will be evaluated separately, since the average costs per foot for manual abatement and the percentages of pipe on which BOA is applicable are significantly different in these two environments.

<u>Total Market Size [LF]</u>

• Department of Energy

The total number of linear feet of pipe within the main DoE nuclear facilities (Hanford, Oak Ridge, Savannah River, Rocky Flats, INEL, and Fernald) was determined by direct data analysis and estimated projections based on this analysis. For those sites from which we have specific data, determination of total market size is straightforward. For those sites we do not have specific data from, we used various scaling methods to produce rough estimates for total market size. We took the ratio of the average linear feet of pipe per square foot of building (based on data we have from other sites), and applied it to the total square footage of buildings containing asbestos at the non-inventoried sites. The use of this ratio as a scaling factor is not exact, but it should produce reasonable results. In addition, to confirm these projections, estimates are not available, estimates of overall cleanup costs for the various sites were used to scale the total linear footage estimates.

• Industrial

The total number of linear feet of pipe in the industrial market segment is not as directly obtainable as it is for the Department of Energy facilities. Within the time frame and monetary limits of this study, it has been infeasible to gather enough data to create statistically significant estimates of the total market size. Instead, we relied on information from surveys and an independent asbestos industry consultant[1]. The total linear feet of pipe within the industrial segment will be determined by the following general equation:

$$\begin{bmatrix}\text{Total}\\ \text{LF of pipe}\\ \text{within}\\ \text{Industrial Market}\\ \text{Segment}\\ \text{(LF/yr.)}\end{bmatrix} = \frac{\begin{bmatrix}\text{Total}\\ \text{Industrial Market}\\ \text{Segment Revenue}\\ \text{(\$/yr.)}\end{bmatrix}\begin{bmatrix}\text{Work on}\\ \text{Thermal}\\ \text{Insulation (TSI)}\\ \text{(\%)}\end{bmatrix}\begin{bmatrix}\text{\% of TSI}\\ \text{Work done on}\\ \text{Pipes}\\ \text{(\%)}\end{bmatrix}\begin{bmatrix}\text{\% of Revenue}\\ \text{attributed to}\\ \text{Direct Labor}\\ \text{(\%)}\end{bmatrix}\begin{bmatrix}\text{Avg. Productivity}\\ \text{of an}\\ \text{Asbestos Worker}\\ \text{(LF/hr.)}\end{bmatrix}}{\begin{bmatrix}\text{Avg. Labor Rate}\\ \text{for}\\ \text{Asbestos Worker}\\ \text{(\$/hr.)}\end{bmatrix}}$$

1. "Asbestos Abatement Contracting Industry Report", 1993, The Jennings Group, Inc., Columbia, NJ, Copyright 1993

BOA-Applicable Market Size [LF]

To determine the total footage of piping accessible to the BOA system within the two target market segments, we have used the following reduction factors to scale the estimated total market size:

- **Department of Energy**

  - *% of pipe within 4"-8" outside diameter range*
    Pipe-size data from several DoE sites, as well as projections for the remaining sites, will be used to scale down the total DoE market to account only for those pipes with a 4"- 8" outside diameter. The total linear feet of pipe within the DoE nuclear complex (as determined above) will be multiplied by an estimate of the percentage of pipes within this range of pipe sizes, which is approximately 40% of the pipes within most of the sites.

  - *% of pipe on which BOA is applicable*
    In addition, the BOA system will not be able to operate on all pipes within the 4"- 8" outside diameter pipe-size range (due to obstacles, valves, bends, junctions, etc.) Through site tours and surveys, the percentage of pipes within this range upon which BOA can be used (% applicable) will be estimated. This applicability percentage varies significantly from site to site and even from building to building. Estimates ranging from 25% to 75% are used. The total linear feet of pipe within the 4"- 8" OD range will be multiplied by this applicability percentage, therefore determining an estimate of the total BOA-applicable market size.

- **Industrial**

  - *% of abatement work done with glovebags*
    As will be discussed in more detail later in this document, BOA will compete with manual abatement in areas that could be cost-effectively done by glovebags (or with full-containment if regulatory restrictions exist.) To determine the percentage of abatement work done by glovebagging, we surveyed asbestos abatement contractors in the general industrial market and obtained an estimate of 22% of all abatement work.

  - *% of 'glovebaggable' pipe on which BOA is applicable*
    For estimating purposes, we have assumed that BOA can be used on a percentage (40% to 60%) of "glovebaggable" pipes and will scale the results accordingly. This estimate is conservative because it accounts for all work on small bore pipes (approximately 30-40% of all pipes) and the percentage of "clear" pipe runs that is taken up by hangers and obstacles (estimated at 10-20%). The intent is not to come up with a single estimate of the total BOA-applicable market size, but rather to determine a reasonable range of values.

The equation used to determine the amount piping that a BOA system could abate within each market segment is:

$$\begin{bmatrix}\text{Total}\\ \text{LF of pipe}\\ \text{within Market Segment}\\ \text{Abateable by a}\\ \text{BOA-like robot}\\ \text{(LF)}\end{bmatrix} = \begin{bmatrix}\text{Total}\\ \text{Market Segment}\\ \text{Piping}\\ \text{(LF)}\end{bmatrix}\begin{bmatrix}\text{\% Piping}\\ \text{within 4 to 8}\\ \text{inch Diameter}\\ \text{(\%)}\end{bmatrix}\begin{bmatrix}\text{\% Piping}\\ \text{applicable to}\\ \text{BOA-like system}\\ \text{(\%)}\end{bmatrix}$$

Typical Savings [$/LF]

A detailed cost-benefit spreadsheet was developed that incorporates the factors affecting the cost of both manual and robot-assisted abatement projects. This analysis estimated the savings per linear foot of pipe [$/LF] for indoor and outdoor piping in the two main market segments (DoE and Industrial.) The $/LF savings estimates are conservatively based on comparisons with the glovebag removal method. As mentioned previously, the use of glovebagging for gross abatement is prohibited in some states. In these cases, the true cost savings of an automated abatement system will be even greater due to the increased costs associated with the construction of a full- or mini-containment area.

Oak Ridge

The K25 site within the Oak Ridge complex had most of the amenable characteristics for a BOA system including: (i) long, straight, obstruction-free runs of pipe, (ii) large buildings which make full enclosure set-up difficult or impossible, (iii) elevated pipe runs that would require the construction of scaffolding for manual abatement, (iv) good access to pipe runs from below, and (v) a significant percentage of pipe with diameters of 4" or greater.

Another key feature of the K25 site was the repeatability of the physical layout of the buildings and the pipe networks. When we toured the facility and located a given run of pipe that was a candidate for automated abatement, the extent of this type of run was not limited to that specific area, but rather, was characteristic of multiple areas. For example, pipe runs within a given process cell could be characteristic of up to 63 other cells (54 in Bldg. K25 and 9 in Bldg. K27). In addition, detailed surveys were available that had been completed by an independent contractor[1] and completely described (and quantified) the asbestos problem at the K25 site. Job-cost information for prior asbestos abatement projects was also available. Although we did not tour all other sites within the Oak Ridge complex, Y-12 (Portsmouth and Paducah) can be accurately characterized as multiples of what was contained in several of the buildings at the K25 site.

- *Indoor*

Linear footage and pipe-size totals for buildings K27 and K33 were taken directly from the asbestos surveys prepared by Radian Corporation. Totals for the other buildings at the K25, Portsmouth, and Paducah sites were estimated using multiplication factors based on the type of process and number of process cells in each building or site. The total linear footage of ACM-covered pipe per building/site is shown in Table 1.6:.

Table 1.6: Oak Ridge K25 and Y-12 total linear footage of piping

BLDG. # / SITE NAME	MULTIPLIER	TOTAL [LF]	% OF PIPE AT OAK RIDGE
K27	n/a (direct from data)	12,045	6.5%
K25	= K27 x 6	72,270	39.2%
K31	n/a (direct from data)	8,720	4.7%
K29	= K33 x 3/8	4,360	2.4%
K33	= K31 x 4/3	11,630	6.3%
Portsmouth	= K33 x 3	34,881	18.9%
Paducah	= (K33+K31) x 2	40,694	22.0%
TOTAL		**184,600**	**100%**

The percentage of pipes within the 4"- 8" pipe OD range and the BOA-applicability percentage within this range is summarized in Table 1.7:. The values for the total length of pipe within the given range are taken directly from data in the Radian survey for buildings K27 and K31, and are

1. Radian Corporation

scaled appropriately to the other buildings and sites as was done for the linear footage totals in Table 1.6:. The applicability percentages for K27 and K31 were estimated from site visits and the results were then applied to the other buildings as appropriate.

Table 1.7: Oak-Ridge K25 and Y-12 site piping in 4" to 8" diameter and percentage applicable to BOA

BLDG. # / SITE NAME	TOTAL (ALL INDOOR PIPE) [LF]	TOTAL W/IN 4"-8" RANGE [LF]	% W/IN 4"-8" RANGE	% BOA APPLICABLE (W/IN RANGE)	TOTAL APPLICABLE TO BOA [LF]
K27	12,045	3,800	31.5%	50-75%	1,900-2,850
K25	72,270	22,800	““	““	11,400-17,100
K31	8,720	928	9.4%	25-35%	230-330
K29	4,360	464	““	““	120-160
K33	11,630	1,237	““	““	310-430
Portsmouth	34,881	3,711	““	““	930-1,300
Paducah	40,694	4,330	““	““	1,080-1,520
TOTALS	**184,600**	**37,270**	**~ 20%**	**~ 45%**	**~ 17,000**

- ***Outdoor***

Unfortunately, no survey has been done for the outdoor piping at the K25 site. Based on our site visit, discussions with site and contractor personnel, and estimates from scaling information from site maps, a rough estimate was made that there is approximately 20,000 to 40,000 linear feet of pipe outdoors at the Oak Ridge site (K25 and Y12). Approximately 50% of the outdoor pipe seen at K25 was between 4" and 8" in diameter. We assumed this to be characteristic of the Y12 site and applied the same percentage to the total pipe linear footage estimate for the site. Also, within this 4"- 8" OD range, the percentage of pipes on which the BOA system could be used was high. We estimate the %Applicability to be 75% and applied this to the total as well. The estimated total linear footage of outdoor pipe at Oak Ridge upon which BOA is applicable, is hence:

$$\begin{bmatrix}\text{Total}\\ \text{Outdoor [LF]}\\ \text{at Oak Ridge on}\\ \text{which BOA can be used}\end{bmatrix} = \begin{bmatrix}\text{Total Outdoor}\\ [LF]\\ \text{Pipe}_{OakRidge}\\ \text{(20,000 to 40,000LF)}\end{bmatrix}\begin{bmatrix}\text{Outdoor}\\ \text{\%Range}_{OakRidge}\\ \text{(50\%)}\end{bmatrix}\begin{bmatrix}\text{Outdoor \%Appl}_{OakRidge}\\ \text{(75\%)}\end{bmatrix} = \text{7,500 to 15,000 [LF]}$$

Fernald

There is an estimated 120,000 linear feet of ACM-covered piping (indoor and outdoor) at Fernald. As with the K25 site, Fernald provided us with actual inventory data[1] on the indoor piping from which we were able to extract the appropriate information.

- ***Indoor***

The total linear footage of indoor ACM-covered pipe within the 4"- 8" OD range was taken directly from the DEI survey. The percentage applicable to BOA (% Appl) was estimated by breaking the site down into three building types (Process, General/Maintenance, and

1. DEI Survey

Administrative), estimating a % Appl within each building type, and scaling these applicabilities by the perçentage of pipe at Fernald that are within each type of building. The results are as follows:

Table 1.8: Fernald piping breakdowns

BUILDING TYPE	TOTAL PIPE (LF)	TOTAL W/IN 4"-8" RANGE (LF)	% OF 4"-8" PIPE W/IN BLDG. TYPE	%APPL. (W/IN BLDG. TYPE)	WEIGHTED %APPL	TOTAL FOOTAGE APPLICABLE TO BOA [LF]
Process (Bldgs 1,2a-d, 3a-d, 5,6,8a,9,37,54,55)	28,729	5,405	59%	30%	18%	1,621
General/Maintenance (Bldgs 8b,10a,11,12a-b, 13a-b,20a-g, 24b, 25a,31,32,38,66,69,71)	16,556	3,121	34%	50%	17%	1,561
Administrative (Bldgs 14,15,28a-b,45)	3,409	598	7%	75%	5%	448
TOTALS	**48,694**	**9,124**	**100%**	**N/A**	**40%**	**3,650**

The total building square footage containing ACM-covered pipes at Fernald is approximately 1,043, 100 sq.ft. Dividing the total applicable linear footage at Fernald by this square footage translates to 0.0035 LF/sq. ft. This number was used to estimate the linear footage of piping in other DoE sites for which we have no data.

- *Outdoor*

Unfortunately, a detailed survey of the amount of ACM-covered outdoor pipe does not exist for Fernald, although we were able to obtain an estimate by subtracting what we know is indoor (~50,000 LF) from the total site estimate of 120,000 LF. From this, we estimate that there is approximately 70,000 linear feet of ACM-covered outdoor pipe at Fernald, of which about 50-75% is within the 4"-8" pipe diameter range. BOAs applicability on these pipes is estimated at 50% since most runs are fairly obstacle-free. The estimated total footage of outdoor pipe at Fernald upon which BOA is applicable, is hence:

$$\begin{bmatrix} \text{Total} \\ \text{Outdoor [LF]} \\ \text{at Fernald on} \\ \text{which BOA can be used} \end{bmatrix} = \begin{bmatrix} \text{Total Outdoor} \\ [LF] \\ \text{Pipe}_{Fernald} \\ \text{(70,000 LF)} \end{bmatrix} \begin{bmatrix} \text{Outdoor} \\ \text{\%Range}_{Fernald} \\ \text{(50-75\%)} \end{bmatrix} \begin{bmatrix} \text{Outdoor \%Appl}_{Fernald} \\ \text{(50\%)} \end{bmatrix} = \text{17,500 to 26,250 [LF]}$$

Hanford

- Indoor

Estimates provided by the Hanford DoE site[1] indicate that there is approximately 402,350 linear feet of ACM-covered pipe, of which approximately 75% is indoors. A reported 40% of indoor pipe is between 4"and 8" in diameter. If we conservatively estimate that BOA will be applicable on 25%-35% (estimated from site visit) of these pipes, the total footage of indoor pipe at Hanford suitable for use with the BOA system is:

$$\begin{bmatrix}\text{Total}\\ \text{Indoor }[LF]\\ \text{at Hanford on}\\ \text{which BOA can be used}\end{bmatrix} = \begin{bmatrix}\text{Total Indoor}\\ [LF]\\ \text{Pipe}_{Hanford}\\ (300{,}000\text{ LF})\end{bmatrix}\begin{bmatrix}\text{Indoor}\\ \%\text{Range}_{Hanford}\\ (40\%)\end{bmatrix}\begin{bmatrix}\text{Indoor}\\ \%\text{Appl}_{Hanford}\\ (25\%\text{ to }35\%)\end{bmatrix} = 30{,}000 \text{ to } 42{,}000\ [\text{LF}]$$

The estimated piping totals for Hanford were taken from 142 buildings, totalling 3,403,456 square feet. Dividing the total applicable linear footage at Hanford (~36,000 LF) by this square footage translates to 0.0106 LF/sq. ft. This number, along with the equivalent for Fernald, were used to estimate the linear footage of piping in other DoE sites for which we have no data.

- Outdoor

A similar technique was used for estimating the total footage of outdoor pipe at Hanford upon which BOA is applicable. Outdoor pipe comprises approximately 25% of the total amount of ACM-covered pipe at Hanford, which translates to about 100,000 lf. An estimated 50% of outdoor pipe is between 4"and 8" in diameter, and due to the relatively obstacle-free nature of these pipelines (hangers/obstacles approximately every 30 feet), BOA's applicability on outdoor runs within this size range is estimated at 75%. The estimated total footage of outdoor pipe at Hanford upon which BOA is applicable is therefore:

$$\begin{bmatrix}\text{Total}\\ \text{Outdoor [LF]}\\ \text{at Hanford on}\\ \text{which BOA can be used}\end{bmatrix} = \begin{bmatrix}\text{Total Outdoor}\\ [LF]\\ \text{Pipe}_{Hanford}\\ (100{,}000\text{ LF})\end{bmatrix}\begin{bmatrix}\text{Outdoor}\\ \%\text{Range}_{Hanford}\\ (50\%)\end{bmatrix}\begin{bmatrix}\text{Outdoor}\\ \%\text{Appl}_{Hanford}\\ (75\%)\end{bmatrix} = 37{,}500\ [\text{LF}]$$

Savannah River

- Indoor

Estimates provided by the Savannah River DoE site[2] were broken down by building type and characteristic length of pipe within each type of building (See Table 1.9: below). These estimates translate to a total of approximately 562,600 linear feet of ACM-covered pipe located within these buildings.

1. Hanford Report to CMU
2. Savannah River Report to CMU

Table 1.9: Savannah River piping breakdown

BUILDING TYPE	NUMBER OF SIMILAR BLGDS	AVG. LENGTH OF PIPE PER BLDG (LF)	TOTAL PIPE PER BLDG TYPE (LF)
Process	22	10,000	220,000
Auxiliary Facilities	60	1,500	90,000
Powerhouse/Tank Farm	3	75,000	225,000
Administrative	23	1,200	27,600
TOTALS	**108**	**n/a**	**562,600**

An estimated 35% of this pipe is between 4"and 8" in diameter. We conservatively estimated that BOA will be applicable on 25%-35% of these pipes (similar to the estimate for Hanford), and the total footage of indoor pipe at Savannah River upon which BOA is applicable is:

$$\begin{bmatrix}\text{Total}\\ \text{Indoor } [LF]\\ \text{at Savannah River on}\\ \text{which BOA can be used}\end{bmatrix} = \begin{bmatrix}\text{Total Indoor}\\ [LF]\\ \text{Pipe}_{SavRiver}\\ (562{,}000\text{ LF})\end{bmatrix}\begin{bmatrix}\text{Indoor}\\ \%\text{Range}_{SavRiver}\\ (35\%)\end{bmatrix}\begin{bmatrix}\text{Indoor}\\ \text{Weighted }\%\text{Appl}_{SavRiver}\\ (25\%\text{ to }35\%)\end{bmatrix} = 50{,}000\text{ to }70{,}000\ [\text{LF}]$$

- ***Outdoor***

According to estimates provided by Savannah River, they have six "process areas" that each contain about 3,220 lf of 4"-8" pipe, and one "admin area" with approximately 6,000 lf in this pipe size range, totalling about 25,000 lf. We estimate that BOAs applicability within this size range will be at least 75%, and therefor, the estimated total footage of outdoor pipe at Savannah River upon which BOA is applicable is therefore:

$$\begin{bmatrix}\text{Total}\\ \text{Outdoor [LF]}\\ \text{at Savannah River on}\\ \text{which BOA can be used}\end{bmatrix} = \begin{bmatrix}\text{Total Outdoor}\\ \text{Pipe}_{SavRiver}\\ \text{w/in 4-8 Range}\\ (25{,}000\text{ LF})\end{bmatrix}\begin{bmatrix}\text{Outdoor}\\ \%\text{Appl}_{Hanford}\\ (75\%)\end{bmatrix} = 19{,}000\ [\text{LF}]$$

<u>INEL</u>

- ***Indoor***

We were unable to acquire specific data on the total linear footage or pipe-size breakdowns for the INEL site. We acquired a summary of an asbestos survey for the Chemical Processing Plant (CPP) from the industrial hygiene contractor[1] that performed the survey. Although this information was somewhat useful, it contained only total length data, with no reference to pipe size. We were therefore forced to make projections for pipe size and total linear footage for the rest of the site based on the information we had for the CPP and other DoE facilities.

To estimate the total amount of pipe within the rest of the INEL complex (on which we have no specific data or estimates), we computed the average linear footage of pipe per building square

1. Pickering, Inc.

footage within the CPP and applied this to the total building square footages of the rest of the site. Based on this analysis, we estimate that there is approximately 189,000 linear feet of pipe within INEL.

The results from Fernald and Hanford produced weighted averages for the percentages of pipes within the 4"-8" OD range as well as BOA's applicability. This was done by taking these two percentage results from the two sites and scaling them according to the relative amount of pipe each site contains:

$$\begin{bmatrix}\text{Weighted}\\ \%\text{Range}_{DoEavg}\end{bmatrix} = \sum_{CPP}^{n}\begin{bmatrix}\text{Weighted}\\ \%\text{Range}_{Site}\end{bmatrix}\begin{bmatrix}\dfrac{\text{Total Pipe}_{Site}}{\text{Total Pipe}_{Fernald+Hanford}}\end{bmatrix} = \sim 37\%$$

$$\begin{bmatrix}\text{Weighted}\\ \%\text{Appl}_{DoEavg}\end{bmatrix} = \sum_{CPP}^{n}\begin{bmatrix}\text{Weighted}\\ \%\text{Appl}_{Site}\end{bmatrix}\begin{bmatrix}\dfrac{\text{Total Pipe}_{Site}}{\text{Total Pipe}_{Fernald+Hanford}}\end{bmatrix} = \sim 31\%$$

By multiplying the estimated total linear footage of pipe within INEL (189,000 lf) by these weighted percentages, we predict that the total number of linear feet BOA will be applicable on at this site is approximately 21,680 lf.

- Outdoor

We were unable to acquire data or estimates for outdoor piping at INEL. We used the estimates provided by Hanford as a scaling factor to determine an estimate for outdoor piping totals based on the indoor estimate calculated above. This analysis is presented below:

$$\begin{bmatrix}\text{Total}\\ \text{Outdoor [LF]}\\ \text{at INEL on}\\ \text{which BOA can be used}\end{bmatrix} = \frac{\begin{bmatrix}\text{Total}\\ \text{Outdoor [LF]}\\ \text{at Hanford on}\\ \text{which BOA can be used}\\ \text{(37,500 LF)}\end{bmatrix}}{\begin{bmatrix}\text{Total}\\ \text{Indoor [LF]}\\ \text{at Hanford on}\\ \text{which BOA can be used}\\ \text{(36,000 LF)}\end{bmatrix}} \times \begin{bmatrix}\text{Total}\\ \text{Indoor [LF]}\\ \text{at INEL on}\\ \text{which BOA can be used}\\ \text{(21,680 LF)}\end{bmatrix} = 22{,}580\ \text{[LF]}$$

<u>Rocky Flats</u>

Very little information was available for the Rocky Flats site. Rough estimates were made based on the total square footage estimates for buildings within this site that are known to contain asbestos.

- Indoor

To estimate the total amount of indoor pipe within Rocky Flats upon which BOA will be applicable, we multiplied the total building square footage estimates we were given for the site (2,500,000 sq. ft.) by the weighted LF/sq.ft. ratio computed for Hanford and Fernald (.0089 LF/sq.ft.). The resulting estimate for amount of applicable pipe at Rock Flats is 22,290 LF.

- Outdoor

For outdoor piping, we scaled this indoor estimate by the ratio of applicable outdoor to applicable indoor piping at Hanford (37,500/36,000 = 1.04), giving an estimate of 23,220 LF.

Summary of DoE Market

Table 1.10: Summary of piping totals within six main DoE sites

SITE NAME	TOTAL INDOOR PIPE [LF]	TOTAL PIPE INDOOR APPLICABLE TO PIPE [LF]	TOTAL OUTDOOR PIPE [LF]	TOTAL PIPE OUTDOOR APPLICABLE TO BOA [LF]
Oak Ridge	184,600[c]	17,000[b]	30,000[c]	11,250[b]
Fernald	48,694[a]	3,650[b]	70,000[c]	6,250[b]
Hanford	300,000[c]	36,000[b]	100,000[c]	37,500[b]
Savannah River	562,000[c]	60,000[b]	110,000[c]	19,000[b]
INEL	189,000[d]	21,650[b]	60,000[d]	22,580[d]
Rocky Flats	186,000[d]	22,290[d]	60,000[d]	23,220[d]
SUBTOTALS	**~1,470,300**	**~160,600**	**~430,000**	**~119,800**
TOTAL	**~302,650**			

a. From data
b. Estimated from study results and site visits
c. Estimated by site
d. Estimated by scaling site or other site data

1.4.3 Detailed Market Assessment of the Industrial Segment

Obtaining data from a statistically-significant number of industrial sites to determine the available footage of asbestos pipe insulation was not possible due to our resource and time constraints. Therefore, other methods were utilized to determine the size of the industrial market. First, using data from an independent asbestos industry consultant[1], the total annual revenue value of the market was determined. The total annual linear feet was derived from this revenue number by factoring in data (labor rates, productivity rates, etc.) obtained from a survey conducted of 20 asbestos abatement contracting companies (see *Industrial Contractors Survey Forms & Results* for the survey and responses). This method is described in detail below. We view this approach to be reasonable and well-justified, and have used it to yield a conservative estimate of the annual market size.

$$\begin{bmatrix}\text{BOA-Applicable}\\ \text{Industrial}\\ \text{Market}\\ \text{[LF/YR]}\end{bmatrix} = \frac{\begin{bmatrix}\text{Total}\\ \text{Industrial}\\ \text{Abatement}\\ \text{Market}\\ \text{[\$/YR]}\end{bmatrix}\begin{bmatrix}\text{\% of}\\ \text{Revenue}\\ \text{Due to Labor}\\ \text{[\%]}\end{bmatrix}\begin{bmatrix}\text{\% of Work on}\\ \text{Thermal}\\ \text{Insulation (TSI)}\\ \text{[\%]}\end{bmatrix}\begin{bmatrix}\text{\% of TSI}\\ \text{Work on}\\ \text{Pipes}\\ \text{[\%]}\end{bmatrix}\begin{bmatrix}\text{\% of Work}\\ \text{Done Using}\\ \text{Glovebags}\\ \text{[\%]}\end{bmatrix}\begin{bmatrix}\text{\% of Glovebag}\\ \text{Work Appl.}\\ \text{to BOA}\\ \text{[\%]}\end{bmatrix}\begin{bmatrix}\text{Avg. Human}\\ \text{Abatement}\\ \text{Rate}\\ \text{[LF/HR]}\end{bmatrix}}{\begin{bmatrix}\text{Avg. Asbestos Worker}\\ \text{Labor Rate}\\ \text{[\$/HR]}\end{bmatrix}}$$

1. The Jennings Group, Inc., Asbestos Abatement Contracting Industry 1993, May 1993

1.4.3.1 Justification

The two pertinent classifications of the asbestos abatement market are the Industrial market segment and the thermal system insulation (TSI) removal business. According to The Jennings Group's report, the remaining market potential for removal and O&M contracting services is estimated at $70 billion over the 25 year predicted life of the industry. This translates to an average of $2.8 billion per year, of which 25%, or $700 million, is within the Industrial market segment. Since the robotic device is to be used for removing pipe insulation, only the thermal insulation work is relevant. Thermal insulation removal accounts for 31% of all asbestos removed. Therefore, the first step in defining the size of the market applicable to BOA is to take 31% of the $700 million which produces a target market size of $217 million (see summary calculation in Table 1.11:).

1.4.3.2 Industrial Market Size

The next step determining how many feet are available in a year is to determine how much labor is involved in generating this $217 million in revenues. According to The Jennings Group's report, on average labor accounts for 37% of each revenue dollar.[1] The labor portion of the revenue is therefore $80,290,000. The average labor rate as determined by our survey was $14.74/hour. When the annual labor revenue of $80,290,000 is divided by this $14.74/hour, the hours of labor spent removing insulation in a year is 5,447,080 hours.

The next step is to multiply the number of hours by the average productivity rate (average number of feet removed/hour) to arrive at the total feet of thermal insulation available to be removed in a year. The average productivity as determined from our survey results was 7.18 feet/hour. The total number of feet of thermal insulation available for removal is therefore 39,110,050. According to Jennings, approximately 85% of all thermal insulation was used on pipes. The other 15% is used on boilers and around ducts. Subtracting this 15% from the thermal insulation footage leaves the available pipe insulation at over 33.2 million linear feet (33,243,550).

Even though we are targeting BOA to compete with full-containment and glovebagging, in the industrial market, its initial competition will be glovebagging. We are not ruling out the use of BOA in full-containment situations, but feel that competition with full-containment will become a reality over time, hence increasing the potential market size.

As found in the survey results, glovebagging accounts for approximately 22% of all asbestos removal work. Applying this 22% to the 33.2 million feet of pipe insulation means that over 7.3 million feet (7,313,580) are available for removal each year.

The last step is determining the percentage of glovebagging work that the BOA system is capable of removing. We have estimated that, similar to the DoE, approximately 40% of the pipes within industrial sites are in the 4"-8" diameter range. Accounting for this, and conservatively assuming that the unit can remove 50% of the insulation typically abated by glovebagging within this range of pipes, we predict that approximately **1.5 million (1,462,716) linear feet per year** could be removed through the automated method.

The total number of linear feet of pipe within the Industrial market over the 25 year life of the asbestos abatement industry is therefore **over 36.5 million (36,567,900) linear feet.**

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1. The Jennings Group, Inc., Asbestos Abatement Contracting Industry 1993, May 1993, p. 2

Table 1.11: Calculation of BOA-Applicable Footage from Annual Industrial Market Segment Revenue

ANNUAL INDUSTRIAL ABATEMENT MARKET [$/YR]		**$700,000,000[a]**
% of Thermal System Insulation (TSI)	31%	
Total Thermal Insulation Market		**$217,000,000**
Labor as % of Revenue	37%	
Total Thermal Labor		**$80,290,000**
Labor Rate/Hour [$/HR]	$14.74	
Hours of Labor		**5,447,080**
Avg. Ft./Hour [LF/HR]	7.18	
Total Raw Pipe Feet [LF]		**39,110,050**
% of TSI on Pipes	85%	
Total Adjusted Pipe Feet [LF]		**33,243,550**
% of Work done by Glovebagging	22%	-
Total Glovebagging Feet [LF]		**7,313,580**
% of Pipes within 4"-8" dia. Range	40%	
Total 4"-8" Dia. Glovebagging Feet [LF]		**2,925,430**
% of 4"-8" Glovebaggable Pipe Applicable to BOA	50%	
BOA-APPLICABLE FOOTAGE WITHIN INDUSTRIAL MARKET SEGMENT [LF/YR]		**~ 1.5 MILLION**

a. Yearly average over life of industry, from The Jennings Group, Inc., Asbestos Abatement Contracting Industry 1993, May 1993, p. 2

1.5 Summary and Conclusions

This market assessment focused on medium bore pipes (4"- 8" OD) due to (i) the variety of limitations that exist on the use of an automated pipe-insulation abatement system on small bore pipe (< 4" OD), and (ii), the evaluation of the most common pipe sizes within the DoE nuclear facilities that are greater than 4" OD. It was determined from evaluation of site data and estimation through site visits of the applicability of an automated abatement system on 4" - 8" OD pipe, that the BOA system will be applicable on approximately 300,000 lf of the 1,470,000 lf (or ~ 20%) of pipe within all six main DoE nuclear facilities.

In addition, the industrial market segment was also analyzed and quantified. Using survey results and data from an independent asbestos industry consultant and accounting for similar limitations on pipe size and applicability of the BOA system, it was estimated that there is approximately 1.5 million lf/ yr. available for robotic abatement over a 25 year market life.

These estimates of total applicable linear footage within both the Department of Energy and industrial market will be used to determine (i) the overall predicted cost savings, and (ii) the total commercial sales potential for BOA systems.

2.0 Cost-Benefit Analysis

The cost-benefit analysis in this section quantifies the costs and associated savings for robotic abatement of asbestos pipe-insulation in the DoE, and industrial market segments. It answers the question of what are the cost-savings associated with use of a robotic abatement system, what variables does one need to describe and compare this approach to the manual method, and from what variables and over what ranges can we expect substantial cost savings. These results were also used to establish critical performance requirements and guide the re-design effort.

This section provides background information to justify the premises and assumptions underlying the analysis. In addition we detail a comparative cost/benefit model that computes the relative savings realized by a robotic abatement system over a fully manual approach, as expressed in dollars saved per linear foot of pipe. We have proceeded conservatively by considering only potential savings during the removal portion of the whole abatement job. The structure of the model allows for parameter variations based on different market segments, facility characteristics, robot system performance and abatement scenarios, which are addressed in a general sensitivity analysis. The details of the model and an example calculation are given to illustrate the use of the spreadsheet, and are contained in *Appendix A - Cost-Benefit Model.*

The cost-benefit analysis shows that a robotic abatement system is cost-effective, with different 'benefit-margins' depending on whether we are in an industrial or government setting, and whether we are indoors or outdoors. The savings, as expressed in dollars-per-foot, are mainly due to the more rapid removal rate of a machine and the resulting savings in total removal labor costs. An additional source of potential savings in full-containment cases will be a substantial portion of the enclosure setup costs. The model predicts a minimum savings on the order of $26 / $5 per linear foot for DoE/Industrial for glovebag abatement, and $39 / $5 per linear foot for DoE/Industrial full-containment abatement scenarios. Overall job-cost savings seem to lie in the range of 25% / 20% for DoE/Industrial glovebagging respectively and 45% / 30% for DoE/Industrial full-containment respectively.

2.1 Cost-Benefit Model Explanation

The focus of the model is on analyzing the relevant portions of a complete abatement job which a robotic removal system might affect, detailing the steps where cost savings will be realized, and then developing a common denominator to allow extrapolation as to the overall potential savings that could be realized.

Since we wanted to account for several important factors that determine the removal costs in the abatement industry, we decided to bring all costs and savings down to a common denominator, namely the cost per linear foot of pipe insulation to be or being abated. This approach allows one to easily compute capital cost recovery using standard utilization models, compute manual abatement costs on a per linear foot basis, and then allows extrapolation of overall savings for various sites and market segments using a few case-studies.

We have completed a detailed analysis of the human abatement and proposed robotic abatement scenarios as detailed below. This illustrates which portions of a current manual abatement process we could affect, what portions of the actual removal can be automated, what the costing categories are, how they can be priced (manually and robotically), what comparison metric(s) should be used and the sensitivity of the model result to variations in key parameters.

2.1.1 Robotic vs. Human Abatement - Areas for potential savings

An abatement job can be broken down into three distinct phases, each of which have substantially similar activities: (i) pre-abatement, (ii) abatement, and (iii) post-abatement. Pre-abatement activities are typically necessary for any size job and are not expected to be modified or substantially altered based on a robotic abatement system. Activities in the abatement and post-abatement time-periods will likely be affected by the use of a robotic system.

We expect to be able to reduce labor-costs in the abatement period, and possibly in the site setup (and hence also the dismantlement) due to reduced need for access to every inch of pipe, and the ability to use a glovebox cleanup approach instead of the manual full-containment approach (this obviates the need for the setup of a containment system). Based on several full-containment and glovebagging job-cost breakdowns[1], we determined that typical abatement job costs break down into five separate activities: (i) site preparation, (ii) enclosure setup, (iii) asbestos removal, (iv) decontamination & demobilization, and (v) project management. Costs have been relatively scaled in Figure 2-1 below, showing that glovebagging is about 84% of the cost of full-containment abatement, or 16% cheaper than full containment abatement.

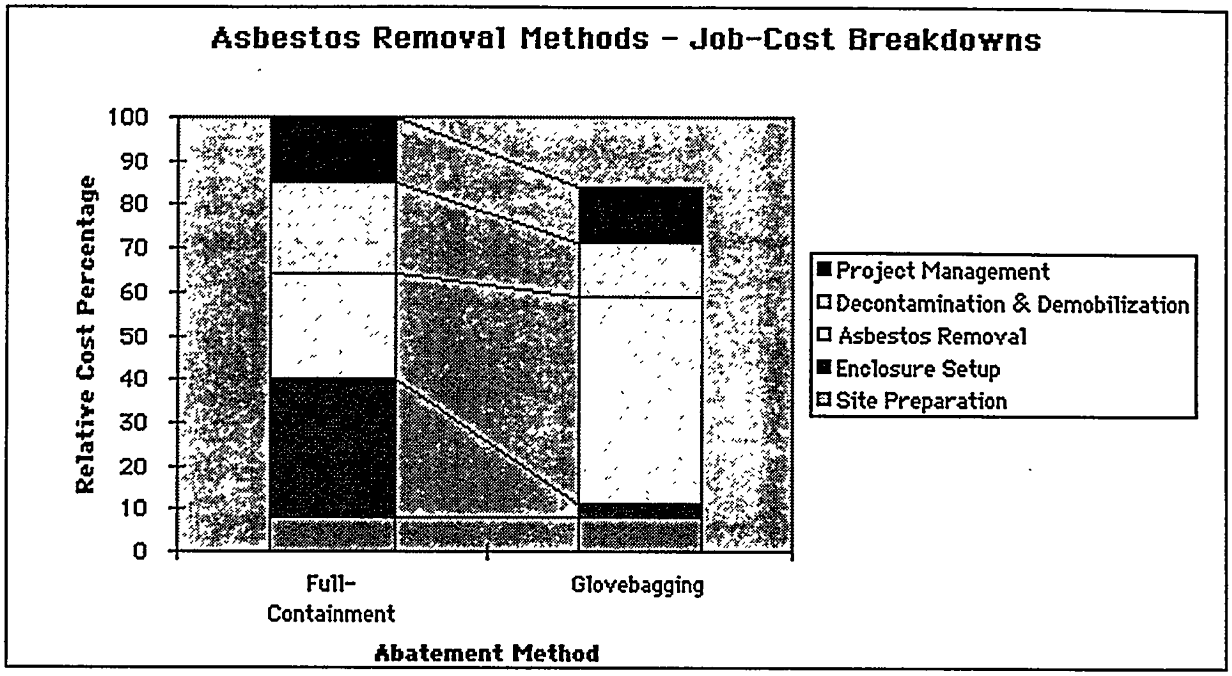


Figure 2-1 : Abatement cost breakdown for full-containment and glovebagging based on DoE job-cost data

The data used to generate Figure 2-1, is detailed in Table 2.1: below.

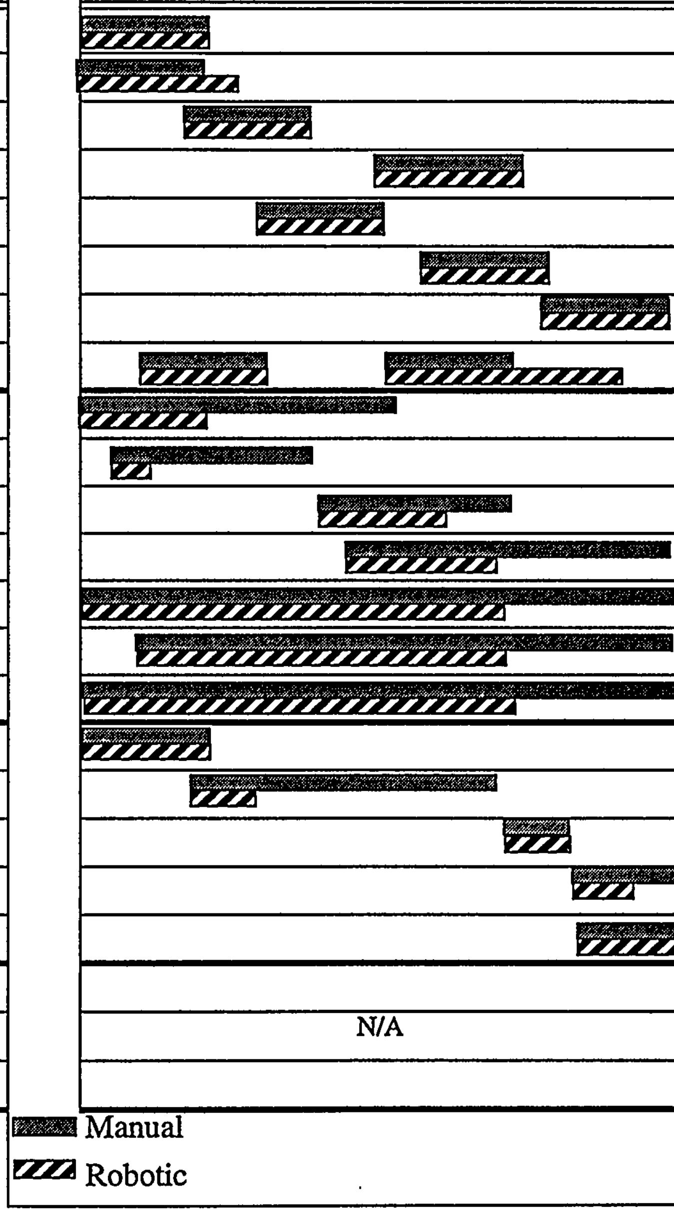
Table 2.1: Abatement Cost Category Breakdown for Full-Containment and Glovebagging

Abatement Cost Categories	Job Cost Percentage	
	Full Containment	Glovebagging
Site Preparation	8	8
Enclosure Setup	32	3
Asbestos Removal	24	48
Decontamination & Dismantlement	21	12
Project Management	15	13
TOTAL	100%	84%

1. Oak Ridge K25 Project 19 Cost Estimate ($733,000.- for 3,400 ft.), Hanford Asbestos Survey Report, 109-N, 105-N, 211-S, 184-N/NA ($5,063,250.- for 29,500 ft.).

Table 2.2: Abatement Activities between Humans and Robots

Abatement Phase	Job Task/Role	Robotic Cost Savings+/-		Timeline Comparison	Comments
Pre Abatement	• Survey				
	• Documentation	-	Recordkeeping		• Documentation for robot
	• Engineering				
	• Project Planning				
	• Contractor Bids				
	• Training				
	• Facility Preparation				
	• Notification/Permitting	-	OSHA Variance		• OSHA Variance Application
Abatement/ Removal	• Build Scaffolds	+	Less scaffolding		• Overall job-time reduction due to faster abatement, and reduced setup requirements and no need for enclosure
	• Setup of Enclosures	+	ONLY criticals		
	• Removal	+	Faster removal		
	• Waste Hauling				
	• Supervision				
	• Support Personnel				
	• Project Management				
Post Abatement	• Waste Removal/Disposal				
	• Clean-up	+	Less airbornes		• Reduced airborne emission
	• Air-clearance sampling				
	• Demobilization	+	Scaffold, Encl.		• Less setup to dismantle
	• Final Documentation				
Other Items	• Materials	+	bags, scaffolds		• Less bags and scaffolding
	• Equipment	-	Robot Cost	N/A	• Purchase/Maintenance Costs
	• Radiation Exposure	+	Red. Exposure		• Reduced Time in cont. area



The above numbers were used to validate the cost/benefit model, in the analysis of the case studies, and during the computation of overall savings realizable through the use of a robotic abatement system.

To evaluate potential cost savings, it is necessary to understand the similarities and differences between the current manual abatement and the proposed robotic abatement process and the necessary steps required for any successful abatement job. Since most, if not all, costs for any abatement job (excluding disposal) are related to labor costs, we will need to explore the chronological arrangement of all tasks requiring any kind of labor, including planning, permitting, supervision, removal, cleanup and wrap-up. A timeline progression with a detailed list of interdependent tasks preceding the removal, activities during the removal and cleanup and final wrap-up has been generated and detailed in *Figure 2-2 : Asbestos abatement job task list comparison for manual and robotic approaches.*

- ***Pre-Abatement***

  Individual activities during pre-abatement can be classified into separate areas, which are further detailed here:

• SURVEYS	Site owner/operator develops a survey of the buildings and facility detailing the type, distribution, etc. of any ACM that needs to be abated. Additional information can also be gleaned from the on-site O&M plan.
• DOCUMENTATION	The facility owner/operator accumulates, collates and cross-references all necessary documentation (bulk sample reports, O&M plan, etc.) for further review by the bidders, and possibly the EPA.
• ENGINEERING	A detailed engineering plan is drafted that details the facility and the constraints that the contractors will have to work under, including, but not limited to, power, access, infrastructure to be covered, moved, etc.
• PROJECT PLANNING	A full project plan is drafted that incorporates the abatement period into the annual cycle of facility use, when to abate, who to talk to, etc.
• CONTRACTOR BIDS	An official bid-package is mailed out and made available. Contractors review the package, receive site-tours and are requested to respond with a bid.
• TRAINING	Once a contractor is picked, certain training of on-site personnel might be needed to achieve the necessary level of readiness for the abatement personnel (i.e. rad-worker training)
• FACILITY PREPARATION	The contractor, in collaboration with the facility/site owner/operator, prepare the site by bringing equipment onsite, setting up offices, bringing and distributing materials, setting up zones, etc.

• **NOTIFICATION/PERMITTING**	The operator and contractor will have to acquire all the necessary local, state and regional permits, including all needed abatement licenses to proceed with the job. Only once every permit and license is granted, can the job actually begin.

We expect the bidding process and the permitting process to be a little lengthier, due to the need for more intricate planning to figure out where/how/when to deploy the robotic system, and the need for filing a report with EPA and OSHA detailing the use of the robot in the proposed abatement job - a process requiring an industrial hygienist or a project designer with PE license. We currently expect this process to not incur more cost as the format and procedures will get better defined as the job numbers increases, but that rather a penalty in the time to start the job will be incurred due to increased regulatory review before a permit/ allowance is issued.

•***Abatement***

In order to understand the differences between the manual and robotic removal it makes sense to look at how the two approaches differ:

- Manual Removal Scenario

Based on our experience and viewing a large number of abatement jobs, we know that one of the first things is setup. Setup involves the removal of all movable items, and the sealing of all 'criticals' (air-gaps on vents, doors, etc.). Should the law require full containment, despite the use of glovebags, the floor and the all the walls and ceilings need to be covered with 6-mil thick poly-sheeting and double-flap taped to be made waterproof. All HEPA units and other internally needed equipment is moved to the area and hooked up. Decontamination and air-locks are installed and additionally needed framework for the containment area is installed. The entire enclosure is tested for leakage before internal work can begin.

Carpenters and laborers show up on site and begin the erection of all needed scaffolding and other reaching structures to allow the asbestos workers access to the pipes. This operation is already performed under full protective clothing and respirator gear. Once sufficiently advanced, the asbestos worker enter the picture and begin removing the asbestos via glovebags and double-bagging the removed insulation, while letting the laborers move the waste bags to a cleanup-area and airlock to remove them from the containment area and placing them into a doubly floor-lined container or transport vessel for disposal. The asbestos workers remove <u>all</u> the insulation from straight-run, hangers, obstacles, bends, junctions, etc. at varying rates depending on the type of job (prevailing vs. competitive wage), presence/absence of radiation, corroded piping, live/dead (steam) line, etc. As specified in the regulations, we assume that two asbestos workers per glovebag are working to clear a 3-foot section (size of a standard glovebag) section of piping at a time. Within DoE, support personnel (1 for every 4 asbestos workers) and supervisors (1 for every 7 people on the job) and laborers (1 for every 5 asbestos workers) are present during the stripping process.

Upon completion of the insulation-stripping, the entire scaffolding is cleaned, dismantled and removed from the site via the laborers. All criticals are cleaned and a final clearance air-sample is run on the area and (ideally) all abated areas are inspected before the area is cleared and all critical barriers can be removed. At this point the job can be considered completed.

- Robotic Removal Scenario

The robotic cleanup scenario is somewhat similar to the manual scenario, except for a few deviations due to the performance of the machine itself, and the fact that it does not require the setup of a full-containment enclosure, but rather only covering of criticals. In general, we are assuming a conservative scenario, in which two operators are needed to handle the robot (tender) and its off-board logistics systems (operator). Depending on the local regulations, it might still be advisable to assume that all critical areas will have to be covered up and the area sealed off from the rest of the world. Additional plastic sheeting needed for additional enclosures is assumed to be identical to the human setup, and hence carpenters and laborer effort will not be diminished under this scenario.

Preparations for providing access to the robot and the tender, carpenters and laborers are involved to some extent, but we strongly believe that we can eliminate anywhere from 25%to 50% of the carpentry labor needed. Once the access-preparation has sufficiently progressed, the tender, with the possible assistance of the operator, raises the robot to the pipe, whether it is standing on a scaffold or on a long-reach boom-vehicle. Once in place, the operator returns to a more remote location (~ 100 to 200 feet away) and powers up the HEP unit, water/encapsulant/wettant supplies as well as all the electrical systems. A remote hand-control box attached to the robot and handled by the tender, allows for local control and supervision by the tender. Should the robot have an integral waste-chute, the removed insulation and lagging will be gravity-conveyed into a separator drum and solids multi-stage filter unit pre-attached to the HEPA unit - this waste collection system will be mounted on a wheeled platform and the off-board logistics and be moved around by the operator.

Once removal of the insulation by the robot is underway, the operator will be responsible for monitoring the off-board logistics, handling the waste-stream and supervising the health status of the machine. The tender could begin abating insulation around such obstacles as valves, bends and junctions, which the robot is not able to handle. Once the robot reaches a hanger, and especially if the insulation is covered with lagging, the robot would stop and await assistance from the tender to fully remove the lagging around the embedded hanger and possibly perform a final high-pressure removal of entrapped insulation (should there be any). The robot would then continue stepping past the hanger (possibly under the supervision of the tender) and then proceed with its continual removal of insulation, while the tender resumes his obstacle-clearing duties. Should the robot reach an obstacle, the tender and possibly the operator, subject to the use of a work-positioner, would man-handle the robot around the obstacle and place it on the next stretch of straight piping run to be abated. The cycle resumes after that. The removal productivity could be timed to coincide roughly with a typical abatement of a glovebag on an obstacle (about 15 to 30 minutes).

Upon completion of the abatement, the robot would be removed from the piping, cleaned and the entire system removed from the site, before an inspection is completed and a final air clearance sample is run. After passing these test, all criticals can be removed and other enclosures torn down. Note that we are not assuming any real savings in removal materials, large HEP filters nor monitoring setups, but rather reduction in person-hours per job, since the job can be completed much faster (an average of about 50%), with the use of the robot system.

Based on the these two approaches, one can see how a robotic abatement system could certainly reduce the time spent at the pipes removing the insulation. In addition, since we project to not require full access to every inch of the pipe, a certain up-front labor savings in scaffolding setup can also be expected. We will however not make this assumption in our savings computation in order to arrive at conservative cost-estimates. Overall, these differences add up to reduction of overall job-time, which can be expressed in labor-hours and hence dollars. Notice that if the robot competes with a manual glovebagging scenario, overall removal labor costs savings can be as high as 50%, or about 15% of overall job costs, assuming a 33/33/33 percent split for the setup/removal/management costs in a glovebagging job. Should the robot compete with conventional full-containment methods, the savings can range from 40% to 50%, since the costs associated with unnecessary enclosure setup (40%) and half the removal costs (20%) can be realized.

•*Post-Abatement*
Individual activities during post-abatement can be classified as follows:

• **CLEAN-UP**	The laborers go about cleaning all exposed and critical areas by wiping them clean and then locking down any loose fibers with encapsulant. Waste bags are also cleaned and removed from the area.
• **AIR-CLEARANCE SAMPLING**	A final air clearance sample is run on the job site and if it passes, gives a green light to the tear-down of all barriers, critical and primary. If the sample does not pass, the area has to be re-cleaned until the sample passes.
• **WASTE HANDLING/DISPOSAL**	Laborers handle the waste bags and store them in a poly-lined container ready for transport to a disposal site. The disposal site depends on the type of contamination.
• **DEMOBILIZATION**	The contractor removes all setup from the site and moves equipment back into storage or to a new job site.
• **FINAL DOCUMENTATION**	The contractor, in collaboration with the operator, draft a final document by compiling all pre-abatement documentation, daily reports and other final lab-test documentation into a final abatement report.

As is evident from this list, we expect some minor impact in the areas of cleanup and demobilization. In the former, the savings will be greater if we compete with full enclosure scenarios, rather than in the latter, where we will have similar and possibly better containment than the on-off-again process of glovebagging. Savings in the latter category apply only if we are able to reduce the up-front setup infrastructure, whether it be for pure glovebagging (less scaffolding) or full containment (enclosures and scaffolding).

2.1.2 Costing Categories

In order to fairly compare the robotic and human removal approaches, we had to limit our analysis to realistic scenarios, comparable metrics and realizable savings categories. Irrespective of what comparison metrics are used, it is important to mention the assumptions or limitations that we have placed on the current analysis, since it lends more reality and results in more believable numbers than a more superficial and less detailed analysis. The selected scenarios also reflect our knowledge of the regulatory restrictions and certification avenues.

This section details the premises upon which the analysis is predicated, and explains the different cost categories used to compare the manual and robotic abatement approaches.

2.1.2.1 Cost-Comparison Assumptions

Several assumptions were made in developing the cost/benefit model. These are based on technical system capabilities, regulatory requirements, and contractor/end-user feedback as to usage, costing and operational scenario. The most important assumptions are as follows:

•***Robot Utility - Impact in removal portion of abatement job only***
We have made a conservative assumption that the BOA system will only save job-costs during the setup of enclosures portion of the job (for full-containment) and the removal portion of the abatement job (glovebagging and full-containment). For now, we are not assuming that we will be realizing any savings in up-front costs during the assessment, planning, engineering nor licensing/permitting stages of any abatement job. The same is true

with the variables used in the analysis.

2.1.2.2 Manual and Robotic Removal - Comparison Categories

We have developed a set of costing categories by which to compare the relative savings between a manual abatement and a robotic abatement approach. The current categories focus solely on the removal portion of the abatement job, and take into account a variety of factors such as hourly wage, human and machine productivity, robot costs (capital & maintenance), radiation exposure, length of removal job, etc. Each of these costs are computed based on a number of variables which can be attributed to manual removal, robotic removal, and then also site-variables that allow one to apply the model to individual case studies.

Table 2.3: Costing categories for manual/robotic thermal pipe insulation glovebag removal

	MANUAL ABATEMENT		ROBOTIC ABATEMENT	
Removal Costs		$/ft.		$/ft.
Radiation Exposure Costs		$/ft.		$/ft.
Setup Costs		$/ft.		$/ft.
Operator Costs	-			$/ft.
Tender Costs	-			$/ft.
TOTAL Labor Costs		$/ft.		$/ft.
Total Labor-Hours per Linear Foot		hrs/ft.		hrs/ft.
TOTAL COST		$/ft.		$/ft.
TOTAL PER LINEAR FOOT SAVINGS	--------------			$/ft.
TOTAL PERCENT SAVINGS	--------------			

The chosen comparison categories, as detailed in Table 2.3:, apply to the DoE. In the case of the industrial market, neither actual nor additional radiation exposure costs are a factor, since there is no assumed radiation exposure in that market segment.

The differences in overall costs occur as follows:

•***Manual Abatement***

We are assuming that asbestos workers will be abating the insulation at a certain rate and getting paid a certain salary, which we can normalize to a cost per linear footage (removal costs). Should the work-area be radiologically contaminated, irrespective of whether at a low-level (LC) or a high level (HC), certain productivity slow-downs will be incurred, and possibly even incurred exposure (person-Rems) might be computed as realizable savings. The addition of all these categories yields an approximate relative (<u>not</u> absolute) cost-per-linear-foot for pipe insulation removal (excluding removal materials).

A total removal time can be computed in order to ascertain the theoretical length of the job, based on an average removal rate (total person-hours per linear foot). An overall comparison for total removal cost savings can then be calculated for the robotic abatement method.

•***Robotic Abatement***

A linear footage cost can be computed for the robot system by computing the labor time required for the operator and tender to assist BOA and to clear the sections of insulation at

- ***Glovebagging Job-Costs***

  A comparison to glovebagging can be accomplished by accounting for reduced manual abatement productivity (reduced from 3 lf./hr. from full-containment to 1.5 lf./hr. for glovebagging). Based on the model using the reduced manual productivity, we would predict a savings of about $26.1/lf - our base for indoor situations with no radiation.

  Should radiation be present indoors, we would use the same approach as outlined above, yielding a larger savings number. For instance, Savannah River's radiation-exposed piping accounts for 90% of their total, and hence their potential savings would be as high as $26(1+(.5)(.9) = $37.7/lf.

  For outdoor glovebagging operations a similar argument as the one used above can be used for scaling the projected per-linear-foot savings, resulting in an estimated $17/lf. = $26 x (75/115). Remember that we omit the radiation case since no contamination is assumed to be present.

All of the above numbers will play a role in determining overall savings by site and market segment. Based on review of the model and the above data, we believe the model to be in agreement with field data from DoE and industry to within 5% ($^{+}$/- 2.5%).

The above numbers can thus be summarized as shown in Table 2.4: below.

Table 2.4: Model and DoE/Industry Data Comparison for Model Validation of Abatement Costs

			Baseline Linear Footage Savings	**Radiation Multiplier**
			Per-Linear-Foot-Savings [$/LF]	
DoE	Glovebag	Indoor	26	0.50 x %$Pipe_{contaminated}$
		Outdoor	17	N/A
	Full Containment	Indoor	38.7	0.50 x %$Pipe_{contaminated}$
		Outdoor	25.2	N/A
Ind.	Glovebag	Indoor/ Outdoor	3 to 4	N/A

The above numbers were in part based on a feed-forward analysis, and partly on an analysis that evaluated savings a robotic system would be able to generate over the full abatement job cycle and additional DoE data. The resulting comparison, showing the relative job-cost for a manual full-containment and glovebag abatement job vs. a robotic abatement approach, is shown in Figure 2-2:

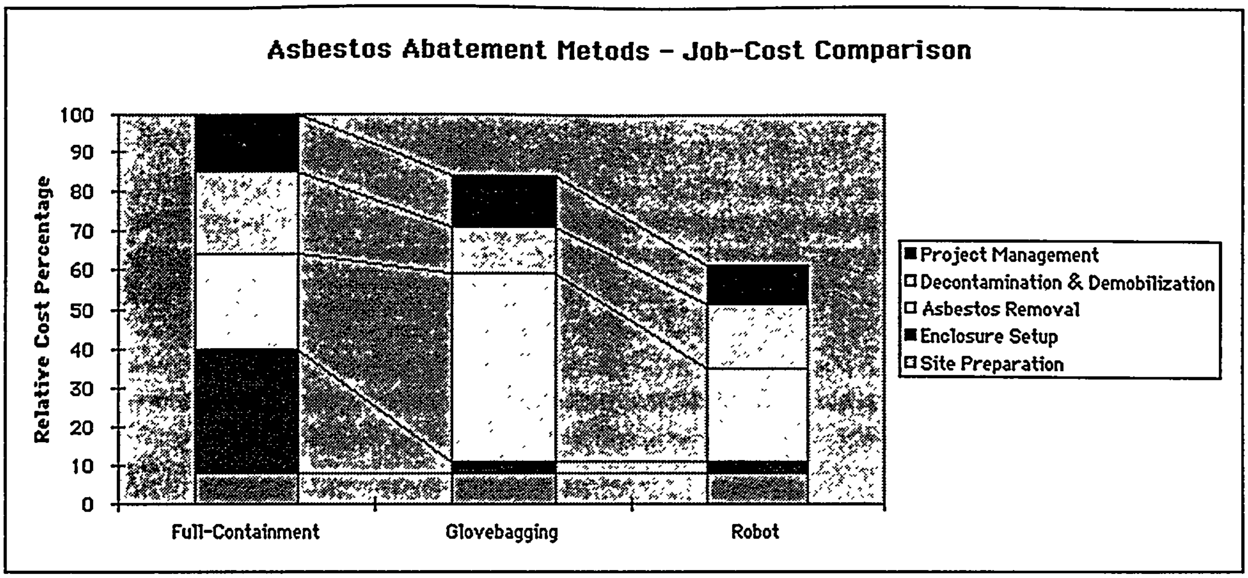


Figure 2-2 : Abatement Job-cost comparison between full-containment, glovebagging and robotic abatement

The net effect is that robotic abatement jobs are on average 36% cheaper than full-containment, and 20% cheaper than glovebagging.

2.1.4 Variable Use and Sensitivity

An accurate cost-benefit model analyzing human vs. robotic asbestos pipe-insulation abatement is a highly multi-variable problem. The most general classification we developed splits the variable set into three groups, namely variables associated with the (i) manual approach, the (ii) robotic approach, and (iii) job-site descriptors. Since we set out to analyze two different market segments, we determined that not only does the model structure vary somewhat, but variables vary to different extents.

The best way to get a first-order general analysis performed on this model was to look at the sensitivity of the model to variations in individual variables, and classify these according to percentage effects on the overall savings. Based on such an analysis, one can classify the individual variables into three distinct groups of varying sensitivity, namely high, moderate and low. The purpose of this classification will be to draw special attention to a set of variables that clearly dominate the overall savings percentage, in order to drive the design, operations or even the need to further narrow the spread on the variable range.

The most efficient way to accomplish this sensitivity analysis is by tabulating the list of variables, their low, medium and high values, the corresponding savings percentages, and the total range on percentage savings. Based on this tabulation, a prioritized listing of variables was generated, which was used further for analysis, design and market assessment.

2.1.4.1 Variable Listing and Variability

The variables used in the model are structured into three separate groups: (i) manual, (ii) robotic and (iii) site. For each of these groups, a set of variables can be considered to have variable ranges, which are affected by a variety of factors. This section details each of these variables and provides a rationale for justifying the proposed variation for each variable.

•Manual

The variables grouped under the manual heading relate to descriptors that define the manual abatement job during the actual removal portion of the job. As such the following variables have been considered and with the following associated variability

- *W_{aw}: Prevailing Hourly Wage - Asbestos Worker; [$/hr]*
  The asbestos worker hourly wage could lie somewhere between $20 and $50 (industrial vs. government), based on discussions with industrial (low-end) and government (high-end) contractors who made the distinction between competitive and prevailing wage jobs. The average has been set at $40/hr.

- *W_{cp}: Prevailing Hourly Wage - Carpenter; [$/hr]*
  Similar to the asbestos worker, the carpenter hourly wage can range from $18 to $45 per hour. The average has been set at $30/hr.

- *W_{lb}: Prevailing Hourly Wage - Laborer; [$/hr]*
  Similar to the asbestos worker, the laborer hourly wage can range from $10 to $30 per hour. The average has been set at $20/hr.

- *W_{sp}: Prevailing Hourly Wage - Support Personnel; [$/hr]*
  Similar to the asbestos worker, the support personnel hourly wage can range from $18 to $50 per hour. The average has been set at $40/hr.

- *W_{pr}: Prevailing Hourly Wage - Project Manager/Supervisor; [$/hr]*
  Similar to the asbestos worker, the manager/supervisor hourly wage can range from $30 to $60 per hour. The average has been set at $45 per hour.

- *P_m: Manual Abatement Productivity; [ft./hr]*
  Manual productivity of glovebag abatement can range from as low as 2 feet per person-hour to as high as 5 feet per person-hour. The wide differences depend on the setting, but if an ineffective bagging process is used or worked is done on live steam lines, the low rate of 2 ft./hr is very reasonable, as supported by discussions with industrial and government contractors. The high-end figure of 5 feet per person-hour reflects a commercial setting where job-time is more important than necessarily following the rules to the letter. We are convinced that contractors are not truly obeying the 2-person-per-glovebag rule all the time, as such high productivity figures are physically impossible to achieve on average <u>while following the regulations by the letter</u>, rather than the interpretive spirit. We have set the average rate at 3 ft./hr, which is corroborated by DoE operators and contractors.

- *B_{mf}: Manual Brushing Productivity Reduction Factor; []*
  Slow-down of production due to brushing could be either non-existent (=1), to as much as adding 50% (=1.5) of additional time on those sections of piping that are corroded. We have set our value at 1.25, which seems to be corroborated by industrial and government abatement sources.

- *O_{mf}: Obstacle Productivity Reduction Factor; []*
  Similarly to the brushing productivity reduction factor, clearing an obstacle is lengthier than clearing straight runs of piping. Our factor that accounts for that lies between 1 (no slow-down) to 1.5, or 50% more time. Our average value is set at 1.125, based on job-data from industrial contractors.

- R_{ec}: *Radiation Exposure Cost; [$/person-Rem]*

The cost associated with annual cumulative person-Rem exposure is a very disputed figure. We have erred on the conservative side, and had it range from $1,000 per person-Rem to as high as $10,000 per personRem, based on figures from the commercial nuclear industry, which we consider to be comparable to the DoE. Our average figure is set rather low and at $2,000 per personRem, in order to not overplay the effect of this variable, since it might be misleading to the analysis. In the end, the larger this number really is, the more benefit there would be for the robotic system anyway.

- R_{lev}: *High Radiation Contamination Level; [mRem/hr]*

The level of radiation beyond which the contamination is considered to be high (HC) can vary, and due to the inconsistency in available numbers, we have set it to range from 1 to 5 mRem per hour. The average number of 1.5mRem/hr was determined based on a maximum cumulative annual human exposure level of 3 person-Rem within the DoE, and the fact that we assumed 2,000 working hours per year per DoE employee.

- R_{mil}: *Low Contamination (LC) labor-hour Increase Factor; [%]*

Based on discussions with other DoE sites, it was determined that due to procedural requirements for working in low-contamination abatement areas, a certain fraction of time is lost and hence reduces the net productivity of any human operator/tender. The current range is set anywhere from 10% to 50%. The average value has been set at 30%, based on discussions with DoE contractors.

- R_{mih}: *High Contamination (HC) labor-hour Increase Factor; [%]*

Similarly as for R_{mil}, this factor is set to range between 50% and 150%. The average number has been conservatively set at 100%, or a reduction in productivity of 50% overall for all personnel within the HC area!

- $W_{\%cp}$: *Carpenter Wage Ratio; [%]*

This ratio denotes the fraction of a carpenter needed for each asbestos worker, and hence a relative additional cost per asbestos worker can be calculated. We have set the ratio from 50% to 90%, meaning 1 carpenter for every 2 asbestos worker, and 9 carpenters for every 10 asbestos workers. The average is based on previous job-case budgetary figures for K-25 abatements, and lies at 76%, or about 3 carpenters for every 4 asbestos workers.

- $W_{\%lb}$: *Laborer Wage Ratio; [%]*

The laborer ratio is identical to that of the carpenter.

- $W_{\%su}$: *Support Personnel Wage Ratio; [%]*

The support personnel ratio is based on figures obtained from K-25, and includes supervisors, guards, escorts, etc., due to the presence of radiation and possibly confidential settings. The actual number or ratio might vary from 15% (1 for every 7 people on the job) to 35% (1 for every 3 people on the job). the average is set at 25%, or 1 support person for every 4 people on the job.

- $W_{\%pr}$: *Project Manager/Supervisor Wage Ratio; [%]*

Based on a standard construction estimation guide, there will normally be between 1 project manager for every 10 people on the site (10%) to as low as 1 for every 4 people on the job (25%). Our average has been set at 14%, which represents the industry standard, or about 1 project manager for every 7 people on the job.

- *W_{mat} = {4($22.- per respirator) + $15.-/tyvex suits}/8: Material Costs; [$/hr]*
In radiation environments within the DoE, it was determined that for every break a person on the job takes, material costs are incurred involving the replacement of respirator and tyvex suits, and which are then spread over an 8-hour shift. The average accounts for 4 daily breaks during which the person gets a new respirator and a new disposable suit. The range has been set anywhere from 1 break per day ($3/hr) to 6 breaks a day ($19/hr). Additional DoE data, shows that additional material costs can go as high as $20.- per person-hour. We will set the range to be from $10 to $20, with an average of $15/hr.

- *H_{cpr}: Carpenter Effort Labor Reduction Factor due to mechanized system; [%]*
One would be able to save labor costs in the setup portion of the job, ranging in savings from 0% to 20% labor cost savings for carpenters and laborers due to the reduced need for access to the pipe. A more realistic figure, due to distribution of obstacles and other obstructions, 0% of labor savings seems a conservative assumption.

•*Robotic Abatement*

- *P_r: Robot Abatement Productivity on straight-run piping; [ft./hr]*
Robot abatement productivity depends largely on the design of the machine, but we have bracketed the productivity of what the current system is capable of doing between 20 feet per hour, and what we expect the new system design to be able to do, namely 60 feet per hour. We have decided on a minimum average of 40 feet per hour as a technically achievable figure, which is technically achievable.

- *E_r: Robot Equipment Cost; [$/unit]*
The manufacturing costs of the robot system are somewhat hard to estimate, but based on the prototype development costs of the first version, we know that it will be no more than $200,000 per system, since it was deemed rather complex and did not take manufacturability into account. On the other hand, we know that it could cost no less than $75,000 based on simple sums of basic equipment and minimum production figure estimates. Our average cost has been set at $125,000, which will be our uppermost target price during the design of the commercial prototype. Note also that we are currently estimating to need $50,000.- for the ground-support system, and three separate cutter/locomotor heads, each costing $50,000.- to abate the full 4, 6 and 8-inch diameter pipe range we are targeting, resulting in a worst-case uppermost estimate of $200,000.-.

- *L_r: Robot Life/Amortization Time; [yrs]*
Depending on how well designed and maintained the system is, it would seem reasonable to expect a life anywhere between 3 and 7 years, with 5 years being the average. These figures correlate well with other heavy-work systems out in the construction industry and the materials processing fields.

- *O_r: Abatement Operating Hours per year; [hrs]*
This number reflects the range of available work-hours per year, bracketed by 1,500 hours (excludes 25% of time lost to administration) and 3,000 hours (adding an extra half-shift per job). The average has been set at 2,080, an industry standard.

- *U_r: Percentage of time robot is in use per year; [%]*
Base on available jobs and successful bids and subsequent scheduling, it would seem reasonable to assume that the robot will be operating anywhere between 15% and 35% of the time (1 to 2 days a week). The average has been set at 25%, or about 1 week every month, based on typical job-lengths and utility of such a system.

- P_{rh}: *Productivity of robot and tender at hangers; [hr/ft.]*

Since hangers can not necessarily be abated by the robot alone, human assistance in the form of removal of lagging and manual pressure-jet cleanup by the tender would create additional job-time which we estimate can be as low as 10 minutes (using the robot as the glovebag) or as high as 20 minutes (using an actual separate glovebag for the job). Our average value has been set at 15 minutes to be conservative yet realistic, since we will attempt to design the system for the former.

- P_{ro}: *Productivity of robot and tender at obstacles; [hr/ft.]*

Since the robot can not abate obstacles, we need to account for the time it takes the tender and/or operator to remove the robot from the pipe in front of the obstacle and re-emplace it on the pipe behind the obstacle. We have bracketed that action to take anywhere from 15 minutes (easy access) to 45 minutes (hard to reach access areas), with 30 minutes being the average.

- $R_{rp\%}$: *Percentage of per unit cost needed as annual parts cost; [%]*

Replacement parts cost have been set as a percentage of capital cost, and have been bracketed to be between 2% and 10% of the purchase price, with 5% being the average. These numbers represent an average cost to operators of construction equipment and inspection robot businesses, reflecting the differences in wear and tear.

- R_{ml}: *Number of weeks per year spent maintaining the robot; [wks/yr]*

Since maintenance is needed on a regular basis we assumed that this might need to be done once every 4 months to as frequently as once every month. The average value was set to be a bi-monthly maintenance cycle.

•*Site Description*

- H_s: *Average Hanger Spacing; [ft.]*

Based on site visits and construction standards, we determined that hanger spacing can be as frequent as every 6 feet, to as infrequently as every 15 feet, on average. We used the current construction industry standard of 10-foot spacings as our average.

- O_s: *Average Obstacle Spacing; [ft.]*

Similar to hanger spacings, site-dependency drives the spacing of obstacles, which we have bracketed to lie between 10-foot and 30 foot intervals, with an obstacle every 20 feet being our conservative estimate based on site visits at the DoE.

- L_{shc}: *Characteristic Hanger length; [ft.]*

The typical length of asbestos insulation remaining around a hanger should a mechanical system abate the straight-run of piping, can lie between 0.50 and 2 feet, with 1 foot being more representative of the current system capability. The average value we use is 1 foot.

- L_{soc}: *Characteristic Obstacle Length; [ft.]*

Typical length of obstacles requiring human glovebag removal varies depending on the type of obstacle, but we have bracketed it to be between 1 foot (bends, flanges, junction) and 3 feet (pipe cross- over, valves, trays, etc.), with 2 feet being or conservative and realistic average value.

- C_s: *Percentage of corroded piping-runs; [%]*

Since baked-on insulation seems to sometimes be present, we had to bracket it to lie between 0% (no bake-on such as possibly in indoor networks), to as high as 25% (outdoor steam and condensate lines), with 5% being our conservative estimate, which limits the corrosion to the areas of obstacles (flanges, valves, bends, junctions, etc.).

- *R_{sl}: Average level of on-site high contamination radiation levels; [mRem/hr]*
Depending on whether a site has high contamination or not, we needed to bracket the potential levels of high radiation present at DoE sites. Based on figures supplied by the K-25 site at Oak Ridge, radiation levels can range anywhere from 1 to 5 mRem/hr, with 3 mRem being our extremely conservative average estimate (basically severely restricting radiation as a major cost-savings factor).

- *$R_{\%l}$: Percentage of piping with low contamination levels; [%]*
Based on site descriptions and case studies from within the DoE, it was determined that anywhere from 0% (no contamination) to as high as 90% of a facility could contain low levels of radiation contamination (< 1.5mRem/hr). The average percentage has been conservatively set at 5%.

- *$R_{\%h}$: Percentage of piping with high contamination levels; [%]*
Based on site descriptions and case studies from within the DoE, it was determined that anywhere from 0% (no contamination) to as high as 25% of a facility could contain high levels of radiation contamination (> 1.5mRem/hr). The average percentage has been conservatively set at 5%.

2.1.4.2 Variable Sensitivity

A pictorial way to render this influence- or sensitivity-chart would be in the form of a pie-chart, broken down by what 'category' used in the model, has the greatest influence in overall incremental savings (shown in Figure 2-3):

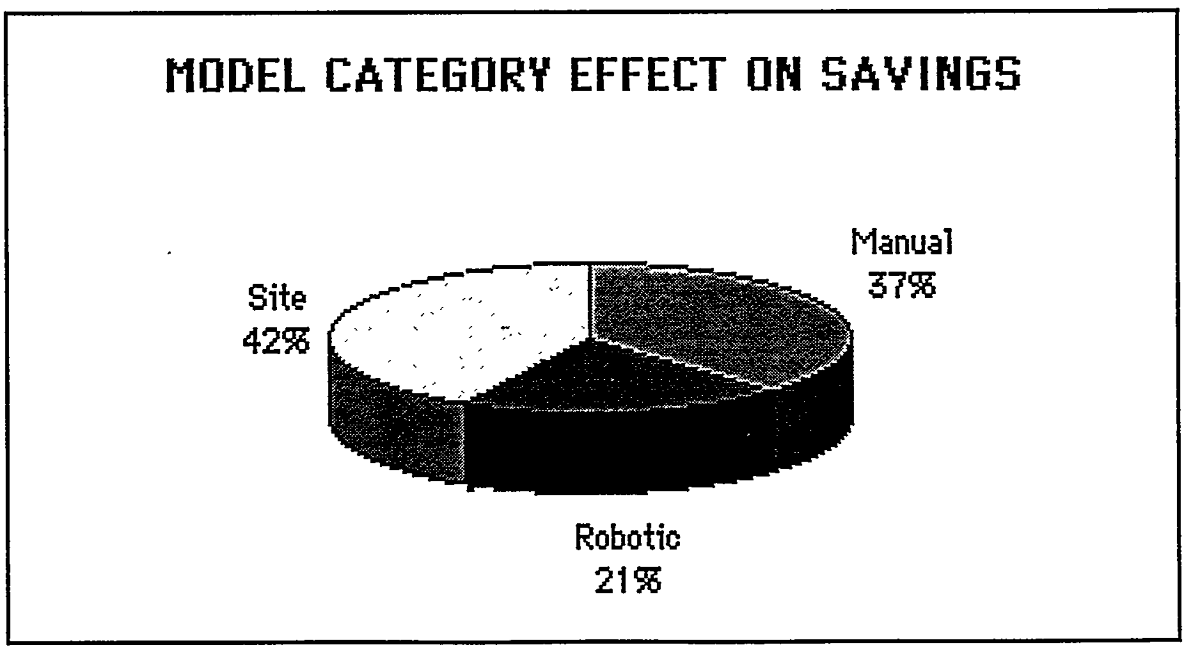


Figure 2-3 : Sensitivity-chart describing impact of model categories on incremental savings

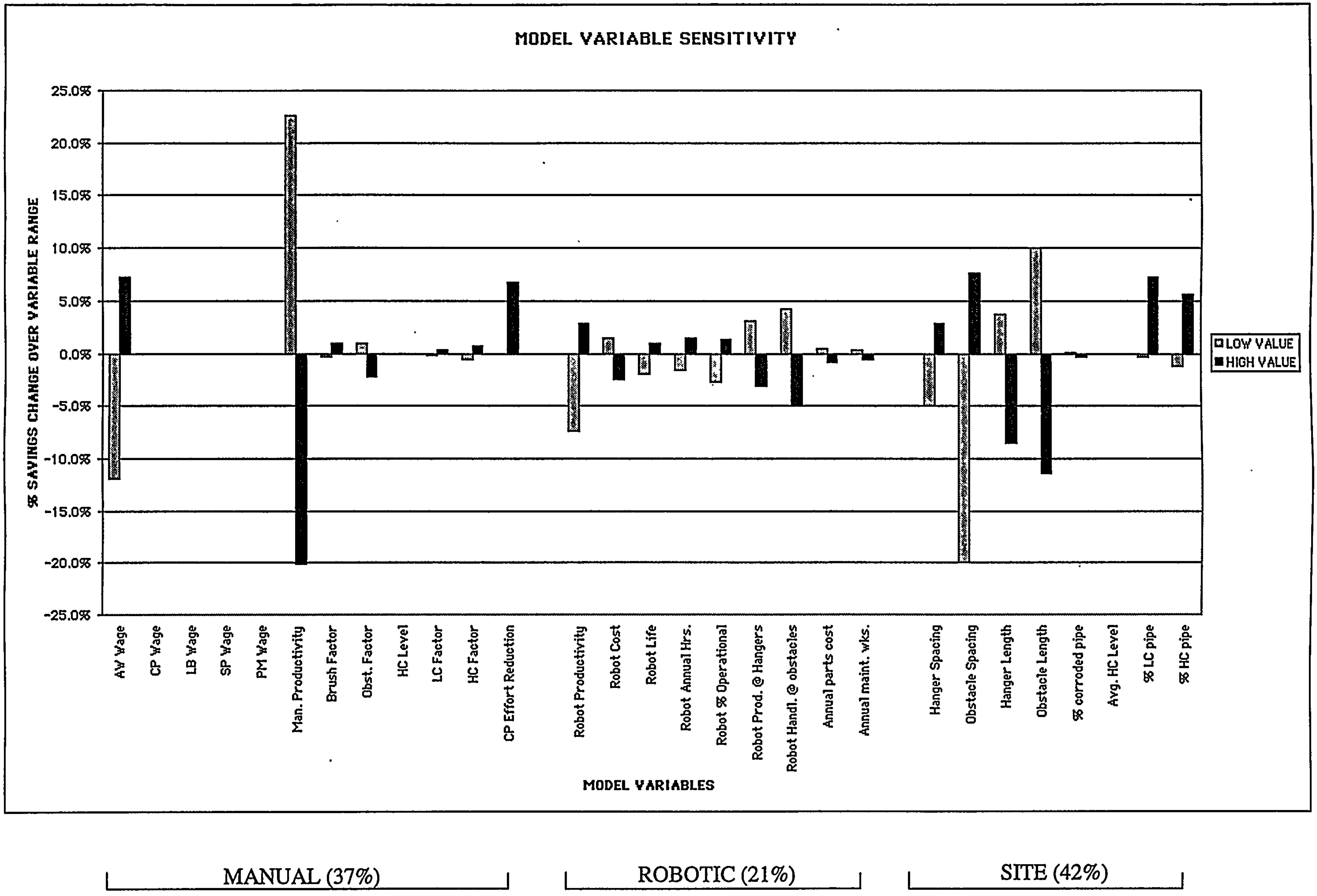


Figure 2-4 : Model Variable Sensitivity Analysis - Incremental Savings Data

- *Involvement of the human at aiding in removal of insulation at hangers should be kept to a minimum, the remaining waste around the hanger should be minimized, while hanger spacing is a moderately important multiplying factor.*
  Requiring the need for human assistance at hangers should clearly be minimized, and is probably superfluous in non-lagged piping situations. However, in the presence of lagging, a human might need to aid by manually ensuring that all the lagging has been removed before the robot uses water/grit-blasting to remove the insulation. Allowing the human to handle a hand-held nozzle to ensure complete clean-up might be necessary anyway. We are currently assuming a 10-minute interaction per hanger in lagged insulation, with the potential for complete removal of assistance in non-lagged situations. Should human assistance be needed, it is advantageous to leave as little remaining insulation around the hanger as possible to reduce the intervention time. It is clear that the more frequent the hangers are, the more labor-cost (due to prolonged abatement time) will be accrued. Even if the spacing drops to/rises to 6/15 feet between hangers we would realize no more than a +/- 4% reduction/increase in percentage removal labor-cost savings.

- *Obstacle abatement and corrosion-brushing are not that big a time-sink for human abatement.*
  Given a reasonable estimate on the frequency of obstacles, and the potential for corrosion (typically at flanges, valves, etc.), even with reduced human productivity, the effects are not as marked as one would have expected. However, should more than 25% of piping be corroded, which could be possible in outdoor scenarios, the overall effect goes from low-impact to medium-impact with more than a 5% effect on percent removal labor cost savings.

- *The cost of the robot, its average usage time, its maintenance costs and the life of the system have little impact.*
  It was determined that depending on the cost of the logistics support systems, this robot system might cost anywhere from $75,000.- to no more than $200,000.- in eventual serial per-unit production costs. Even with such large variation in equipment cost, the effect on overall percentage savings is insignificant. This figure does become important if we need to have separate robots for separate pipe sizes/ranges, thus multiplying the capital expenditure cost. Hence the challenge still remains to make the system simple, easy to operate and maintain and also as cheap to manufacture as possible to increase acceptability, on-site usage, multi pipe-diameter applicability and thus overall profit. Our current estimate pegs the production cost at $50,000.-, where even a total of 3 separate robots (thus a cost of $200,000.-) still only has a negative 5% change effect on percentage removal labor cost savings.

- *The removal and re-emplacement of the robot around obstacles needs to be fine-tuned to minimize the 'non-removal' time of the machine and the need for tender and operator.*
  By fine-tuning the process of removal and re-emplacement of the robot around obstacles, intervention time for the tender and/or operator could be radically reduced, thereby affecting potential savings in abatement time and hence labor costs, which reflect themselves in as much as +/- 3% in overall percentage savings for reducing/increasing the intervention time by 5/15 minutes over the nominal 15 minutes we currently expect this operation to take.

- *Radiation contamination slowdowns are not as important as expected in common LC/HC environments.*
  The level of contamination is not as important as long as the percentage of piping remains low (< 5%). Should levels increase to more than 25% contamination (low or high), this effect grows more pronounced and can have a significant effect. For example a $60\%_{LC}$/ $20\%_{HC}$ contamination area, can cause a 30% additional savings in overall per-linear-foot

costs, hence making radiation into a medium-impact variable.

- *The frequency of corrosion along the straight-runs of piping can only be significant if it exceeds 25% of the pipe-run length.*
The more corroded pipe on a job, the more cost-effective the robot becomes, since humans must brush the pipe within each glovebag, which slows down their productivity. Since the robot treats all pipe the same, its cost remains unchanged while manual abatement costs rise. Percentage cost savings in excess of 5% can be realized, should more than 20% of overall piping be corroded, which might not be the case indoors, but possibly outdoors. Realistically though, we do not perceive corrosion to be an important cost-contributing factor.

- *The frequency of hangers and the relative size of hangers do not affect the net savings in an appreciable way.*
The relative spacing of hangers within a given facility, and the amount of insulation left behind or not abated by the robot which a human has to clean up (via glovebag or reaching into the robot), has very little effect on overall savings. This is due to the fact that doing a glovebag at every hanger or stopping the robot to access the hanger to abate the left-over lagging and insulation, does not require a lot of time based on human productivity. In addition, if the robot can pass by the hanger unaided, even if it has to stop to wait for the human to abate the hanger, the time lost is not severe, since the robot remains on the pipe. Hence penalty for having to remove the robot off the pipe can be quite severe since it affects the net loss of time when the system could be abating insulation and lagging.

•*Medium-Impact Variables*

- *The net wages paid to the asbestos workers have an influence, which brings out the difference between a competitive- vs. prevailing-wage job.*
The type of job and hence the wages paid to the asbestos workers has a non-negligible effect in that it defines the actual removal cost itself, rather than influencing the remainder of the abatement activity costs. Hence a robotic system is more likely to have higher payoff in jobs with prevailing wage structures (i.e. government), rather than commercial job settings (competitive wages structures).

- *The relative distribution of low- and high-contamination radiation has a moderate effect on the human productivity, even with contamination distributions of $60\%_{LC}/25\%_{HC}$.*
Given the fact that certain facilities within the DoE could have radiation levels anywhere between zero (0) and 35 mRem/hr, it becomes important to consider the frequency of this condition. Even for a low level of radiation (LC) of about 1.5 mRem/hr, having a distribution of $60\%_{HC}/20\%_{LC}$, can result in potential percentage savings increases of as much as 6%, which could be quite significant, since it represents about 1/10 of the overall savings. Should no radiation levels be present, the percentage savings are reduced by no more than 1% across the board. The message here is that radiation only increases the benefit of using a robot system, while non-radiated benefits remain somewhat unaffected.

- *Reduction in setup costs due to carpenter and laborer labor by virtue of using a robotic system is an important cost driver.*
It is a known fact that setup costs, which encompass carpenter and laborer wages, time on the job and required scaffolding to get the asbestos workers to the pipe, are a substantial percentage of any abatement job cost. We believe the reduction in carpenter/laborer labor costs and materials of at least 20% is realizable with our new design concept, resulting in a net savings of about $10 per linear foot. Should no setup material/

labor be saved (worst case), our savings would not really drop significantly. The message here is clear, in that designing a robot requiring minimal interactions at hangers and obstacles and even conveyance/bagging of the removed insulation moderately contributes to realizable savings.

- *Robotic straight-run productivity [ft./hr] also has a marked effect on cost/benefit figures, with an asymptotic behavior.*
The productivity of abatement provided by the robot is an important figure, as it affects the rate of removal and the overall robotic abatement job-time. It was determined that with abatement productivity ranging from 20 feet per hour to 40 feet per hour, removal labor cost savings ran from $4 to $8 per linear foot (+/- 9% savings). Increasing the productivity to 60/120 linear feet per hour raises the savings by a not so significant amount, indicating an asymptotic behavior working in favor of the robotic system, as it indicates that as long as our productivity lies between 40 and 60 feet per hour, benefits are still quite significant. This due to the fact that we are relegating the humans to work in sequence with the robot and eventually their time spent clearing hangers and obstacles will become the driving factor. Should the manual abatement portion be accomplished a-priori or in parallel to the robot, the net productivity is increased by an order of magnitude, which clearly favors the robotic system and can result in savings of as high as $17.-/ft., or almost triple the savings realized during sequential operations. The message is quite clear: Achieve as high a productivity as possible and let manual abatement of hangers and obstacles occur a-priori or in parallel to the robot to maximize cost savings.

•***High-Impact Variables***

- *Manual abatement productivity [ft./hr] in different market segments is a key figure in determining robotic cost/benefit margins.*
Based on different figures related to us by DoE site operators and contractors, as well as industrial abatement contractors, manual productivity varies based on the type of job (competitive wage vs. prevailing wage) and setting (industrial with less oversight vs. government with tight regulatory oversight). The main difference we believe to be in how closely the letter of the law is followed during the abatement, which can result in differences in productivity of up to 100%, namely from 3 feet per person-hour [DoE] to up to 6 feet per person-hour [industrial]. There will always be savings by the robotic system, but they will be significantly reduced should human productivity be doubled. This is one of the most sensitive parameters in the entire model, and indicates that human productivity must at all cost at least be doubled if any savings are to be realized.

- *Frequency and length of obstacles, requiring complete manual removal and re-emplacement are a key figure in determining cost savings.*
It is important to note that pipe-runs where obstacles occur more frequently than every 10 to 15 feet, requiring the manual removal and re-emplacement of the robot unit, have a substantial effect on the productivity of the system. In addition, it becomes important to devise a scheme that and logistics support unit(s) to enable this operation to be handled rather quickly and easily by the human tender and/or operator.

The 'top-ten' list of factors affecting the overall variation in savings is thus:

Table 2.6: List of 'Top-Ten' Factors Affecting Savings Sensitivity

Rank	Factor	% Sensitivity	Group
1	Human Abatement Productivity	21	H
2	Average Obstacle Spacing	14	H
3	Characteristic Length of Obstacle	11	H
4	Hourly Worker Wage	9	M
5	Robot Abatement Productivity	6	M
6	Characteristic Length of Hanger	6	M
7	Robot Productivity at obstacles	4	L
8	Average Hanger Spacing	4	L
9	Distribution of LC piping	4	L
10	Distribution of HC piping	3	L

Notice that the biggest contributors to overall removal labor cost is the manual removal productivity, the wage structure present on the job (prevailing or competitive), as well as the frequency and spacing of obstacles along a particular run of piping. The abatement productivity of the robot has a medium effect, as well as characteristic lengths of hanger (length of insulation left behind for humans to abate. Hence, four of the top five criteria are outside of the control of any technology development, while robot productivity only ranks fifth. The message here is that cost savings will be highly sensitive to crew-productivity, abatement market sector and site configuration.

Contrary to earlier beliefs, pipe-corrosion and radiation (with effects measured in person-hour increase rather than person-Rem savings) do not have more than a moderate effect on job cost. Other labor wage rates and even equipment costs have only minor effects on the overall cost, which is an interesting phenomenon. This trend makes sense in a job-class that is highly labor-intensive and site-specific and would thus mainly be sensitive to overall productivity and site characteristics. The immediate conclusion is thus that getting a clear understanding of the true manual productivity as well as the description of the site, has a great impact on realizable savings. Savings in government settings, where prevailing wages are present and productivity is typically lower due to the clear adherence to the established abatement rules, as well as outdoor settings with longer runs of straight piping with infrequent obstacles, will be the areas where a larger savings potential exists. Notice further that the above figures only relate to savings realized during the removal portion of the abatement job, which would be the case in situations where the robot system would have to compete with manual glovebagging work practices. Should the competition be with full-containment situations, the savings will clearly be larger due to the additional savings of not having to put up a full enclosure, which we have found typically translates into an additional $30.- per linear foot. This implies that savings for full-containment replacement are split 6:1 between savings due to obviated-enclosure and removal-cost savings.

2.2 Summary and Conclusions

The cost-benefit model analyzes the benefit of using a robotic pipe-insulation abatement system in jobs where humans currently employ full-containment and glovebagging abatement techniques. Since thermal insulation abatement is a highly regulated industry, it is conservatively estimated that the robotic abatement system will only be able to realize savings by reducing costly enclosure setups and during the removal period, rather than during the planning and post-cleanup periods. The analysis of a robotic abatement method shows that the robot system will save job costs due to obviating the need for enclosure setup and reducing abatement labor because of the increased robot productivity.

Based on conservative cost estimates, it is predicted that baseline savings (excluding the effects of radiation) within DoE, will range between $26 and $17 per linear foot where glovebag abatement is applicable (indoor and outdoor), and between $39 and $25 per linear foot where full containment is applicable (indoor and outdoor), respectively. In the presence of radiation (assumed indoors only), we predict a multiplier on savings of (1 + 50% x %Contaminated piping), which can range from 1.1 (Hanford - 20% piping contaminated) to 1.45 (Savannah River - 90% piping contaminated). These numbers can now be used to project baseline overall savings for DoE.

The industrial market segment was approached in a flat-rate savings approach based on the model, prediciting savings between $3 and $4 per linear foot for indoor and outdoor abatement jobs. These numbers are for glovebag comparison, and are bound to be higher for full-containment.

The established savings margins are the representative indicators to be provided through different case studies, which will be used to arrive at characteristic savings figures for different piping systems, such as indoor process- and steam-piping and outdoor steam lines, at the DoE and industrial settings.

It was determined that the top five contributors, or variables with the most cost savings sensitivity, included manual abatement productivity, frequency and sizes of obstacles, wage structures on the job and the productivity of the robot. The message is that the robot is most likely to reap the largest savings in prevailing-wage jobs, typically in government installations, where straight-runs with fairly infrequent obstacles are abundant (hangers are not as much an issue as we locomote past them). Additionally, if the productivity of the BOA system can be maximized and the amount of human assistance necessary at the pipe is reduced (i.e. by getting by hangers and obstacles quickly and easily), the cost savings for the system will increase.

3.0 Case Studies

The purpose of the case-studies is to provide a real-world baseline for developing cost savings figures for the DoE and industrial markets. The study team took part in several DoE-site visits and plant-trips to industrial settings, in order to accumulate a portfolio of 'typical'[1] job-site conditions, to which the costing model could be applied and savings figures computed. The overall frequency or likelihood of finding similar situations in the indoor and outdoor areas then reflects the relative percentages of these conditions in the overall market segment. Based on the per-case savings per linear foot and the relative frequency of each case, an average savings per linear foot can be computed, which can then later be applied to the overall length of piping across the DoE and industrial settings, which is within the robot's pipe-size range and furthermore 'doable' by the robot.

The individual market segments that were explored, include the DoE and general industrial segments. Each segment has been described by a set of several 'typical' pipe-run configurations which have been encountered during site- and plant-trips. Each case study is further detailed below, with a pictorial rendition and model-description factors collected in the appendix of Chapter *Appendix B - Case Study Data and Images.*

3.1 Department of Energy

3.1.1 Indoors

- *Case Study I: Fernald - Indoor Steam Line - Administrative Setting*

  In one of the administrative buildings on the FERMCO site, a cellar-section contains 3 to 4 runs of 4 to 6 inch diameter horizontal piping with asbestos insulation with a total length of about 150 feet. Heights range from 6 to 8 feet, with hangers every 10 feet and obstacles such as walls and other pipes every 30 feet. Clearances range from 3 to 6 inches due to adjacent pipes. The insulation is painted plaster tape with no visible clamps, but assumed to have spiral wire-wrap under the coating. No radiation is present, and the pipe is assumed to be in pretty good shape. A human abatement team could abate this area with a full enclosure or glovebag without any major scaffolding and at a rate of about 2 feet per person-hour.

  This run is typical of indoor steam-heating supply lines for buildings where 'creature comfort' is necessary. Even though not very frequently found across the sites in this configuration, it is a setting where the robot system could be used.

- *Case Study II: Fernald - Indoor Steam Line - Maintenance Building*

  In the maintenance shop/building a set of pipes were found running along one end of the building. The pipes are about 40 feet off the ground, and range in size from 4 to 6 inches and are either on 20-foot hanger supports or supported by i-beams every 40 feet. Most of the runs are horizontal, and all are covered with aluminum lagging with clamps. There is no radiation present in this building, and the pipes are assumed in good shape (no corrosion). A human abatement crew would probably need major scaffold setup to perform a glovebag abatement operation, since full containment is not feasible, with a rate of about 2 feet per person-hour.

  This run is typical of process/steam supply lines for indoor non-radiated environments. This setting is somewhat frequent within the DoE in this pipe range.

- *Case Study III: Fernald - Indoor Process Line - Building 2/3*

  In building 2/3 on the FERMCO site, a large number of process and steam piping run in all directions in a 8 to 40 foot high arrangement, with most (85%) of them in the horizontal and some in the vertical direction. All piping is in the 4 to 6 inch range

1. 'typical' in so far as we can say that other sites are <u>similar</u> and can be described with the same model variables.

(pipe O.D.), with unknown insulation type, aluminum clad with banding, and sometimes even only paper-tape. The pipe is very corroded (about 25% of all runs) due to corrosive air, moisture and condensation over time. Radiation levels are somewhat high at 5 mRem/hr, with 20% of piping at that level, and 80% at a lower level. Hangers are spaced every 25 feet, with major obstacles such as I-beams and valves/bends/junctions about every 50 feet. A human abatement crew would probably either glovebag all runs, or set up partial containments (hard to do) to clear sections of pipe - manual abatement will require substantial scaffolding due to the intricate and long reaches, with an expected productivity not exceeding 2 feet per hour due to the contamination and critical abatement regulations.

This run of piping is typical of process piping with a DoE processing plant, and as such amounts for a large percentage of all the piping that would be applicable for the use of a robot.

- *Case Study IV: Oak Ridge - Indoor Process Steam Line - K27-Building*

  The pipe runs in building K27 at Oak Ridge range in size from 6 to 8 inches pipe O.D., running at heights between 6 and 12 foot above the ground. The majority of the pipe is horizontal (90%), and all of it is clad with painted plaster tape and aluminum clamps/bands, in varying states of deterioration. Hangers are spaced every 15 feet, in addition to obstacles such as I-beams or other pipes and walls about every 40 feet. A substantial portion of the pipe is assumed to be corroded (50%), with overall radiation levels around 3 mRem/hr for 20% of all piping, and the remainder at a lower level. A human abatement crew would abate this piping using glovebags only and would need little to moderate amounts of scaffolding to reach the pipe.

  These pipe-runs within the K27-building is an identical replica of multiple such runs within the K25-plant and building, and are thus representative of the process steam lines within the K25-plant, and other such processing plants within the DoE.

- *Case Study VII: Hanford - Indoor Process Steam Line - Bldg. 109N*

  The pipe runs in this heat exchanger building that are applicable to us are about 8" diameter and aluminum lagged. Obstacles are spaced every 20 feet, with hangers at every 15 feet or larger. Clearance ranges from 6 inches to up to one foot, with heights from 8 to 20 feet. We assume that no corrosion is present, and that radiation contamination is negligible.

- *Case Study VII: Hanford - Indoor Steam Process Line - Bldg. 221-U*

  These pipe run in these (4 total) canyon-like building structures that are each about 700 to 1,000 feet long, and contain up to 3 levels. The pipe is typically 4 inches in diameter (excl. insulation), and is only supported by hangers every 10 feet, with obstacles about every 25 feet. Clearances are about 3 to 6 inches, and contamination levels are low, yet present in the entire site. Reaches for the pipe range from 3 to 10 feet.

3.1.2 Outdoors

- *Case Study VII: Fernald - Outdoor Interbuilding Steam Supply Lines - FERMCO Site*

  On the FERMCO site, all roadways are paralleled by process and steam lines coming from/going to the boiler house. These steam lines supply steam to all process buildings and also office/maintenance buildings on site. All piping ranges in size from 6 to 8 inch pipe O.D. with unknown insulation type clad with aluminum bands and internal heat-tracer wire on the condensate line. Anywhere from 4 to 6 separate pipes run in parallel on 30 to 40 foot high I-beam weldement supports, with some piping internally supported on the I-beams and others externally hung from hangers. Clearances range from 6 to 15 inches for structure and other pipes, respectively.

Hangers, or I-beam supports are spaced every 40 feet, with cross-bracing obstacles every 10 feet. Due to the outdoor environment, we expect that at least half the piping will be corroded, but no radiation is assumed outdoors. A human abatement crew would perform either a line-by-line glovebag abatement job or a full containment sectional abatement job on these pipes, with substantial scaffolding required to gain access to the pipes.

This piping run is characteristic of denser sites with process and steam lines running between buildings. Due to the size of Fernald, the total number of linear feet is moderately nigh, but is bound to be higher for other more spread-out sites as well as petro-chemical plants, and hence the frequency of this type of piping arrangement is somewhat higher.

- *Case Study VIII: Oak Ridge - Outdoor Building Steam Line - K33-Building*

All of the buildings within the K25-site have steam lines that run the outside of buildings with t-offs that enter the building or tap into the main steam supply lines feeding the building. There are two main lines of 6 and 8-inch pipe O.D., clad with aluminum lagging and an excess of bands, supported by hangers or I-beam supports every 20 to 40 feet, respectively. The piping is about 35 to 40 feet above the floor and exposed to the elements, giving at moderate chance of being corroded, but without any radiation contamination. A human abatement crew would abate this piping with glovebags only and would need substantial scaffolding or infrastructure support to reach the piping.

This type of piping is representative of process buildings where steam supply is a major portion of the process, as is the case in Oak Ridge and Hanford. It is somewhat frequent and hence a good DoE-wide representative.

- *Case Study IX: Oak Ridge - Outdoor Interbuilding Steam Line - K25-Plant*

Across the K25-site and even ORNL or X-10, steam is supplied from the boiler house(s) to the spread-out buildings across the complex by steam lines running close to the ground, about 3 feet off the floor, and supported by welded I-beam supports from below or hung using hangers from welded T-shaped supports. Typically one to two steam lines and a condensate return line run for miles along roadways or across wild terrain. All piping is aluminum clad and banded, with supports every 60 feet, and a good likelihood that the piping is corroded but without the presence of any radiation contamination. A human abatement crew would most likely do this job in glovebags for sectional abatement, rather than in a full containment, without the need of any scaffolding, since the piping is at waist-height and hence very reachable.

This type of run is very typical of outdoor steam feedlines across the DoE complex and is thus a very important contributor to overall footage available for robotic abatement.

- *Case Study X: Hanford - Outdoor Building Steam Lines - Outside of 109-N*

These outdoor pipes run along the lengths of buildings in racks that can be as tall as the building. Pipe size ranges from 6 to 36 inches in diameter (8x 36", 4x8"/10"/12"), with all piping aluminum clad, uncontaminated, and supported every 40 feet by the pipe-rack it resides in. Typically, each rack contains about 12 pipes, 1,000 feet long, hence yielding 12,000 feet at this building alone. Pipe heights range from 8 to 24 feet, and clearances are fairly good and as large as 1 foot (radially).

- *Case Study X: Hanford - Outdoor Intersite Steam Lines - Hanford Reservation*

All of the different process sites on the Hanford Reservation are connected through outdoor steam runs ranging in size from 4 to 36 inches in overall diameter. Supports are spaced every 20 to 30 feet, and are in the form of a vertical post sit-on/roller support or even an L-shaped bracket with a welded-on hanger. The state of the insulation, base on wire-wrapped tar-paper to aluminum-lagged ranges from poor to acceptable, with many maintenance sections encapsulated for protection. Access to these lines is from the road, and human abatement would be done through a crane-movable enclosure, with productivity on the order of 12 feet per 2-person day (i.e. 12 feet for 16 person-hours or about 1 foot per person-hour!). This situation is typical at Hanford, and represents about 150,000 linear feet of applicable piping for a robot system. Hanger abatement is done at about 2 to 4 person-hours each and represents a task still needed. The pipes are assumed to be corroded over 50% of their runs, but without any significant radiological contamination levels.

3.2 Industrial

The industrial portion of the market was extremely hard to categorize through site-visits due to their variety, dispersion, and the limited time and funding for this study. Based on contractor surveys and discussions, it was determined that overall the industrial settings are similar to the DoE settings, except for difference in wage structures and overall abatement productivity. The approach taken, was to modify the DoE's cost/benefit model and account for these differences and then calculate potential per-linear-foot savings and overall job-cost savings. The modifications involved reducing wages in general, removing support and project manager personnel, increasing the manual productivity to 7.18 lf/hr. and eliminating radiation effects. The net result was that a manual/setup cost comparison between model and actual costs, yielded numbers to within $^{+}/-$ 2%. The actual per-linear-foot job-cost and removal-cost numbers were extracted from a contractor survey, used for indoor glovebagging situations, and then scaled to apply to outdoor scenarios. The details of the numbers and the results are summarized in Section 3.3. Pictorial case study examples are added to the gallery of DoE case-studies for completeness, and are located in the appendix.

3.2.1 Indoors

- *Case Study X: Steam Lines, Boiler Control Room, Pittsburgh, PA*
  These steam lines in a boiler control room of a large boiler plant represent a set of piping that contains pipes in the range of 4 to 12 inches in O.D. which is fairly accessible from the floor. Obstacles are rather frequent, making this a good example of a site where due to pipe-size the robot would be very applicable, but due to a high frequency and large-sized obstacles, a robot would hence not be very productive not cost-effective.

3.2.2 Outdoors

- *Case Study X: Oil Refinery, Oil/Steam Lines outside distillation column, Oahu, HA*
  These steam and pre-heated crude-oil lines feeding a distillation column in an oil refinery range in size from 1 inch to 12 inches in O.D. They are very tightly packed in the small-diameter case, making it virtually impossible to abate using a robotic device - we hence term these conditions as 'spaghetti'. On the contrary, the pipes running along the wall and carrying the crude/raffinate product, are more applicable, as long as the vertical runs are long and uninterrupted enough to warrant access and reduced scaffolding and without any full-containment.

- *Case Study X: Oil Refinery, Pre-heated crude-oil feeders - Crockett, CA*
  These ground-based pre-heated oil-refinery feeder lines are a prime example for the use of a robotic system. They are between 2 and 6 feet of the ground and range in size from 4 to 12 inches with substantial clearance between them. These types of scenarios would allow substantial use of a mechanical removal system, due to its high productivity and infrequent obstacles. Competition with glovebagging and full-

containment would yield substantial savings in these conditions.

- *Case Study X: Chemical Plant, Steam Process Heating Lines - Niagara, NY*
  The conditions of these steam-heat feeder lines in a cat-walked outdoor pipe gallery at a chemical plant are also a prime target for a robotic removal system, for similar reasons as stated in the previous case.

3.3 Summary and Conclusions

Based on these case studies, a simple table was developed (see below). Individual case studies are listed, and their relative savings computed based on the model ($/ft and overall removal labor percentage savings). Notice that there is only a slight difference in the DoE market segment for relative savings for indoor and outdoor applications, which is an important distinction, since typically more piping is accessible to BOA outdoors.

- *Department of Energy*
  The variation in indoor savings for DoE are due to the fact that for typically congested non-radiation areas, we expect our lowest savings of around $15 to $30 per linear foot. Should such a situation include radiation exposure, which is typically 19% (25% at K25 in Oak Ridge and 90% in Savannah River) of all indoor piping within the DoE, the savings can range from $25 to $45 per linear foot. Should hangers and obstacles be less frequent, such as in certain sites (K25 and Hanford), savings can go as high as $40 to $45 per linear foot. Typically, these numbers represent about a 55% to 60% savings of removal and setup labor costs, which in turn represent a certain percentage of overall job cost (see *Figure 3-1 : Abatement cost breakdown for full-containment and glovebagging based on DoE job-cost data* on page 29). Since setup and removal account for about 57% of a glovebag job, the overall job-cost savings are in the area of 30%
  Outdoor savings for DoE are pretty steady at around $35 to $40 per linear foot, which is lower than indoors due to the higher productivity in outdoor (full-containment) abatement. Hence the robot system is still able to save about 45% to 50% of the removal and setup labor cost, which represents about 24% of the overall job cost. In addition, it is also able to save the 32% of overall job cost to set up enclosures and about 43% of the 21% portion of dismantlement, since it does not require any enclosures to operate, since it is itself a traveling negative pressure mini-containment system. The overall job-cost savings are thus about 40% to 55% of overall job-cost, if we include half-time savings in the enclosure cleanup and dismantlement processes which a robot system does not have.

- *Industrial*
  Overall model analysis based on industrial contractor feedback, place the overall per linear foot indoor job cost at about $\$15.^{\underline{33}}$/lf. Since glovebagging abatement productivity in industry is higher, at about 7.18 ft./hr., the expected overall savings are lower if a robot is to be used. Since prior job-cost data indicates that about 57% of any job-cost is attributable to removal and setup, we expect that manual removal/ setup costs would lie around $\$8.^{\underline{75}}$/lf. Our model predicted a robotic removal cost of about $\$4.^{\underline{57}}$/lf, which in turn translated into about a $\$4.^{\underline{31}}$/lf savings. This number hence represents about a 49% savings of removal labor costs, or about a 29% overall job-cost savings.
  Outdoor savings for industrial settings are based on a similar model as the DoE

approach. Hence, based on the approach that outdoor abatement costs are about 67% of indoor abatement costs, an outdoor industrial abatement job cost should be based on $10.27/lf. Our outdoor industrial model predicted the manual removal/setup cost to be $6.79/lf, which represents about 66% of overall job cost, which is off by about 10% w.r.t. our assumption, but still within the error margins of this analysis. Hence the robotic removal costs were model-computed at $3.96/lf, for about a savings of $2.83/lf, or about 42% of overall removal/setup costs or about 24% of overall job costs.

Since both these cases are so similar, we decided to use the more conservative indoor savings figures since they are more prevalent within the industry market segment.

4.0 Commercialization Assessment

At the outset of the BOA development project, Carnegie Mellon solicited the participation of RedZone Robotics, Inc. as industrial partner. RedZone's role has been to bring the perspective of a commercial entity to key reviews and throughout the project, thus ensuring that the work will lead toward a commercially viable technology. During the current phase of the project, RedZone was given a specific assignment to assist in developing a cost/benefit assessment model, defining and evaluating the potential markets for this technology, and to make a preliminary assessment of the costs, risks and rewards of bringing BOA to market. By doing this now, we have helped to defined targets for critical design parameters which must be achieved in the next phase of development to ensure commercial viability.

In this chapter we examine alternative models for completing the commercial development, establish projections for potential sales, and examine the value of BOA to a potential customer and to a potential commercialization entity. We conclude with several guidelines regarding objectives and roles for the further development of the technology.

4.1 Models for Commercialization

For BOA to proceed beyond a demonstration prototype, a reliable commercial source must be established. By "commercial source" we mean one or more manufacturers who are capable of fabricating, delivering, supporting, and warranting a BOA system over a period of several years. Technology delivered as a commercial product offers several advantages compared to technology delivered as a one-of-a-kind system:

- **The cost of a single unit will be lower:**
  - *the development costs can be spread across many units;*
  - *batch production methods can reduce parts and assembly costs;*
  - *training and support costs can be spread across many units;*
- **The risks of using the system will be lower:**
  - *bugs can be engineered out of the system in beta-testing;*
  - *multiple systems yield better reliability;*
  - *multiple systems enable more extensive warranty, support, and spare parts capability.*
- **Purchase and delivery of a single unit should be easier and faster:**
  - *the purchase will be on a catalog-item basis;*
  - *delivery can be from stock or from pre-planned manufacturing slots.*

Converting a prototype technology into a commercial product yields cheaper, safer, better systems. The DoE as a *user* of BOA is best served if it can ensure the transfer of the BOA technology into a commercial program.

In outlining the commercial potential of the BOA technology, we start from the current state of the technology, and consider alternative paths toward the desired end state. We consider that the CMU project will culminated in a pre-application prototype, that is, the technology existing at the end of the current project will prove the concepts of the system but cannot be used in the field, other than for demonstration purposes. There thus remains an undefined amount of additional engineering to complete the development of a prototype that approaches the cost and performance characteristics of a commercial product. Initial planning issues are: What is the nature of this additional development activity? and who should bear the costs? The principal alternatives are these:

1. CMU completes the development of a commercial prototype, under DoE funding, then licenses the technology to one or several commercial entities.
2. CMU transfers the technology in its prototype state to one or more commercial entities, which then complete the development with their own funding.
3. A hybrid approach, in which the further development is undertaken jointly by CMU and a selected commercial entity, with funding from both DoE and the commercial partner.

Before the DoE or a commercial partner could chose from among these alternatives, we must make some estimate of the commercial market size because the size of the potential market will dictate (a) the number of vendors that can succeed in the market, and (b) the amount of up-front investment than can be justified under conventional expectations of return on investment. Through iterative analysis, models of the market also dictate price and performance targets for the commercial BOA technology. These targets in turn define the scope of additional development.

4.2 Potential Customer Base and Demand

Potential customers exist primarily in the asbestos abatement contractor industry (over 1600 companies), with some additional sales possible directly to facility owners who conduct their own abatement. Because BOA is most applicable to the industrial segment of the market, we have used data primarily from this industry to determine the potential customer base and projected unit sales volume. DOE is also a potential customer base and is discussed separately at the end of this section.

The following methods were employed collectively in quantifying the total sales potential and anticipated market share for BOA:

1. Determine the total number of linear feet in the industrial market available to BOA and then determine the number of BOA units needed remove this amount of insulation. This number brackets the maximum number of BOAs which could be sold.
2. Characterize the buying trends of the potential customer base by assessing the number of units of comparably-priced equipment bought by contractors in the asbestos abatement industry. From this information we can generally characterize the number of companies capable of purchasing a BOA system (this is considered a gross estimate since the relative worth (cost/benefit) of BOA vs. comparably-priced equipment is not clear).
3. Determine the number of companies which do enough asbestos removal work to justify purchasing a BOA system (i.e., they could pay off the investment) and develop sales projections for the total number of BOAs these companies would buy. This was done by determining the break-even point in linear feet of asbestos removal (or revenues) for a company and then looking at the distribution of companies based on revenues.

The projections obtained from each of these methods were compared and used to develop an estimate of total sales potential and to bracket the general price break points.

• Method 1 - Total Feet Model

The total number of linear feet available for BOA per year (as determined previously in the Target Markets section) is over 1.4 million feet of pipe insulation. BOA is expected to be operational at least 520 hr/yr. (25% of the 2080 work hours in a year). Given the productivity rate of 40 ft/hr for two people using BOA, it is projected that BOA can abate 20,800 ft of insulation per year. When the available 1.4 million linear ft/yr. is divided by BOA's 20,800 ft/yr. productivity rate, it is projected that 70 BOAs would be needed per year.

Since the asbestos abatement industry is anticipated at having a 25-year life and BOA is predicted to have a five-year life, a BOA system could be replaced up to five times within the total market life. However, we believe that due to the projected decline of this market that this may not be achieved and that repurchasing twice is more likely. Therefore, the maximum number of BOAs which would be justified using this method is 140.

Table 4.1: BOA Sales Volume Projections

Total BOA Footage per Year	1,459,158
BOA Feet/Hour	40
BOA Hours/Year (25%*2080 hours/yr.)	520
BOA Feet/Year (40*520)	20,800
# of BOAs/Year (1,459,158/20,800)	70
Maximum Potential BOA Sales (70*2)	**140**

• Method 2 - Purchase Price Model

The number of potential BOA sales can also be projected by looking at the buying habits of companies and determining those which have purchased similarly-priced equipment. Using data collected during a survey of asbestos abatement companies it was found that 25% of the companies surveyed have purchased equipment priced $100,000 or higher. The percentage drops to 15% when the price rises to $125,000. Multiplying this factor by the 1600 asbestos abatement companies (not branch locations) indicates that there are approximately 240 companies capable of purchasing BOA based on past buying trends. By further assuming that each of these companies would buy at least a second unit (in the sixth year), this projection can be doubled to 480 units.

When using this same calculation with a $100,000 price, approximately 400 units (25% of 1600 companies) could be sold and another 400 units after the fifth year. As in the previous scenario, these two projections (480 and 800), are the maximum number of units the market is projected to support.

This analysis provides an alternate method for bracketing total sales potential, but may not provide very accurate results. Generally, the most expensive piece of equipment used in this pricing analysis is a vacuum loading system, and the relevance to a robotic device is questionable. None-the-less, this method demonstrates the price-sensitive nature of this industry and indicates that there may be a significantly larger market if BOA can be priced closer to $100,000.

• Method 3 - Company's Linear Footage/Revenue Prerequisites

This is perhaps the most complicated and detailed method used to estimate the sales potential for BOA. First, we determined the gross revenue at which a BOA system's 20,800 linear ft/yr. productivity could be utilized. In performing the industrial market assessment (see previous section) a model was developed starting with industrial sales projections and working down to the number of BOA-applicable linear feet that were contained within that sales figure. This model was used again here, but in the reverse order. It has already been estimated that BOA is capable of removing pipe insulation from 20,800 ft/yr. Since we are now starting with the BOA-applicable linear feet goal of 20,800 (the model ends up targeting 20,845 linear feet), the same model can be utilized in reverse to determine the revenue number a company must have to support this productivity. The model, as shown below, indicates that a company must have $40 million in total revenues, or $10 million specifically in industrial asbestos abatement.

Table 4.2: Targeted Company Revenues to Support One BOA Unit

Company Revenue (in millions)	**$40**
Industrial Revenue (in millions)	**$10**
Thermal Insulation	31%
Total Thermal Insulation @ Industrial Sites (in millions)	$3
Labor as % of Revenue	37%
Total Thermal Insulation Labor	$1,147,000
Labor Rate/Hour	$14.74
Hours of Labor	77,829
Average Feet/Hour	7.18
Total Feet	558,626
Assume 15% is Non-pipe Thermal Insulation	15%
Total Thermal Pipe Insulation Feet	474,832
Glove Bagging % of Work	22%
Total Glove Bagging Feet	104,226
Assume 40% Pipes are 4-8"	41,690
BOA Feet in a Year	**20,845**
Years Remaining in Industry	25
Total Feet for BOA	521,128

Next, we determined how many companies have either $10 million in industrial abatement revenue or who have $40 million in total revenues. Based on a special report prepared by The Jennings Group, Inc. (summarized in Appendix TK), there are only 2 out of 61 companies (or roughly 3% of the abatement companies) with revenues equal to or greater than $40 million. Based on the prerequisite for $40 million in total sales, there are 52 companies (3.28% of 1600 companies) which could buy a BOA system. These two companies have over $40 million in total revenue and could therefore purchase multiple systems. A slightly different approach can be taken to determine this higher potential. The two companies with revenues greater than $40 million have total revenues of approximately $175 million, which is equivalent to four $40 million revenue units. By dividing the four units by the 61 total companies surveyed (or these two companies with the equivalent purchasing power of four companies) results in over 7% of the companies with the ability to purchase a system. Therefore, approximately 115 company-equivalents (7.17% of 1,600) have sufficient business to justify purchasing a BOA system.

We also determined an estimate based on the number of companies with industrial revenues of $10 million or more. Again, approximately 3% of the asbestos abatement companies responding to Jennings' survey in 1993 (2 out of 61 total companies) have industrial revenues of $10 million or greater. When the 3% is applied to the 1,600 total asbestos abatement companies, it means there are potentially 52 companies (3.28% of 1,600) which could support a BOA system.

Since these two companies have more than $10 million in industrial business, they could justify buying more than one robotic system. The total industrial revenue of the companies with industrial revenues of greater than $10 million in the Jennings report is $36.25 million. When this number is divided by the $10 million prerequisite industrial revenue needed to justify buying a system, there are then three and a half $10 million units out of the total companies, or approximately 6% of the companies. There are only two surveyed companies with the justification to buy a system, but these two companies have the purchasing equivalent of three and a half companies (3.625 out of 61 = 5.94%). Therefore, 95 companies (5.94% of 1600 companies) could potentially buy a BOA system.

• Summary of Results

In summary, the following first-time and maximum purchase estimates have been derived from the preceding methods:

Table 4.3: Summary Table for Sales Potential of BOA Systems

	First-Time Purchase Only	**Maximum Possible (twice)**
Method 1	70	140
Method 2	240	480
Method 3a	115	230
Method 3b	95	190

It should be noted that these figures are not exactly what a particular company manufacturing BOA would expect to sell. The number of units a company forecasts would be some percentage of these numbers, based on market penetration and competition. For this and other reasons noted below, we have considered only the first-time projections to be relevant at this time and have used these in the remainder of this commercialization assessment. The close proximity of the first-time numbers gives a reasonable degree of assurance for using them as the basis for sales projections. We view that this conservative approach should be taken, given the dynamic nature of the market and difficulty of making future projections. As covered earlier in the Market Assessment section, the asbestos abatement industry is in a state of decline (-13% in 1991, -6% in 1992). The number of asbestos abatement companies is also declining. While there are approximately 25 years left to abate the remaining asbestos, given the rate of decline, there will obviously be more asbestos companies with justification to buy a system in the next five years then there will be in the last 15-20 years of the industry's life.

The other source of potential sales we have considered for BOA is the DoE sites. The sites investigated (Savannah River, INEL, Oak Ridge, Hanford, Rocky Flats, and Fernald) appear to have enough linear footage in the range applicable to BOA that sufficient cost savings can justify buying BOA. Five of the six main sites (all but Fernald) have enough footage and projected savings to justify buying a system for each site's use. Since the scheduling of the asbestos abatement at the sites overlaps and is therefore being done in parallel, each site will likely need to purchase its own BOA system. Because Savannah River and Hanford have such a large amount of BOA-applicable abatement, depending on how quickly they need to complete the abatement work, they could each justify purchasing two systems, bringing the DoE total potential units to seven.

4.3 Customer Return on Investment Model and Analysis

Each of the potential customers identified above will ultimately evaluate the purchase of a BOA system based on achieving an adequate return on investment. A net present value (NPV) or other similar analysis will likely be performed to compare the initial investment and other associated costs to the anticipated benefits. If the net financial benefit from using BOA exceeds the costs over some reasonable payback period, then the contractor will have reasonable justification (and motivation) to purchase a BOA system. This analysis is essential to evaluating the commercial potential of this technology, as it helps to define the price threshold above which BOA will not provide a net benefit, and therefore will not be salable.

It should be noted that we have performed this analysis based on the industrial market segment's characteristics. This was done because this segment represents the bulk of the total potential sales, and the cost/benefit margins here are the narrowest. If BOA can be shown to be cost-effective and provide adequate return on investment in the industrial segment, the return in the DOE segment will only be higher.

A net present value model takes into consideration an initial investment (in this case, the purchase of a BOA unit) and a desired rate of return over a specified period of time. The resulting stream of 'payments' (in this case the net cost savings yielded by BOA) is then evaluated to determine if it yields the required rate of return. A positive NPV indicates that the actual rate of return meets or exceeds the desired rate, and that the investment is favorable/beneficial. A negative NPV indicates that the investment/payback are not favorable. The following NPV model was used to evaluate, from a contractor's perspective, the viability of purchasing and using BOA.

Based on this analysis, productivity improvements achieved by using BOA will yield sufficient cost savings to justify purchase by a contractor (positive NPV) so long as the purchase price is less than $125,000. We assumed that a contractor would require a nominal return on investment of 20% (typical of service-based industries). Investments/costs considered in this analysis include the initial purchase of BOA and annual maintenance costs (estimated at less than $2,000 per year). This cost stream is offset by income in the form of cost savings related to increase productivity with BOA. The value of BOA's productivity improvement was determined by comparison to the most likely alternative — hiring additional workers and performing the job manually.

The increase in productivity that BOA yields over a purely manual scenario is shown in Table 4.4:. In both scenarios, two asbestos workers are present and working full time. In the BOA scenario, productivity is increased over the period of the year in which BOA is used (we estimate approximately 25% utilization, primarily due to the restrictions on BOA's applicability at any given site and the need to transport and schedule BOA between multiple job sites). For the remaining 75% of the year, the two asbestos workers continue to work at their normal rate; this is added to the linear footage accomplished using BOA to determine a total annual productivity of the BOA scenario.

The productivity increase from using BOA is therefore calculated (on a feet per year basis) by subtracting the standard manual productivity (2 people working for one year) from the BOA scenario productivity. In essence, by owning and operating BOA, a contractor will complete an additional 13,500 ft each year with the same two person crew. This amount of work is equivalent to what could be accomplished by another 0.93 workers per year, therefore we have evaluated this based on the costs to the contractor associated with the added labor. This calculation included the worker's salary and insurance (worker's compensation), and personal protective equipment which would be consumed. Fringe benefit costs were not included, as we have found that many contractors in the industry do not pay these (temporary or part-time staff). Some added management and support costs will likely be incurred by adding personnel to a job, but the increment appears to be relatively small and has therefore been neglected here (the ratio of management/support to asbestos workers is on the order of 1 to 5 and absorbing an additional worker without adding other staff appears to be reasonable).

Table 4.4: Customer Return on Investment Analysis

Assumptions/Constants

Customer ROI rate 20% (industry standard for service business)

	Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Total
Investment/Costs	(125,000)	1,705	1,705	1,705	1,705	1,705	(116,475)
Income/Savings		44,063	44,063	44,063	44,063	44,063	220,314
Cash Flow	(125,000)	42,358	42,358	42,358	42,358	42,358	86,789
Cumulative Cash Flow	(125,000)	(82,642)	(40,284)	2,074	44,431	86,789	

Customer NPV: 1,397

Payback period: within 3 years

Productivity Increase Using BOA

BOA Ownership Scenario		Manual Scenario	
Boa Utilization Rate	25%		
Boa Hours Use per Year	520 hr		
Manual Hours/Year	1,560 hr	2,080 hr	
Boa w/2 person crew rate	40 ft/hr		
2 person crew rate (manual)	14 ft/hr	14 ft/hr	
Boa annual productivity	20,800 ft/yr		
Remaining manual productivity	21,840 ft/yr		*Productivity Difference*
Total	42,640 ft/yr	29,120 ft/yr	13,520 ft/yr more done using BOA Scenario

Annual Cost Differential Between BOA and Manual Scenarios

Annual asbestos worker wages	$31,886
Annual worker insurance	$9,566
Total direct labor per man-yr	$41,452
Protective Equipment $30/day	$6,000
Total cost per man/year	$47,452
Portion of man/yr saved by Boa	0.93
Annual Labor Savings via Boa	$44,063

Annual Maintenance Costs of BOA

Parts (.05% of purchase price)	$625
Labor (1.5 wks/yr @ $18/hr)	$1,080
Total	$1,705

Incorporating all estimated costs (purchase of BOA and maintenance) and income/savings, we determined that this would be an acceptable investment for a contractor (payback of the initial investment in BOA occurs within 3 years, which also fits the general requirements of most service businesses). The acceptability, and therefore likelihood that contractors will purchase BOA, is however strongly influenced by the purchase price of BOA. At a price only several thousand dollars greater than $125,000, the contractor will no longer achieve a 20% ROI and therefore may no longer be interested in this investment. In addition, the productivity increase achieved using BOA is also a critical variable. If the removal rate using BOA decreases significantly below 40 ft/hr then the cost savings will correspondingly decrease, thus making the NPV drop. BOA's utilization rate is also critical to the NPV result, however, we believe that 25% is a conservative number. Of these last two variables, utilization rate is perhaps the most important to focus on in the design of BOA: a 5% increase (i.e., achieving 30% annual utilization) will yield roughly a 20% increase in productivity, and therefore savings. Similarly, a 20% increase in productivity/savings can be achieved by a 13% increase in the removal rate using BOA.

Although this analysis derived the price acceptable by the commercial abatement industry, we also performed a preliminary estimate of manufacturing costs. We determined that this price ($125,000) is within reason, however, it is on the low end of our estimated range ($100,000 to $175,000). Until a more detailed design of the system is completed, more detailed estimates can not be made.

In conclusion, we believe that BOA will present sufficient return on investment to justify purchase by asbestos contractors. However, activities during the next phase of this development must drive to achieving the threshold purchase price ($125,000) and therefore manufacturing costs, as well as the maximum possible asbestos removal rate (at least 40 ft/hr) and utilization rate (at least 25%) to ensure commercial success.

4.4 Commercialization Investment Evaluation

How would a company decide to take on the commercialization of BOA? What is a reasonable investment in development? To answer these questions, we use the tools of business decision-making to quantify the costs, risks and returns. The analyses above establish certain key factors: performance requirements, unit price, total unit sales. We have also utilized the NPV method to evaluate a decision to invest in BOA commercialization (see Table 4.5:). In the analysis presented below, we set values for these variables as follows:

- **Total first-time sales:** We chose a sales estimate of 120 units, slightly below the average of the first-time estimates above.
- **Unit sales over time:** We assumed a general bell-shaped distribution to the sales over a six-year period, beginning with 10 systems in the first year and peaking at 40 in the third year. Five years is the expected field-life of the system, and thus this does not include significant replacement sales.
- **Revenues from sales:** We assumed a consistent unit price of $125,000, based on our analysis of the value of the system to the customer.
- **Net income from sales:** To estimate net income in dollars, we applied a target of 12% to the gross sales estimates (typical of this type of equipment and target market).
- **Rate of return on investment:** We assume a 25% target rate of return on investment. Given the risks of introducing an entirely new type of capital equipment to an industry that is not capital-intensive, this is minimum rate for a prudent investment.

With the initial values established above, we calculated the maximum up-front investment that can be justified from the expected commercialization, as per the table below. The positive cash flows for Years 2 through 7 represent the profits from sales; the negative cash flow in Year 1 represents the maximum that can be spent in pre-market development and still yield a positive net present value at the 25% rate of return.

Table 4.5: Company Return on Investment Analysis

Assumptions & Constants		
Manufactured Cost	$56,250	(estimated)
Gross Margin	55%	(industry standard for high-tech products)
Selling Price	$125,000	(calculated from gross margin)
Company ROI rate	25%	(industry standard for high-tech products
Net income rate	12%	(industry standard for high-tech products)
Net Income/unit	$15,000	(calculated from net income rate)

	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Total
Productization Costs	(900,000)							(900,000)
Sales in Units		10	25	40	25	10	10	120
Sales in $		1,250,000	3,125,000	5,000,000	3,125,000	1,250,000	1,250,000	15,000,000
Net Income		150,000	375,000	600,000	375,000	150,000	150,000	1,800,000
Cash Flow	(900,000)	150,000	375,000	600,000	375,000	150,000	150,000	900,000
Cum. Cash Flow	(900,000)	(750,000)	(375,000)	225,000	600,000	750,000	900,000	

Company NPV: 7,419
Payback period: within 4 years

Using the values discussed above, we calculate a maximum prudent investment of $900,000. This is the total justifiable outlay for engineering (redesign for manufacturing etc.), tooling, prototyping and testing before product roll-out. The model is quite sensitive:

- for each 1% decline in profit margin, the justifiable investment declines by $80,000;
- if the target rate of return (the perceived risk) increases by 5%, the investment declines by $90,000.
- if the manufactured cost rises 10%, without a corresponding increase in selling price, the justifiable investment drops nearly 40%.

The total market size – $15 million over seven years – suggests a commercial undertaking that would only be attractive to a small business. For a small business, an investment of $900,000 is a daunting 'bet the ranch' business decision. A prudent investor would seek to reduce the risks as much as possible. The first good way to reduce the risks is to share them with someone else. In the case of the BOA development program, the DoE represents a developer, an investor, and a customer, and thus has multiple mechanisms for reducing risk and inducing business investment to bring BOA to market.

A special consideration that a small business address before entering this market is that the market is small but dispersed geographically and among a large number of contractors (the top ten largest companies have only 15% of the market). Therefore, a successful marketing strategy must be adopted to minimize cost of sales. This implies the use of a distributor network which is already tied into the asbestos contractor market. DOE can serve as an important marketing vehicle: by providing a demonstration site, promoting the technology across the complex, and favoring use of this technology, DOE will facilitate more direct and immediate market penetration.

4.5 Conclusions

In the sections above we have used several methods to develop a model of the market with sufficient confidence to evaluate the commercialization potential for BOA, and to justify an investment in that activity. The analysis supports the following conclusions:

1. **Selling Price:** Given the costs of manual methods of asbestos abatement, and what the BOA developers predict as its utilization and productivity rates, the BOA selling price must be less than $125,000.
2. **Unit Cost:** To meet the unit gross margin and net income targets a commercial business would expect, the manufacturing cost of a BOA system cannot exceed $60,000. This cost target, along with the performance objectives (productivity and utilization rates) identified here, become the critical goals of further development.
3. **Potential Sales:** Given the size and structure of the asbestos abatement market, and assuming the price and performance characteristics as above, we project first-time sales of between 70 and 240 BOA systems total in the six years after commercial introduction. Based on our familiarity with the market and methods used to make this projection, we believe that the likely sales range is between 100 and 150.
4. **Business Size:** A market for 100 - 150 units, or $15 - 20 million over seven years, is a commercial undertaking that would only be attractive to small businesses. In addition, this small, decentralized market cannot likely support multiple suppliers.
5. **Justifiable Investment:** Depending on the evaluated risk of the market projections, the net income from the sales of 120 units over six years justifies an investment of $600,000 - 900,000 by the commercial partner. If the investment in further engineering and product refinement exceeds $600,000 - 900,000, some of the work must be funded from non-commercial sources.
6. **Further DoE Investment:** Given the calculated financial savings that the DoE can achieve through the application of BOA, and given the need to reduce the business partner's risks to encourage their commercialization role, we conclude that the DoE should invest along with the commercial partner to bring the technology to market.

5.0 Overall Impact

The purpose of this study is to determine if an automated pipe insulation removal system is cost-effective when compared with current manual abatement methods and associated job costs, and if cost-effective, to quantify the overall impact (including cost savings, regulatory issues, worker safety, and quality of work) on the Department of Energy if its development is pursued. Another important consideration is whether an automated system can be cost-effective in the general asbestos abatement market, and if so, what is the overall impact.

Chapter 2.0 Market Assessment described our approach to determine the **total number of linear feet of pipe on which the BOA system could be effective (lf)** for both the Department of Energy and the general industrial market segments. *Chapter 3.0 Cost-Benefit Analysis* detailed the model we used in our cost analysis, and the **savings per linear foot of pipe ($/lf)** predicted for the BOA system when compared to the current manual abatement techniques. In this section, we bring the results of the market and cost-benefit studies together to determine the **total predicted savings ($)** that could be realized by using BOA. Here we present the results of total predicted savings to the DoE using conservative, 'low-end' estimates and also determine savings predictions using 'medium' and 'high-end' savings per linear foot estimates to give a range of potential savings for the BOA system within the DoE market.

5.1 DoE Impact

As discussed in *Chapter 3.0 Cost-Benefit Analysis*, the cost savings per foot of the BOA system versus manual abatement varies depending on several factors. The cost savings of an automated abatement system depends on whether (i) the pipe run is indoors or outdoors, (ii) there is radiation contamination, and (iii) glovebagging is a permissible method of gross abatement within the state (or county or city) where the abatement is to take place. The total cost savings that could be realized by a given site is determined by these factors, as well as the total amount of pipe upon which a BOA system could be operational.

• **Total Cost Savings**

<u>'Low-end' estimates</u>

Table 5.1: and Table 5.2: present a summary the total predicted cost savings for each DoE site using the 'low-end' savings per linear foot estimates from our cost-benefit model. We conservatively estimate that the Department of Energy will save approximately $9.1 million over the life of its total asbestos abatement project.

Table 5.1: 'Low-end' cost savings estimates for sites at which *glovebagging is permitted*

SITE NAME		TOTAL PIPE APPLICABLE TO PIPE [LF]	PREDICTED SAVINGS PER LF OF PIPE [$/LF]	TOTAL PREDICTED SAVINGS	
Savannah River	Indoor (90% Rad[a])	60,000	$38.1	$2,286,000	$2,609,000
	Outdoor	19,000	$17.0	$ 323,000	
INEL	Indoor (25% Rad[a])	21,650	$29.3	$ 634,350	$1,018,210
	Outdoor	22,580	$17.0	$ 383,860	
Fernald	Indoor (25% Rad[b])	3,650	$29.3	$ 106,950	$ 478,900
	Outdoor	21,880	$17.0	$ 371,960	
TOTALS		**148,760**	**N/A**	**~ $4.1 MILLION**	

a. Estimate from site data
b. Assumed

Table 5.2: 'Low-end' cost savings estimates for sites at which *glovebagging is prohibited*

SITE NAME		TOTAL PIPE APPLICABLE TO PIPE [LF]	PREDICTED SAVINGS PER LF OF PIPE [$/LF]	TOTAL PREDICTED SAVINGS	
Oak Ridge	Indoor (15% Rad[a])	17,000	$41.6	$ 707,200	$ 990,700
	Outdoor	11,250	$25.2	$ 283,500	
Hanford	Indoor (20% Rad[a])	36,000	$42.6	$1,533,600	$2,478,600
	Outdoor	37,500	$25.2	$ 945,000	
Rocky Flats	Indoor (25% Rad[b])	22,290	$43.5	$ 969,600	$1,554,760
	Outdoor	23,220	$25.2	$ 585,140	
TOTALS		**147,260**	**N/A**	**~ $5.0 MILLION**	

a. Estimate from site data
b. Assumed

'Medium' estimates

Using the following list of values and assumptions (See Table 5.3:) in our cost-benefit model instead of the 'low-end' values listed next to them, new savings per linear foot values were calculated. Table 5.4: and Table 5.5: present a summary of the total predicted cost savings for each DoE site using these 'medium' savings per linear foot estimates from our cost-benefit model.

Table 5.3: Assumptions used in 'medium' cost savings estimates

	'medium' estimate	'low-end' estimate
% of scaffolding eliminated using BOA	20%	0%
% of clean-up and enclosure dismantling eliminated using BOA	20%	0%
Productivity rate of BOA (lf/hr)	60	40

The net effect on the predicted cost savings per linear foot of modifying these three assumptions is an additional $4.15/lf to the base (non-radiation) cost savings when compared to full-containment costs. The additional cost savings versus glovebagging is $1.80, since the effect of eliminating 20% of the clean-up and dismantling costs is not applicable in this case. Accounting for these additional $/lf savings by scaling the appropriate values in Table 5.1: and Table 5.2:, and using the upper estimates for total applicable market size at the various sites, leads to a total 'medium' savings prediction of approximately $11.1 million.

Table 5.4: 'Medium' cost savings estimates for sites at which *glovebagging is permitted*

SITE NAME		**TOTAL PIPE APPLICABLE TO PIPE [LF]**	**PREDICTED SAVINGS PER LF OF PIPE [$/LF]**	**TOTAL PREDICTED SAVINGS**	
Savannah River	Indoor (90% Rad[a])	70,000	$40.3	$2,821,000	$3,164,900
	Outdoor	19,000	$18.1	$ 343,900	
INEL	Indoor (25% Rad[a])	21,650	$31.3	$ 677,650	$1,086,350
	Outdoor	22,580	$18.1	$ 408,700	
Fernald	Indoor (25% Rad[b])	3,650	$31.3	$ 114,250	$ 589,370
	Outdoor	26,250	$18.1	$ 475,125	
TOTALS		**163,130**	**N/A**	**~ $4.8 MILLION**	

a. Estimate from site data

b. Assumed

Table 5.5: 'Medium' cost savings estimates for sites at which *glovebagging is prohibited*

SITE NAME		TOTAL PIPE APPLICABLE TO PIPE [LF]	PREDICTED SAVINGS PER LF OF PIPE [$/LF]	TOTAL PREDICTED SAVINGS	
Oak Ridge	Indoor (15% Rad[a])	23,700	$46.1	$1,092,570	$1,512,570
	Outdoor	15,000	$28.0	$ 420,000	
Hanford	Indoor (20% Rad[a])	42,000	$47.2	$1,982,400	$3,032,400
	Outdoor	37,500	$28.0	$1,050,000	
Rocky Flats	Indoor (25% Rad[b])	22,290	$48.3	$1,076,600	$1,726,760
	Outdoor	23,220	$28.0	$ 650,160	
TOTALS		**163,710**	**N/A**	**~ $6.3 MILLION**	

a. Estimate from site data
b. Assumed

'High-end' estimates

It can be seen from cost-savings calculations above that BOA is significantly more cost-effective when compared to full-containment manual abatement. If, in the future, the regulations change (like they are expected to) and glovebagging for gross abatement becomes prohibited by OSHA or by the states that now allow glovebagging (SC, ID, and OH), BOA's total cost savings could increase to over $13.7 million. The specific affect of this possibility is presented in Table 5.6:.

Table 5.6: 'High-end' cost savings estimates if *glovebagging is prohibited*

SITE NAME		TOTAL PIPE APPLICABLE TO PIPE [LF]	PREDICTED SAVINGS PER LF OF PIPE [$/LF]	TOTAL PREDICTED SAVINGS	
Savannah River	Indoor (90% Rad[a])	70,000	$62.2	$4,354,000	$4,886,000
	Outdoor	19,000	$28.0	$ 532,900	
INEL	Indoor (25% Rad[a])	21,650	$48.3	$1,045,700	$1,677,940
	Outdoor	22,580	$28.0	$ 632,240	
Fernald	Indoor (25% Rad[b])	3,650	$48.3	$ 176,300	$ 911,300
	Outdoor	26,250	$28.0	$ 735,000	
Oak Ridge	Indoor (15% Rad[a])	23,700	$46.1	$1,092,570	$1,512,570
	Outdoor	15,000	$28.0	$ 420,000	
Hanford	Indoor (20% Rad[a])	42,000	$47.2	$1,982,400	$3,032,400
	Outdoor	37,500	$28.0	$1,050,000	
Rocky Flats	Indoor (25% Rad[b])	22,290	$48.3	$1,076,600	$1,726,760
	Outdoor	23,220	$28.0	$ 650,160	
TOTALS		**326,840**	**N/A**	**~ $13.7 MILLION**	

a. Estimate from site data
b. Assumed

In summary, we estimate that, through the development of an automated asbestos pipe insulation removal system that can operate on pipes within a range of 4"-8" outside diameter, the **Department of Energy will save between $9.1 and $13.7 million** over the life of its total asbestos abatement project.

• Optimistic Savings Projections

In order to round out the potential savings projections, it would be interesting to explore the uppermost end of what potential savings the use of a BOA system could reap. If one asummes that the newly developed BOA system can access more pipe than the current one (40%), say 60%, and that the new cuting scheme would allow 50% faster abatement than currently estimated (namely 60 ft./hr. rather than the conservative 40 ft./hr.), and if we include a dollar value associated with high-radiation person-Rem savings of $10,000/person-Rem/yr., it is possible to predict savings for DoE that could be as high as $33 million over the life of its asbestos abatement program. Worker and liability insurance savings and those attributable to higher and more consistent quality of work were not included due to the fact that they were very hard to quantify up-front and could only be determined once the system was in use and insurance carriers decided on rates and the safety record of operators with a BOA system was better known.

• **% of DoE's Total Asbestos Pipe Insulation Abatement Costs that could be saved with BOA**

The commercialization assessment presented in the preceding chapter predicts that the DoE will need approximately five to seven BOA systems to meet the abatement needs and schedules of the sites listed above. The price estimate for a single BOA system to be used on pipes within the 4"-8" OD range is $125,000. We also estimate that over the five year life of a BOA system, replacement parts will cost an additional 5% of the total system cost per year, and repair labor (estimated at 6 weeks/year @ $18/hr) will cost $4,300/year. The total cost of a BOA system over its predicted five year life is therefore $135,500, totalling approximately $0.7 million for five units. Therefore, to optimize use of this technology and fully realize the predicted $9.1 to $13.7 million savings, the DoE will need to invest $0.7 million + the development cost of $2 million, totalling $2.7 million. The respective **return on investment for the DoE is therefore approximately 340% ($9.1M/$2.7M) to 500% ($13.7M/$2.7M).**

To determine the percentage of the Department of Energy's asbestos pipe insulation abatement costs the savings of $9.1 to $13.7 million represents, this savings is divided by the total job cost if the DoE were to abate all 1.9 million lf of its asbestos pipe insulation manually. Prior asbestos abatement job cost information from Hanford and Oak Ridge (K25) indicates that on average, indoor abatement jobs cost approximately $115/lf, and outdoor jobs cost approximately $75/lf. Of the 1.9 million lf of ACM-covered pipe within the DoE complex, approximately 1.5 million lf is indoors, and approximately 0.4 million lf is outdoors. Multiplying these linear footage estimates by the appropriate $/lf values gives a total of approximately **$203 million to manually abate all of the pipe within the DoE complex. Therefore, the percentage of overall DoE asbestos pipe insulation abatement costs that could be saved with an automated abatement system approximately 4.5% ($9.1M/$203M) to 6.7% ($13.7M/203M).**

This number compares favorably to figures released by the DoE in its most recent E&M report[1], stating that technology developments are predicted to save about $9 billion in a $200 billion Environmental Management Program. This translates to about a 4.5% reduction in overall costs and indicates that our projected savings figure is acceptable based on these DoE predictions.

Note that these savings can be realized by developing an abatement system that is targeted at a specific pipe range. If there is sufficient need by some of the larger DoE sites, additional, less costly robot systems for larger pipes could be developed to save even more ER&WM monies.

• **Radiation Exposure Savings**

It can be seen in Table 5.1: and Table 5.2: that a significant amount of the pipes within each of the DoE sites listed are within radiation contamination areas. Although specific details regarding the radiation levels (mRem/hr) present in these areas are not available, we have conservatively estimated that average contamination levels are 3-4 mRem/hr. Using our cost-benefit model, we predict that 0.23 person-hours/linear foot can be saved on runs of pipe on which BOA is used. Multiplying this by the estimated 75,650 linear feet within rad areas(see Table 5.7:), we predict that BOA can reduce human exposure to radiation by approximately 17,400 person-hours. This translates to a total radiation exposure savings of approximately 60 person-Rem within the pipe-range BOA is targeted on and applicable to.

1. US DoE - Office of Environmental Management, "Estimating the Cold War Mortgage: The 1995 Baseline Environmental Management Report", Volume 1, March 1995

Table 5.7: Total Radiation Exposure Savings

TOTAL LINEAR FEET (LF)	TOTAL RAD LINEAR FEET (LF)	AVG. TIME SAVINGS (HRS/LF)	AVG. EXPOSURE RATE (MREM/HR)	TOTAL PREDICTED EXPOSURE SAVINGS (REM)
300,000	75,650	0.23	3.5	~ 61

5.2 Industrial

The impact of cost savings due to the use of BOA in the industrial market segment is not as straightforward. The best example of the overall impact of this technology is its commercial potential. The commercialization of the BOA system is likely to (i) create jobs related to the production of the commercial systems, (ii) increase competitiveness and/or profits for the abatement contractors that use the BOA system, and (iii) ultimately lower abatement costs to facility owners. To bracket the impact of BOA we have calculated the overall cost savings for the industrial abatement market, we can use a similar approach to that for the DoE. Our industrial market assessment predicts that BOA will be applicable on approximately 1.5 million lf/yr. of pipe within this market segment. Through the cost-benefit analysis, evaluation of the costs associated with the current manual abatement techniques, and the estimates from the commercialization assessment for the number of BOA systems that can be sold in the industrial market segment, the following conclusions regarding potential total savings can be made:

• **Total Cost Savings**

We estimate that BOA will save approximately $3 per linear foot when compared to the costs associated with manual abatement, which is estimated at $15/lf (based on surveys of abatement contractors). The commercialization assessment predicts that approximately 100-150 BOA systems could be sold (at ~ $125,000/system) over the life of the asbestos abatement industry. Within our cost-benefit model, we assumed that BOA would be functional 25% of the working hours in a year (equalling approximately 520 hrs/yr.), would operate at 40 lf/hr, and have a life of approximately five years. The total number of linear feet of pipe a single BOA system can realistically be used on is then 500 x 40 x 5 = 100,000 lf/yr./system. Multiplying this by the total number of systems we expect to sell (125), this translates to 12.5 million lf/yr. If a system saves $3 per linear foot, a **potential cost savings of about $38 million per year** could be realized over the industrial market. Ultimately, over the 25 year predicted life of this market, the total cost savings could approach $1 billion. Although this cost savings will not go directly to any particular group or entity (as in the DoE case), it should yield more competitive abatement contractors and ultimately reduce the overall cost of abatement to facility owners.

5.3 Regulatory Impact

Although the BOA system will have a significant effect on how asbestos insulation is removed from pipes, its impact on the asbestos abatement regulations will be minimal. Within the OSHA regulations, BOA will be classified as an 'alternative control method' per 29 CFR 1926.1101 (g)(6). The only additional requirement of this section over and above compliance with the rest of the regulation is that a written evaluation of the use and effectiveness of the BOA system (by an industrial hygienist or asbestos project designer with a professional engineer license) must be submitted to OSHA on a case-by-case basis. EPA regulations do not specify how abatement must be performed, but rather present general work practices that must be followed. Specifically, these are 'no visible fiber emissions' and 'adequately wet the material prior to and during removal'. Further impact on these existing regulations is speculative at this point, and would only occur if backed up by actual test results over an extensive period of time. The limited scope of this project makes future alteration of any regulations specifically for the BOA system unlikely.

5.4 Worker Safety

A main reason robotic systems are developed for hazardous applications is to increase worker safety and decrease the occurrence of injuries and the associated liability. Although it is impossible to quantify, the BOA system will increase worker safety by reducing the need for human intervention in certain asbestos- (and sometimes radiologically-) contaminated environments. An automated abatement system could greatly reduce worker liabilities and litigation costs. In addition, such technology may have a significant impact on the costs associated with various types of insurance covering asbestos workers, including medical, worker's compensation, short-term and long-term disability, and life insurance.

5.5 Quality of Work

Through this study we have become aware that competition in the asbestos abatement industry has become fierce and abatement contractors have felt the need to 'bend' the regulated work practices to stay competitive. Corners are frequently cut, resulting in a lower quality of asbestos abatement work. In addition, worker productivity typically drops significantly when there is any form of direct supervision. Productivity also drops at the end of the day due to fatigue. The end result is a decrease in the quality of work and an increase in overall job time, and therefore, overall job cost.

In contrast, with a robotic abatement system, there is little need for supervision and the quality of work and regulatory compliance is consistent. An automated system that is designed to follow the regulations will work reliably at a constant rate. Along with cost savings from shorter job times, there is the security of knowing that the certified robotic system is consistently complying with the regulations. Such a capability will ultimately enhance the competitiveness of the abatement contractors using this automated abatement system.

5.6 Liability, Bonding and General Insurance

The use of BOA is expected to impact additional contractor costs in the areas of worker compensation, bonding and even liability insurance. Since BOA is expected to reduce worker force required for a particular job, it is expected that insurance costs associated with the workers will certainly be reduced. In the case that a contractor decides to use the same number of workers as on a manual job, but carry out the job faster than before through the use of BOA, savings would also be generated, but these are harder to actually quantify until real abatement data on the use of BOA becomes available.

Savings generated through reductions in lawsuits from sickened workers is probably not a big issue, since most of these past, current and pending lawsuits were filed by those that mined and aaplied the insulation material, rather than those that remove it, which are quite well protected by EPA and OSHA regulations. Bonding insurance savings will probably also not be realizable, because that amount of insurance is levied to ensure the abatement job is completed irrespective of what happens to the primary abatement contractor - BOA would not really impact that insurance amount unless it was guaranteed that another contractor would finish the job using a BOA-like system and hence be able to accomplish the job faster and/or cheaper than with a manual approach.

6.0 Conclusions and Recommendations

The results of this study indicate that BOA will be cost-effective for use in the Department of Energy's nuclear facilities, and that a total cost savings of $9 to $13 million will be realized by the DoE if this system is developed. In addition, evaluation of the potential of the BOA system for use in the industrial market segment indicates that this system, if developed, will be a commercially viable product. **It is therefore our recommendation that the development of the BOA pipe-insulation abatement system in Phase II be pursued.**

Along the course of this study, we determined many important criteria that affect the development of the BOA system, the market(s) in which it will be used, the predicted cost savings, and its commercial potential. The highlights of these are summarized as follows:

The BOA System

Through this market study and cost-benefit analysis, we have determined the critical design factors, and therefore design goals, for the BOA system to maximize its cost-efficiency. These include:

- Minimize the annular space taken up by the body of the removal unit. - (Goal = 3" outside insulation OD)
- Minimize the amount of human intervention needed at hangers and/or obstacles. (Goal = 10 minutes or less for both. Optimally, if the need for human assistance at hangers is reduced, much of the costs associated with the construction of scaffolding will be eliminated.)
- Maximize the abatement productivity on straight, clear runs of pipe. - (Goal = at least 40 lf/hr on straight runs)
- Ensure ease of use and interchangeability of the removal units.
- Reduce the size and weight of the removal units. - (Goal = a system that is easily assembled from pieces that are each below the Recommended Weight Limit (RWL) for overhead lifting as defined by NIOSH)
- Minimize part count, complexity, and other aspects of the design to reduce production costs. - (Goal = $60,000/unit)

Applicable Market Size

This market assessment focused on medium bore pipes (4"- 8" OD) due to (i) the variety of limitations that exist on the use of an automated pipe-insulation abatement system on small bore pipe (< 4" OD), and (ii), the evaluation of the most common pipe sizes within the DoE nuclear facilities that are greater than 4" OD. It was determined from evaluation of site data and estimation through site visits of the applicability of an automated abatement system on 4" - 8" OD pipe, that the BOA system will be applicable on approximately 300,000 lf of the 1,470,000 lf (or ~ 20%) of pipe within all six main DoE nuclear facilities.

In addition, the industrial market segment was also analyzed and quantified. Using survey results and data from an independent asbestos industry consultant and accounting for similar limitations on pipe size and applicability of the BOA system, it was estimated that there is approximately 1.5 million lf/yr. available for robotic abatement over a 25 year market life.

These estimates of total applicable linear footage within both the Department of Energy and industrial market were used to determine (i) the overall predicted cost savings, and (ii) the total commercial sales potential for BOA systems.

Cost-Benefit Analysis

The following conclusions were drawn with respect to the cost-benefit model developed for this study:

- $/lf values predicted by our model for manual abatement jobs are within +/- 5% of the actual job costs supplied by several DoE sites. Therefore, our cost-benefit model is valid.

- Through a sensitivity analysis on the factors within the cost-benefit model, we determined that there are several key factors that greatly affect the cost-effectiveness of the BOA system. These key factors are:
  - manual and robotic straight-run productivity
  - amount of human intervention needed at hangers and obstacles
  - wage of asbestos workers
  - radiation levels at the work site
- The cost of BOA effects the point at which the BOA system "pays for itself" (or, in other words, when it reaches its break-even point). The sales potential of the BOA system is therefore directly effected by its price, and in this respect, production costs will be kept to a minimum.
- Cost savings is predicted over both glovebagging and full-containment, although, in cases where glovebagging could be used but is prohibited by law, the cost-benefit of the BOA system increases by approximately 20%.

Predicted Savings

The cost savings predicted in this study are very conservative. If the guidelines on the technical development of BOA listed above are followed, the total savings can only go up. We expect that the DoE will see a return-on-investment (ROI) of between 340% and 500% ($9.1M to $13.7M return on $2.7M total investment). Through the development and use of the BOA system, the DoE will see a significant reduction in total worker radiation exposure as well (estimated at ~ 61 Rem). The total savings for the industrial market is estimated at approximately $38 million per year, approaching $1 billion over the 25 year life of the asbestos abatement industry.

Commercial Potential

We have determined that there is substantial market potential for an automated pipe insulation abatement system such as BOA. Using a variety of approaches, we preliminarily estimate that, if BOA systems were to be produced commercially, between 100 to 400 systems could be sold. We also estimate that the DoE should purchase five to seven BOA systems for use in five of the six main sites that have enough footage and projected savings to justify this purchase.

7.0 Additional Opportunities

7.1 Ground-based pipe insulation abatement system

In this report, we have predicted that an automated abatement system that travels along asbestos-containing-materials(ACM)-covered pipes and removes asbestos-containing-lagging-and-insulation-materials (ACLIM) in-situ will be cost-effective for the DoE and that it would have commercial potential for use in the industrial market segment. We have shown that there are significant amounts of pipe in both of these markets to warrant the development of the BOA system. At the same time, though, we have identified certain 'environments' where the use of such a system will be severely limited and/or not cost-effective. These 'environments' are characterized by large quantities of tightly-packed, small bore pipes (< 4" O.D.) where there is little to no annular clearance around the pipe within which the BOA system could travel. Our analysis assumed that all small bore pipe was of this nature, termed 'spaghetti', and was therefore not applicable to in-situ abatement by an automated on-pipe system.

There may, however, be a benefit to developing a ground-based abatement unit in addition to the 'in-situ' BOA unit described in this report. Utilizing the pipe-insulation abatement technology developed for the BOA system, a similar ground-based unit could be cost-effectively developed that could strip ACM from pipes as they are fed through the mechanism.

Background

Through our interviews and surveys of both DoE and industrial abatement contractors and project managers, we learned that, for Decontamination and Dismantlement (D&D) projects involving gross abatement of small bore pipe, the most cost-effective, and therefor preferred method of abatement is the 'wrap-and-cut' method. This method involves wrapping sections of pipe in 6-mil poly-sheet, glovebagging the ends to clear the asbestos insulation from 1 to 2 foot sections, cutting the pipe at these cleared sections, and taking the entire length of wrapped pipe (with ACM still attached) out of the facility and into storage inside a lined container.

A current disposal method at the DoE facilities involves placing the entire 'wrap-and-cut' length of pipe into hazardous waste bins. The ACM and the pipe together become waste that is classified as either asbestos-containing waste, or even worse, if the pipes were removed from irradiated areas, the entire length of pipe must be handled and disposed of as mixed waste (nuclear-contaminated asbestos-containing waste). Currently, there is no acceptable method of disposal for this type of mixed waste, and therefore, DoE sites (such as Fernald) that have previously removed ACM from radiation areas are now storing on site hundreds of containers filled with radiation/ACM waste that they are unable to legally send to a landfill. In addition, waste disposal costs are proportional to volume, but the amount of waste that can be placed in a given container is limited by weight. This creates a situation where, due to the weight of the pipes themselves (and not the ACM), large waste containers reach their weight limit when they are only about a third to half full. The remaining un-used sections of the containers are either 'topped off' with bags of asbestos waste if the weight limit has not been reached, or if this limit has been reached, the remaining volume on top of the pipes is left empty. This creates a situation where the DoE is effectively paying to bury significant volumes of air.

To manage this problem, the DoE is investigating various waste-vitrification techniques that may be used to alter the asbestos waste in some manner as to change its chemical composition, making it non-carcinogenic. The goal of this process is two fold: (i) separation of waste(s), and (ii) volume reduction. It is predicted that a significant cost savings will be realized by using this technology to reduce the problem(s) associated with the disposal of radiologically-contaminated ACM. In addition, it is estimated that an approximate 80% volume reduction of this ACM waste will be possible. The down side to the 'wrap-and-cut' method with respect to this vitrification process is that, for the process to be most efficient, the large pieces of pipe must be separated out prior to the waste entering the system.

Use of a ground-based pipe-insulation abatement system

A system that strips the ACM off the pipes that have been removed by the 'wrap-and-cut' method could accompany this waste vitrification unit, creating a total system that would be cost-effective for disposal of both irradiated - and non-irradiated contaminated pipe ACM waste.

- Radiation-contaminated ACM waste

  A significant amount of radiation-contaminated ACM waste (over 50% at Fernald) is still attached to the removed pipes. A ground-based unit could separate this waste, allowing for vitrification, volume reduction, and disposal of the ACM waste itself, as well as disposal of the new ACM-free pipes through other radiation-contaminated metal disposal technologies. A considerable cost savings could be realized using this technique when compared to existing methods. Disposal through burial of low-level radiologically contaminated ACM-waste, which represents about 30 to 50% of all small-bore piping across the DoE complex, typically runs about $1,200/cu. yd.[1]

- Non-radiation ACM waste

  A ground-based pipe insulation abatement unit should be cost-effective for use in the disposal of uncontaminated ACM waste as well. Using a combined stripper/vitrification system, pipes that would have otherwise been classified as asbestos-contaminated waste could now be disposed of or recycled as regular scrap steel. The ACM waste, after vitrification (and therefor volume reduction), could also be sent to a landfill as standard, non-hazardous waste. This process would be applicable to 50 to 70% of the small-bore piping across the DoE complex. Typically, uncontaminated asbestos disposal costs about $14/cu. yd.[2]

At this time, due to limited information, we are unable to quantify what total savings may be realized by the DoE through the development of a ground-based unit, but we predict that, since the design will be leveraged heavily on the technology developed for the BOA project, the development costs for such a system will be minimal. The break-even point to cover this development cost should therefore be relatively 'quick' to reach. The total potential market for this technology would be about 40% of piping that is subject to demolition (the percentage of pipe < 4" OD).

7.2 Market Increase Speculation - The regulatory future of fiberglass insulation

Currently, there is great speculation and debate over whether fiberglass insulation should be added to the federal government's list of carcinogens. Many scientific studies have concluded that fiberglass is not carcinogenic[3], while others have reached the opposite finding.[4] The Department of Health & Human Services (DHHS), which, along with OSHA has the final regulatory say in this issue, has not reached a verdict yet, although the National Toxicology Program, which reports to the DHHS, recently listed fiberglass as a carcinogen in the 7th Annual Report on Carcinogens, Fall 1994. Should fiberglass insulation be deemed a carcinogenic material, and therefore have regulations imposed regarding its removal, BOA's applicable market would increase drastically. At this time, this possibility remains remote.

1. Estimate from Bechtel-Hanford, Inc.
2. Estimate from FERMCO, Inc.
3. "Asbestos: The Big Lie", 21st Century Magazine, Environment Section, Winter 1993-1994, pp.58 - 59
4. "Fiberglass, NTP on Trial next week", Science, Vol. 262, October 1993

VII. Appendices

Appendix A - Regulatory Appendix

Regulations and Notification Forms Listings

Federal

•OSHA:

29 CFR 1926.1101 Asbestos. *Federal Register, Department of Labor, Occupational Safety and Health Administration, 29 CFR 1910, et al., Occupational Exposure to Asbestos; Final Rule, Wednesday, August 10, 1994.*

•EPA:

40 CFR Part 61, Subpart M- Asbestos. *Federal Register, Environmental Protection Agency, National Emission Standards for Hazardous Air Pollutants (NESHAPs), Tuesday, November 20, 1990.*

State

•Ohio:

Chapter 3745-20 - Asbestos Handling. *Ohio Administrative Code, Title 3745, July 1994*

Ohio Environmental Protection Agency Notification of Demolition and Renovation

Chapter 3701-34 - Ohio Department of Health, Asbestos Hazard Abatement Rules. *Ohio Administrative Code, Title 3745, Amended February 1, 1994*

Ohio Department of Health Application for Certification

Section 3710 - Asbestos Abatement Law. *Ohio Revised Code, October 8, 1992*

Ohio Department of Health Prior Notification of Asbestos Hazard Abatement Project

•Tennessee:

Chapter 1200-3-11-.02 Asbestos - Hazardous Air Contaminants. *Rules and Regulations of the State of Tennessee, Tennessee Department of Environment and Conservation, Bureau of Environment, Division of Air Pollution Control*

Tennessee Division of Air Pollution Control Notification of Asbestos Demolition and Renovation

•Pennsylvania:

Commonwealth of Pennsylvania Department of Labor and Industry Application for Asbestos Occupation Certification

Commonwealth of Pennsylvania Asbestos Abatement and Demolition/Renovation Notification

Local

•Allegheny County:

Chapter X - Toxic or Hazardous Air Pollutants, Section 1001 - Asbestos Abatement. *ARTICLE XX - Rules and Regulations of the Allegheny County Health Department, Bureau of Air Pollution Control - County Ordinance No. 16782, July 1, 1989*

Allegheny County Health Department Asbestos Abatement Permit Application

Allegheny County Asbestos Abatement Contractor License Application

Contact List

Occupational Safety and Health Administration (OSHA)

OSHA		
Federal:	**Regional:**	**Local:**
Office of Health Standards: Ms. Carol Jones, or Ms. Maria Walters (Asst.) OSHA Health Standards Room N3718 200 Constitution Ave., NW Washington, D.C. 20210 Ph: (202) 219-7174 Office of Health Compliance: Ms. Wanda Bissell, or Mr. Gail Brinkerhoff U.S. Dept. of Labor - OSHA DCP Room N3467 200 Constitution Ave., NW Washington, D.C. 20210 Ph: (202) 219-8036	Region 3 (PA): Mr. Jim Johnston Regional Administrator U.S. Dept. of Labor - OSHA 3535 Market St., Rm 2100 Philadelphia, PA 19104 Ph: (215) 596-1201 Region 5 (OH): 230 South Dearborn St. 32nd Floor, Rm 3255 Chicago, IL 60604 (312) 353-2220 Region 4 (TN): 1375 Peachtree St., NE Suite 587 Atlanta, GA 30367 (404) 347-3573	Allegheny County, PA: Ms. John Morris OSHA - Allegheny Co. 1000 Liberty Ave. Federal Bldg., Rm 1428 Pittsburgh, PA 15222 Ph: (412) 644-2903

Environmental Protection Agency (EPA)

EPA			
Federal:	**Regional:**	**State:**	**Local:**
Enforcement & Compliance: Mr. Tom Ripp U.S. EPA - 2223A 401 M Street, SW Washington, DC 20460 Ph: (202) 564-7003	Region 3 (PA): Mr. John Daly Asbestos Coordinator (3HW-42) EPA Region 3 841 Chestnut Bldg. Philadelphia, PA 19107 (215) 597-1970	PA (Worker Certifications): Dept. of Labor and Industry Asbestos Occupations Accreditation and Certification P.O. Box 60246 Harrisburg, PA 17105	Allegheny Co., PA (Notifications): Mr. Jim Stanko Allegheny Dept. of Health Bldg. 7 - Asbestos Sec. 301 39th St. Pittsburgh, PA 15201 Ph: (412) 578-8133
New Regs/ R&D: Mr. Jim Crowder, or Mr. Sims Roy U.S. EPA OAQPS/EDS MD - 13 Research Triangle Park, NC 27711 Ph: (919) 541-5569 -JC Ph: (919) 541-5263 -SR	Region 4 (incl. TN): Ms. Alfreda Freeman Asbestos Coordinator (P&TSB) 345 Courtland St., NE Atlanta, GA 30365 Ph: (404) 347-5014 (Atl)	OH (Worker Certifications): Mr. Marty King Ohio Dept. of Health P.O. Box 118 Columbus, OH 43266-0118 Ph: (614) 466-1460	Hamilton Co., OH (Notifications): Mr. Bradley Miller Hamilton County Dept. of Env. Services 1632 Central Parkway Cincinnati, OH 45210 Ph: (513) 333-4731
	Region 5 (incl. OH): Ms. Lolita Hill Asbestos Coordinator (T-SPTB-7) U.S. EPA SP - 14J 77 West Jackson Blvd. Chicago, IL 60604 Ph: (312) 353-1621	TN (Notifications): Mr. Jackie Waynick, or Mr. Bobby Jernigan TN Dept. of Environment and Conservation Air Pollution Control Division 9th Floor, L&C Annex 401 Church Street Nashville, TN 37243-1531 Ph: (615) 532-0570	

Department of Energy (DoE)

DoE	
Site	**Contact**
Fernald	Dave Tashjian (Fermco) - (513) 738-8697 Rick Heath (Fermco) - (513) 648-6291, Rick.Heath%em@mailgw.er.doe.gov Brad Thompson (Wise Construction) - (513) 738-6372
Oak Ridge	Roy Sheely, Asbestos Abatement Project Manager (Martin Murietta) - phone: (615) 576-7742, pager: (615) 873-9850, fax: (615) 241-2533 Paul Larson, Asbestos Abatement Project Engineer (Martin Murietta) - (615) 574-9905 Sylvia Parsons, Engineering Assistant to Roy - phone: (615) 241-4810, pager: (615) 873-6185 Julian Daniel, Documentation (Martin Murietta) - phone: (615) 241-2307, pager: (615) Scott Anderson, Radian Corp. (surveying) - phone: (615) 483-9870. -9061 fax, 220-8168 direct
Hanford	Mark Ganaski, Program Mgr for asbestos abatement, Washington, DC (DOE) - phone: (301) 427-1775, fax: (301) 427-1598 Jeff Bruggemen, Program Mgr for asbestos abatement @ Hanford (DOE) - phone: (509) 376-7121, fax: (509) 376-4360 Brad Mewes (Bechtel Hanford Inc.) - (509) 373-5496
INEL	Neil Allen, Asbestos Coordinator (Lockhead) - (208) 526-5007 George Clark, Rad. Con. Supervisor (Lockhead) - phone: (208) 526-3565, fax: (208) 526-8959
Savannah River	Ms. Pat Stone(DOE) - (803) 725-1192 Mr. L.P. Singh, (DOE OSHA) - (803) 725-3962 Caroline Bruns, Asbestos Coordinator- (803) 952-7154 Paul McDonagh, Asst to Ms. Bruns- (803) 952-7157 Murry Angvall, Estimating - (803) 952-5733
Rocky Flats	Tom Grethel, Dir of Occ. Health and Safety (DOE) - (303) 966-7632 Dero Sargent, Dir. of Stds, Performance, and Assurance (Tom's boss) (DOE) - (303) 966-6222

Samples of Notification and Permit Forms

This appendix lists the following forms for several different states:

STATE	AGENCY	FORM TITLE
Tennessee	Tennessee Division of Air Pollution Control	Notification of Asbestos Demolition or Renovation
Ohio	Ohio Environmental Protection Agency	Notification of Demolition and Renovation
	Ohio Department of Health	Application for Certification
		Prior Notification of Asbestos Hazard Abatement Project
		Application for Asbestos Contractor Licensure
Pennsylvannia	Commonwealth of Pennsylvania Department of Labor & Industry	Application for Asbestos Occupation Certification
	Commenwealth of Pennsylvania Department of Environmental Resources (sent to Allegheny County Health Dept.)	Asbestos Abatement and Demolition/Renovation Notification
	Allegheny County Health Department	Asbestos Abatement Permit Application
		Asbestos Abatement Contractor License Application

Appendix B - Cost-Benefit Model

Model Definitions - Equations, Variables, Constants and Dependents

In order to fully understand the model developed to calculate the realizable savings for the BOA system, it is important to understand the overall structure of the model and the individual constants, variables and calculations being performed therein. The overall structure of the model is as shown in Table 9.4:. The top-most table section contains the costing categories used to develop the cost comparison figures. The lower portion of the table contains all the individual variables, constants and intermediate computed numbers grouped by whether they are related to the manual or robotic abatement approach or whether they are used to describe the characteristics of a job site. Each of these categories and variables/constants and dependents has been given a variable name (see Table 9.4:), and the equations developed for certain fields have also been detailed (see Table 9.1:).

A more in-depth explanation and detailed make-up of all the constants, variables, dependents and all related equations is given below:

Model Nomenclature - Costing Categories

The individual variable names assigned in the model can be detailed as follows:

•*Manual Abatement*

–Manual Removal Costs [\$/ft] : $R_{\$m} = W_{awm} \{ \left(\frac{1}{P_m}\right) [(1 - C_s - L_{so}) + (B_{mf} C_s) + (O_{mf} L_{so})] \}$

Manual removal costs account for the cost to remove the insulation off the entire pipe-network. Thus, costs are based on a modified (incl. materials such as respirators and suits) hourly wage of the asbestos worker (W_{awm} [\$/hr]) and the worker productivity (P_m [ft./hr]) as applied to the length of piping that is free of obstructions, including a percentage reflecting obstacles (L_{so} [%]) and the reality that obstacles take longer to abate (O_{mf}). In addition, should the piping runs have a certain percentage of baked-on insulation pipe-runs (C_s [%])due to corrosion, we reflect that by increasing the time needed for abatement (B_{mf}).

- Setup Costs [\$/ft] : $S_{\$m} = (W_{cpr} + W_{lbr}) \{ \left(\frac{1}{P_m}\right) [(1 - C_s - L_{so}) + (B_{mf} C_s) + (O_{mf} L_{so})] \}$

Setup costs reflect the need for carpenters and laborers to set up the site, build scaffolds, etc. The computation is based on the fact that carpenters and laborers spend a fraction of the asbestos worker's time on the job. This fraction is based on prior abatement jobs and is about 16/21 (see K-25 data sheet). As such, the equation is identical to the removal cost equation, except that the asbestos worker wage has been replaced with those of the carpenter (W_{cpr} [\$/hr]) and the laborer (W_{lbr} [\$/hr]).

Currently, this cost is not calculated into our average model, but could be a source of additional savings should the envisioned robot allow for operations with reduced need for scaffolding. By setting carpenter effort labor savings to zero, no savings will be able to be realized by the robot.

	MANUAL ABATEMENT		ROBOTIC ABATEMENT	
Removal Costs (AWs only)	$R_{\$m}$	$/ft	$R_{\$r}$	$/ft
Set-Up Costs (Carp. & Laborers only)	$S_{\$m}$	$/ft	$S_{\$r}$	$/ft
Radiation Exposure Costs (AW & Carpenters ONLY)	$E_{\$m}$	$/ft	$E_{\$r}$	$/ft
Operator Costs	-		$O_{\$r}$	$/ft
Tender Costs [assisting BOA at hangers(abatement) & obstacles(handling)]	-		$N_{\$r}$	$/ft
Total Labor Costs: Asbestos Workers, Carpenters and Laborers	$T_{\$m}$	$/ft	$T_{\$r}$	$/ft
Total: AW Manhours/foot	T_{mm}	man-hrs/ft	T_{rm}	man-hrs/ft.
Percentage Manhour Savings (Manual vs. Robotic)	-		S_{rm}	%
Additional labor costs due to longer manual job	$L_{\$m}$	$/ft	-	
Additional Exposure Costs due to longer manual job	$E_{\$ma}$	$/ft	-	
TOTAL COST	$M_{\$}$	$/ft	$R_{\$}$	$/ft
TOTAL PERCENT SAVINGS	N/A		$S_{\%}$	%

MANUAL	CONST/VARS		COMPUTED	
Prevailing Hourly Wage (Asbestos Worker - AW)	W_{aw}	$/hr	W_{awm}	$/hr (incl. mat)
Prevailing Hourly Wage (Carpenters - Carp)	W_{cp}	$/hr	-	
Prevailing Hourly Wage (Laborer - Lab)	W_{lb}	$/hr	-	
Prevailing Hourly Wage (Support Personnel - Sup)	W_{sp}	$/hr	-	
Prevailing Hourly Wage (Project Manager - Prj.)	W_{pr}	$/hr	-	
Manual Straight-Run Productivity	P_m	ft/man-hr	-	
Manual Brushing - Production Reduction Factor	B_{mf}	-	-	
Obstacle - Productivity Reduction Factor	O_{mf}	-	-	
Radiation Exposure Cost (Comm. Nuclear)	R_{ec}	$/ManRem	-	
High Radiation Contamination Levels (Comm. Nuclear)	R_{lev}	mRem/hr	-	
Low contamination (LC) Manhour Increase Factor (DoE)	R_{mil}	%	-	
High contamination (HC) Manhour Increase Factor (DoE)	R_{mih}	%	-	
Carpenter Wage (16/21 of AW cost - ratio of avg. %s at K-25 job)	$W_{\%cp}$	%	W_{cpr}	$/hr
Laborer Wage (16/21 of AW cost - ratio of avg. %s at K-25 job)	$W_{\%lb}$	%	W_{lbr}	$/hr
Support Pers. Wage (1/4 of AW cost - K-25 estimate)	$W_{\%su}$	%	W_{spr}	$/hr
Project Manager Wage (1/7 of AW's hrs. - Means Const. Estimating Guide)	$W_{\%pr}$	%	W_{prr}	$/hr
Carpenter Labor effort reduction due to mechanized system	H_{cpr}	%	-	
Addt'l material costs per AW man-hr ((4 resps+tyvex suit)/8 hrs)	-		W_{mat}	$/hr
ROBOTIC				
BOA Abatement Productivity on straight-run piping	P_r	ft/hr	-	
BOA Equipment Cost	E_r	$/unit	-	
BOA Ammortization Time	L_r	yrs	-	
Abatement Operating Hours per year	O_r	hrs/yr	-	
Percentage of time BOA is in use per year	U_r	%	-	
Productivity of BOA & Tender at hangers	P_{rh}	hrs/ft of hanger	-	
Productivity of BOA & Tender at obstacles	P_{ro}	hrs/ft of hanger	-	
Annual BOA Replacement parts cost	M_{rp}	$/yr	$R_{rp\%}$	%
Annual BOA Repair Labor	M_{rl}	$/yr	R_{ml}	wks/yr
Annual BOA Availability	-		A_r	hrs/yr
Hourly BOA Maintenance Costs	-		M_r	$/hr
Hourly BOA Equipment Costs	-		W_r	$/hr
SITE				
Average Hanger Spacing	H_s	ft	-	
Average Obstacle Spacing	O_s	ft	-	
Characteristic Length of Hanger	L_{shc}	ft	-	
Characteristic Length of obstacle	L_{soc}	ft	-	
Cumulative obstacle length as % of entire pipe-run	-		L_{so}	%
Cumulative hanger length as % of entire pipe-run	-		L_{sh}	%
Percentage of corroded Pipe	C_s	%	-	
Average Level of HC radiation	R_{sl}	mRem/hr	-	
% of piping with LC (DoE)	$R_{\%l}$	%	-	
% of piping with HC (DoE)	$R_{\%h}$	%	-	

Table 9.1: Cost/Benefit model structure and list of variables

EQUATION DEFINITIONS			
MANUAL		**ROBOTIC**	
$R_{\$m}$	$W_{awm}\{(\frac{1}{P_m})[(1-C_s-L_{so})+(B_{mf}C_s)+(O_{mf}L_{so})]\}$ Manual Removal Costs (incl. obstacles, bake-on} [$/ft]	$R_{\$r}$	$W_r(\frac{1}{P_r})\{1-(L_{so}+L_{sh})\}+\left\{W_{aw}\left(\frac{O_{mf}}{P_m}\right)L_{so}(1+B_{mf}C_s)\right\}$ Robotic Removal Costs (excl. hangers & obstacles) [$/ft]
$S_{\$m}$	$(W_{cpr}+W_{lbr})\{(\frac{1}{P_m})[(1-C_s-L_{so})+(B_{mf}C_s)+(O_{mf}L_{so})]\}$ Setup Costs (proportional to removal costs) [$/ft]	$S_{\$r}$	$(W_{cpr}+W_{lbr})(1-H_{cpr})\{(\frac{1}{P_m})[(1-C_s-L_{so})+B_{mf}C_s+O_{mf}L_{so}]\}$ Setup Costs (prop. to manual removal costs) [$/ft]
$E_{\$m}$	$(R_{\$m}+S_{\$m})(R_{mil}R_{\%l}+R_{mih}R_{\%h})+\left(\frac{2}{P_m}\right)(R_{sl}-R_{lev})\frac{R_{ec}}{1,000}R_{\%h}$ Human Exposure Costs in radiation environments [$/ft]	$E_{\$r}$	$\left(W_{aw}\left(\frac{L_{so}}{P_m}\right)+S_{\$r}+O_{\$r}+N_{\$r}\right)(R_{mil}R_{\%l}+R_{mih}R_{\%h})+2\left(\frac{1}{P_m}\right)(R_{sl}-R_{lev})\frac{R_{ec}}{1,000}R_{\%h}$ Human Exposure Costs in radiation environments [$/ft]
$T_{\$m}$	$\Sigma\{R_{\$m}+S_{\$m}+E_{\$m}\}$ Total Costs: Asbestos Workers and Carpenters [$/ft]	$O_{\$r}$	$W_{awm}\{(\frac{1}{P_r})(1-L_{so}-L_{sh})+P_{rh}L_{sh}+\frac{1}{P_m/O_{mf}}L_{so}\}$ Operator Wage Costs during BOA operations [$/ft]
T_{mm}	$\left\{\left(\frac{(1-L_{so})+L_{so}O_{mf}}{P_m}\right)\right\}\{1+B_{mf}C_s\}(1+R_{mil}R_{\%l}+R_{mih}R_{\%h})$ Labor manhours per foot (to calc. time savings) [man-hrs/ft]	$N_{\$r}$	$W_{awm}(P_{rh}L_{sh}+P_{ro}L_{so})$ Tender Wage Costs during hanger/obstacle clearing [$/ft]
$L_{\$m}$	$(T_{mm}-T_{rm})(W_{awm}+W_{cpr}+W_{lbr}+W_{spr}+W_{prr})$ Additional laborer cost due to incr. manual abatement time [$/ft]	$T_{\$r}$	$\Sigma[R_{\$r}+S_{\$r}+E_{\$r}+O_{\$r}+N_{\$r}]$ Total costs for robotic operations [$/ft]
$E_{\$ma}$	$(T_{mm}-T_{rm})(1+W_{\%cp}+W_{\%lb}+W_{\%su}+W_{\%pr})\,x\left((R_{sl}-R_{lev})\frac{R_{ec}}{1,000}R_{\%h}\right)$ Additional Exposure costs due to longer manual job [$/ft]	T_{rm}	$\left\{\left(\frac{1-(L_{sh}+L_{so})}{P_r}\right)+2P_{rh}L_{sh}+\left[\frac{O_{mf}}{P_m}(L_{so}(1+C_sB_{mf}))\right]\right\}x\,(1+R_{mil}R_{\%l}+R_{mih}R_{\%h})$ Labor manhours per foot (to calc. total abatement time) [man-hrs/ft]
$M_\$$	$T_{\$m}+L_{\$m}+E_{\$ma}$ Total manual abatement costs [$/ft]	S_{rm}	$(T_{mm}-T_{rm})/T_{mm}$ Percentage Abatement Job Time Reduction [%]
W_{awm}	$W_{aw}+W_{mat}$ Asbestos Worker Hourly Wage incl. materials [$/ft]	$R_\$$	$T_{\$r}$ Total cost of robotic abatement [$/ft]
W_{cpr}	$W_{aw}W_{\%cp}$ Relative Wage Ratio for carpenters w.r.t. asb. workers [$/ft]	$S_\%$	$(M_\$-R_\$)/M_\$$ Total percent savings for removal portion on a job [%]
W_{lbr}	$W_{aw}W_{\%lb}$ Relative Wage Ratio for laborers w.r.t. asb. workers [$/ft]	M_{rp}	5% of E_r Estimated part replacement costs per year as 5% of capital costs [$/yr]
W_{spr}	$W_{aw}W_{\%sp}$ Relative Wage Ratio for support pers. w.r.t. asb. workers [$/ft]	M_{rl}	6 weeks per year; 5 days per week; 8 hrs per day; $40.-/hr. Estimated maintenance labor costs per year [$/yr]
W_{prr}	$W_{pr}W_{\%pr}$ Relative Wage Ratio for Project Mgr. w.r.t. asb. workers [$/ft]	A_r	O_rU_r Availability of robot for removal based on schedule, maint., etc. [hrs/yr]
W_{mat}	[4 ($22/respirator) +$15/tyvex-suit] /8 Material costs per day per person (4 exchanges/8-hr day) [$/hr]	M_r	$(M_{rp}+M_{rl})/A_r$ Hourly robot maintenance costs per year (parts & labor) [$/hr]
		W_r	$E_r/(A_rL_r)+M_r$ Hourly robot operational costs per year [$/hr]
		L_{so}	L_{soc}/O_s Cumulative percentage of obstacle length on site per job [%]
		L_{sh}	L_{shc}/H_s Cumulative percentage of hanger length on site per job [%]

Table 9.1: Cost/Benefit model computational equations

- Human Exposure Costs [$/ft] : $E_{\$m} = (R_{\$m} + S_{\$m})(R_{mil}R_{\%l} + R_{mih}R_{\%h}) + \left(\frac{2}{P_m}\right)(R_{sl} - R_{lev})\frac{R_{ec}}{1,000}R_{\%h}$

Exposure of human workers to radiation, irrespective of what level can be calculated in two ways. The first is more tangible, in that it accounts for the fact that productivity is reduced, since more time is spent getting in and out of the work-area and more protective clothing and procedures are needed. The second is less tangible, but reflects that costs can be saved if human exposure, as measured in man-Rems per year, is kept below the official limit (3 man-Rem/yr. at DoE). Note that we are not counting exposure to carpenters nor laborers.

As such, we assume that additional costs are incurred on-site for extended abatement time during removal ($R_{\$m}$ [$/ft.]) and setup ($S_{\$m}$ [$/ft.]), depending on the present levels of low (R_{mil} [mRem/hr]) and high (R_{mih} [mRem/hr]) contamination and their relative prevalence ($R_{\%l}$ [%] and $R_{\%h}$ [%], respectively). In addition, using a basic cost per man-Rem (R_{ec} [$/man-Rem]), the actual level of high radiation (R_{lev} [mRem/hr]), a cut-off level below which continuous exposure is not an issue (R_{sl} [mRem/hr]), and the percentage of piping with high contamination levels ($R_{\%h}$ [%]), one can compute the exposure cost to both workers on a per linear foot basis by knowing their productivity (P_m [ft./hr]).

- Total Labor Costs [$/ft] : $T_{\$m} = \Sigma\{R_{\$m} + S_{\$m} + E_{\$m}\}$

The total labor costs per linear foot of piping, is simply the sum of all manual costs accrued during the removal process, namely the actual asbestos worker removal cost ($R_{\$m}$ [$/ft.]), the setup costs for carpenters and laborers ($S_{\$m}$ [$/ft.]) and the radiation exposure costs due to slow-down and man-Rem savings ($E_{\$m}$ [$/ft.]).

- Total Asbestos Worker Productivity [man-hr/ft] : $T_{mm} = \left\{\left(\frac{(1-L_{so}) + L_{so}O_{mf}}{P_m}\right)\right\}\{1 + B_{mf}C_s\}(1 + R_{mil}R_{\%l} + R_{mih}R_{\%h})$

It is necessary to determine the net abatement productivity of the manual approach, in order to ascertain the overall time savings that a robotic system might have over a manual approach in terms of productivity and radiation exposure reduction. The proposed way is to compute the human productivity [man-hrs/ft.], and then compare it to the robotic productivity.

Average manual productivity is computed by computing productivity on straight runs of piping, excluding obstacles (L_{so} [%]) which are abated at a slower rate (O_{mf}), abated at a specified rate (P_m [ft./hr]), while accounting for the fraction of corroded pipe (C_s [%]) which will exhibit bake-on and thus require more time to abate (B_{mf}), as well as the fact that the presence of low and high radiation levels (R_{mil} and R_{mih}, respectively) to varying degrees ($R_{\%l}$ and $R_{\%h}$, respectively) will reduce/increase the productivity/abatement time.

- Total Cost [$/ft] : $M_{\$} = T_{\$m}$

The total cost for manual removal, based on a per linear foot basis, is simply the total labor cost ($T_{\$m}$ [$/ft].). This figure can now be used to compute per-linear-foot and percentage labor-cost savings for the robotic abatement approach.

•*Robotic Abatement*

- Robotic Removal Costs [$/ft] : $R_{\$r} = W_r\left(\frac{1}{P_r}\right)\{1-(L_{so}+L_{sh})\} + \left\{W_{aw}\left(\frac{O_{mf}}{P_m}\right)L_{so}(1+B_{mf}C_s)\right\}$

Robotic removal costs are computed for the robot working on straight runs of piping, excluding hangers which are abated with the assistance of the tender, while the obstacles are also left for the tender to remove. Straight-run and hanger abatement costs are based on a per-hour cost of the machine, namely a computed hourly operating cost of the machine (W_r [$/hr]), the productivity of the robot (P_r [ft./hr]) and the effective percentage of piping, excluding hangers (L_{sh} [%]) and obstacles (L_{so} [%]). Additional costs are computed for the abating of obstacles, based on the hourly wage of the asbestos worker (W_{aw} [$/hr]), the manual removal productivity (P_m [ft./hr]), the percentage of obstacles present (L_{so} [%]), the productivity reduction on obstacles (O_{mf}) and the slow-down factor (B_{mf}) on the percentage of corrosion and bake-on present on these obstacles (C_s [%]).

- Setup Costs [$/ft] : $S_{\$r} = (W_{cpr}+W_{lbr})(1-H_{cpr})\left\{\left(\frac{1}{P_m}\right)[(1-C_s-L_{so})+B_{mf}C_s+O_{mf}L_{so}]\right\}$

Setup costs for the robotic abatement approach are similar to those of the manual approach, except that we are accounting for the possibility of reducing the need for equally elaborate scaffolding setups, and hence can reap the benefits from labor hour reductions.

Setup costs reflect the need for carpenters and laborers to set up the site, build scaffolds, etc. The computation is based on the fact that carpenters and laborers spend a fraction of the asbestos worker's time on the job. This fraction is based on prior abatement jobs and is about 16/21 (see K-25 data sheet). As such, the equation is identical to the manual removal cost equation, except that the asbestos worker wage has been replaced with those of the carpenter (W_{cpr} [$/hr]) and the laborer ($W_{lbr}$ [$/hr]), and that we are accounting for the reduction in needed carpenter and laborer support (H_{cpr}).

Currently, this cost is not calculated into our average model, but could be a source of additional savings should the envisioned robot allow for operations with reduced need for scaffolding. By setting carpenter effort labor savings to zero, no savings will be able to be realized by the robot.

- Human Radiation Exposure costs [\$/ft] : $E_{\$r} = \left(W_{aw}\left(\frac{L_{so}}{P_m}\right) + S_{\$r} + O_{\$r} + N_{\$r} \right)(R_{mil}R_{\%l} + R_{mih}R_{\%h}) + \left(\frac{2}{P_m}\right)(R_{sl} - R_{lev})\frac{R_{ec}}{1,000}R_{\%h}$

Since even the robotic abatement approach involves human tenders and operators, we will have to account for costs associated with their presence in irradiated environments. Again, we have identified two cost categories, involving increased abatement time due to radiation procedures, and potential man-Rem exposure cost savings related to radiation levels.

Costs associated with the tender assisting in removal of insulation around hangers ($N_{\$r}$ [\$/ft.]), handling the robot around obstacles and removing the insulation on said obstacles ($W_{aw}(L_{so}/P_m)$), the exposure during setup ($S_{\$r}$ [\$/ft.]), and the exposure of the operator ($O_{\$r}$ [\$/ft.]), whom we assume is also present in the contaminated area, can all be applied to the increased time spent in the contaminated area which has certain distributions of low ($R_{\%l}$ [%]) and high ($R_{\%h}$ [%]) contamination and certain increased abatement factors (R_{mil} and R_{mih}). In addition, potential man-Rem exposure cost could be incurred for the tender and operator (2) based on their exposure time, as expressed by the manual productivity (P_m [ft./hr]), the level of relative radiation present (R_{sl}-R_{lev}), the percentage of high contamination on the job ($R_{\%h}$ [%]) and the cost figure attached to a cumulative man-Rem of exposure (R_{ec} [\$/man-Rem]).

- Operator Costs [\$/ft] : $O_{\$r} = W_{awm}\left\{\left(\frac{1}{P_r}\right)(1 - L_{so} - L_{sh}) + P_{rh}L_{sh} + \frac{O_{mf}}{P_m}L_{so}\right\}$

The operator will be present during the entire operation of the robotic abatement system, and hence will add labor costs to the robotic abatement system. We are assuming here that the operator receives an equal wage to that of the asbestos worker.

The costs of the operator are hence evaluated based on his/her hourly wage (W_{awm} [\$/hr]), the productivity of the robot (P_r [ft./hr]) on the sections of straight-run piping which excludes hangers (L_{sh} [%]) and obstacles (L_{so} [%]), plus the inverse productivity of the tender assisting the robot (P_{rh} [hr/ft.]) at hangers (L_{sh} [%]) and the manual productivity (P_m [ft./hr]) on obstacles (L_{so} [%]) with a productivity reduction factor (O_{mf}).

- Tender Wage Costs [\$/ft] : $N_{\$r} = W_{awm}(P_{rh}L_{sh} + P_{ro}L_{so})$

The tender spends a portion of his time also assisting the robot in removing the insulation off hangers (L_{sh} [%]) at a certain rate (P_{rh} [hr/ft.]), as well as handling the robot around obstacles (L_{so} [%]) at a certain rate (P_{ro} [hr/ft.]), while getting paid the modified asbestos worker wage which includes materials such as respirators and suits (W_{awm} [\$/hr]).

- Total Cost for Robotic Operations [\$/ft] : $T_{\$r} = \Sigma\,[R_{\$r} + S_{\$r} + E_{\$r} + O_{\$r} + N_{\$r}]$

The total costs per linear foot for robotic abatement are simply the sum of the removal costs for straight piping runs and obstacles ($R_{\$r}$

[\$/ft.]), setup costs ($S_{\$r}$ [\$/ft.]), exposure costs ($E_{\$r}$ [\$/ft.]), operator ($O_{\$r}$ [\$/ft.]) and tender ($N_{\$r}$ [\$/ft.]) costs.

Total man-hours per foot [man-hrs/ft] : $T_{rm} = \left\{ \left(\frac{1-(L_{sh}+L_{so})}{P_r} \right) + 2P_{rh}L_{sh} + \left[\frac{O_{mf}}{P_m} (L_{so}(1+C_sB_{mf})) \right] \right\} (1+R_{mil}R_{\%l}+R_{mih}R_{\%h})$

The computation to determine the average productivity of the robotic abatement approach is based on the sums of robot productivity on straight runs of piping, tender assistance productivity around hangers, and overall manual productivity of insulation removal around obstacles, even in the presence of corrosion, with an overall slow-down due to potential presence of radiation which affects the operator and tender.

Given the straight-run robot productivity of the robot (P_r [ft./hr]) on straight run of piping, excluding hangers (L_{sh} [%]) and obstacles (L_{so} [%]), the tender-assisted and operator backup (2) hanger abatement productivity (P_{rh} [hr/ft.]) on hanger sections (L_{sh} [%]) and the abatement of obstacles (L_{so} [%]) based on manual productivity (P_m [ft./hr]), reduction in productivity (O_{mf}) and the bake-on productivity reduction ($1+C_sB_{mf}$), one can apply the standard time-increase relation due to additional job-time because of radiation procedures ($1+R_{mil}R_{\%l}+R_{mih}R_{\%h}$).

- Percentage manhour savings [%] : $S_{rm} = ((T_{mm} - T_{rm}) / T_{mm})$

The percentage in time savings of the robotic approach over the manual approach can be computed as a ratio of the difference between the manual (T_{mm} [man-hrs/ft.]) and robotic (T_{rm} [man-hrs/ft.]) abatement man-hours, and the total manual abatement labor hours (T_{mm} [man-hrs/ft.]).

- Total Cost per linear foot [\$/ft] : $R_{\$} = T_{\$r}$

The total cost per linear foot for the robotic abatement approach is purely the previously calculated total man-hour per foot cost.

- Total percent savings [%] : $S_{\%} = ((M_{\$} - R_{\$}) / M_{\$})$

The total percent savings defines the percentage savings over the manual abatement labor costs. As such, this number can be flatly applied to the labor costs of any typical job (based on the case studies) to calculate the overall savings in real dollars. The percentage savings is the ratio of the difference between per-foot cost of the manual abatement cost ($M_{\$}$ [\$/ft.]) and the total robotic abatement cost ($R_{\$}$ [\$/ft.]) and the total manual abatement cost ($M_{\$}$ [\$/ft.]).

Model Input Variables

The model input variables are grouped into three separate groups relating to the manual abatement variables, those needed to describe the robotic abatement approach, and then those variables deemed necessary to generally describe a selected case-study, building, facility, site or even market segment. Each of these groups is further detailed below:

•*Manual Abatement*

- W_{aw}: *Prevailing Hourly Wage - Asbestos Worker; [$/hr]*

  The asbestos worker is the person that stands at the pipe and physically removes the lagging and insulation off the pipe. He/she collaborates with the rest of the crew during the abatement process. As required by law, two workers are required to abate a glovebag at a time.

  The hourly wage of the asbestos worker, depending on whether it is prevailing or competitive, is an important factor in these calculations. Numbers vary anywhere from $21.- to $50.- an hour depending on the commercial or government settings.

- W_{cp}: *Prevailing Hourly Wage - Carpenter; [$/hr]*

  The carpenter is the person that erects all the scaffolding, provides access to all pipes for the asbestos worker, and sets up all barriers and structures to isolate the work area from the rest of the world.

  The hourly wage paid the carpenter is on a sliding scale with that of the asbestos worker. Again this figure is dependent on whether the abatement is commercial, government or commercial nuclear.

- W_{lb}: *Prevailing Hourly Wage - Laborer; [$/hr]*

  The laborer is used to aid the carpenters and the asbestos workers in ferrying materials and supplies, assisting in the building of scaffolds and containments, ferrying waste bags inside and out of containment, etc.

  The hourly wage paid the laborer is also linked to the asbestos worker and depends on the type of abatement job, but is typically between $10 and $18 per hour.

- W_{sp}: *Prevailing Hourly Wage - Support Personnel; [$/hr]*

  The support personnel are those people supporting the abatement personnel on the inside by providing materials, doing the paperwork, checking the site every day and reporting back to the contractor.

  Their hourly wage is independently fixed and depends on the contractor and/or operator, but is around $45 per hour.

- W_{pr}: *Prevailing Hourly Wage - Project Manager/Supervisor; [$/hr]*

  The project manager/supervisors are persons that oversee the overall job on-site and off-site. On average it is budgeted that about 1 manager is required for every 7 workers, whether on-site or not.

  Their wage is also independent of the job, and is estimated (based on job data) at around $55 per hour.

- $W_{awm} = W_{aw} + W_{mat}$: *Asbestos Worker Modified Wage; [$/hr]*

The modified hourly asbestos worker wage includes the materials that are used on an hourly basis (W_{mat} [$/hr]) by a worker who takes up to 4 breaks during a working day, and hence consumes respirator(s) and cartridges as well as tyvex (disposable) suits. The number is obtained through addition of the prevailing hourly wage and the hourly material costs.

- P_m: *Manual Abatement Productivity; [ft./hr]*

The manual abatement productivity is an important number as it describes the net rate at which insulation is removed, and can be used to set job costs as well as abatement duration. Typically this number is described in feet abated per man-hour. In essence this number does reflect the regulatory requirement that two people per glovebag do the abatement, and then their productivity is reflected in a per man-hour number. The actual numbers very widely, and typically go from 3 feet per hour in a DoE environment to about 6 to (supposedly) even 9 feet per hour. We strongly believe, that the latter number is not physically achievable without severely 'bending' the regulations, which most often occurs in commercial abatement settings. In DoE and commercial nuclear settings, we strongly believe in, and have gotten good corroborations that 3 to 4 feet per man-hour is a valid number to use.

- B_{mf}: *Manual Brushing Productivity Reduction Factor; []*

Some times due to internal or external seepage of moisture which condenses on the pipe, the pipe corrodes and traps fibers/paper that are part of the insulation. Removal of this 'product' after several decades, requires strong brushing, sometimes even with wire-brushes. As such, since the operations are performed inside a glovebag, it takes more time to abate a glovebag section. Typically, corrosion effects are strongest along welded/bolted pipe-seams, valves, etc., which are obstacles in our world. Typical numbers we have been able to glean from contractors is that factors between 25% to 50% more time (1.25 to 1.5) are realistic numbers for such scenarios.

- O_{mf}: *Obstacle Productivity Reduction Factor; []*

Abating insulation around an obstacle such as a valve, junction, bend, etc. is a more lengthy job, due to the trickier glovebag setup and then access to all surfaces and cleaning of all the possibly contaminated areas. Typical numbers we are using are based on the abatement industry, and run anywhere from an additional 15% to 25% in required abatement time (factor is hence between 1.15 to 1.25).

- R_{ec}: *Radiation Exposure Cost; [$/man-Rem]*

One way to compute long-term costs associated with cumulative radiation exposure, is to attach a cost to the annual man-Rem a worker is exposed to. This number is always hotly debated, but it is typically in the range of $5,000 to $10,000 per man-Rem, and we have even heard of numbers as high as $25,000/man-Rem. Typically, allowable cumulative exposure limits range from 3 to 5 man-Rem per year, and hence additional protection or reduced working time for any worker, based on an average annual work-period of around 2,000 hours lies in the 1.5 to 2.5 mRem/hr exposure.

Our model accounts for this scaled exposure cost, with the ability to set the threshold and the cost-figure, both numbers we have currently set at 1.5 mRem/hr and $2,000/man-Rem.

- R_{lev}: *High Radiation Contamination Level; [mRem/hr]*

The radiation Exposure level denotes the level below which cumulative annual exposure, based on a total of around 2,000 hours per work-year, will not result in any excessive cumulative dose for a human. The absolute exposure levels vary for DoE and commercial nuclear sites, but they typically lie in the 3 to 5 man-Rem per year. The puts this number between 1.5 and 2.5 mRem/hr. This level also represents a contamination below which no additional protection beyond the asbestos protection is necessary. Once above that level, reduced exposure times and additional protection and check-in/out procedures become the rule.

- R_{mil}: *Low Contamination (LC) Manhour Increase Factor; [%]*

An alternate approach to account for short-term cost when working in radiation environments, is to consider the additional time required to perform suit-up/dn and scanning procedures, which in turn reduce the available daily remediation timespan and hence lower the daily man-hour productivity. A typical DoE approach is to split the man-hour increase factor into two factors: one for low radiation and one for high radiation.

The low-radiation factor has been set to lie at around 30%.

- R_{mih}: *High Contamination (HC) Manhour Increase Factor; [%]*

The high contamination manhour increase factor is similar to the LC-factor, except that is up to debate at what radiation level this factor should be used. Current practice seems to point at placing that threshold between 2.5 to 5 mRem/hr, with our model using the low-end of the range.

The high-radiation factor has been set to lie at around 100%, based on DoE-specific numbers reliant on past job experience.

- $W_{\%cp}$: *Carpenter Wage Ratio; [%]*

Based on previous DoE abatement costing figures[1], it was determined that for each asbestos worker a certain fraction of a carpenter is needed to perform the setup tasks. For the DoE market segment, that number has been determined to be about 16/21, or 0.762.

- $W_{\%lb}$: *Laborer Wage Ratio; [%]*

Similarly to the carpenter wage ratio, there is a certain fraction of a laborer associated with each asbestos worker. This number has also been determined from the same source, and is currently pegged at 16/21, or 0.762.

1. Oak Ridge Abatement Job, K-25 Area, Package 19 and Vaults, MK-Ferguson Comp. Estimates are based on percentage for each labor category out of the total labor cost for the job.

- $W_{\%su}$: *Support Personnel Wage Ratio; [%]*

  Similarly to the carpenter wage ratio, there is a certain fraction of a support person associated with each asbestos worker. This number has been determined from discussions with on-site personnel and accounts for security guards, escorts, etc. That number is currently pegged at 1/4, or 0.250.

- $W_{\%pr}$: *Project Manager/Supervisor Wage Ratio; [%]*

  Based on an official construction industry estimation document[1], it is recommended to apportion 1 project manager or supervisor for every 7 people on the job. In order to be conservative, we assumed this ratio to apply to the asbestos workers, and hence applied the 1/7 ratio as the percentage, i.e. 14.3%.

- $W_{cpr} = W_{aw}W_{\%cp}$: *Carpenter Wage - Revised; [$/hr]*

  Based on the previously determined ratio, the carpenter wage is adjusted as a fraction of the asbestos worker wage.

- $W_{lbr} = W_{aw}W_{\%lb}$: *Laborer Wage - Revised; [$/hr]*

  Based on the previously determined ratio, the laborer wage is adjusted as a fraction of the asbestos worker wage.

- $W_{spr} = W_{aw}W_{\%su}$: *Support Wage - Revised; [$/hr]*

  Based on the previously determined ratio, the support person wage is adjusted as a fraction of the asbestos worker wage.

- $W_{prr} = W_{aw}W_{\%pr}$: *Project Manager Wage - Revised; [$/hr]*

  Based on the previously determined ratio, the project manager wage is adjusted as a fraction of the asbestos worker wage.

- W_{mat} = *{4($22.- per respirator) + $15.-/tyvex suits}/8: Material Costs; [$/hr]*

  On DoE and commercial nuclear jobs, asbestos workers typically take about 4 breaks every shift (assumed to be 8 hours), and each time don a new tyvex suit and a new respirator - the contaminated ones are sent off for cleaning and are not wiped clean on site and immediately re-used as is the case in commercial settings. Each (assumed half-face) respirator is $22.- and the total cost per shift per worker for the disposable suits amounts to about $15.- (these numbers were obtained from several on-site representatives who deal with contractors on a daily basis).

- H_{cpr}: *Carpenter Effort Labor Reduction Factor due to mechanized system; [%]*

  Due to the use of the robotic abatement system, we expect to need less scaffolding and carpentry labor, since the robot can run on straight runs and past hangers, and only needs to be accessed at obstacles. We currently believe that about 20% less setup will be needed, in essence reducing manpower requirements for carpenters and associated laborers.

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1. Means Facilities Construction Cost Data, 10th Annual Edition, 1995, R.S. Means Company

•*Robotic Abatement*

- *P_r: Robot Abatement Productivity on straight-run piping; [ft./hr]*

The robotic abatement system has an inherent removal rate based on the locomotion and cutting speeds along the pipe. This number is used to capture the rate of removal without any assistance from either tender nor operator along straight runs of piping, and should be compared to the human productivity.

This number is not applicable at hangers nor obstacles, where we currently expect some human supervision and intervention, respectively. At hangers the tender will aid in the removal of the lagging, and perform a final clean-up and inspection to ensure that the hanger is clean. At an obstacle, the tender will remove the robot from the pipe, and re-emplace it on the pipe beyond the obstacle to continue abatement, and then glovebag the obstacle and abate the insulation (if he/she has not already done so).

- *E_r: Robot Equipment Cost; [$/unit]*

In order to determine an hourly operating cost for the robot, it is imperative to bracket the projected manufactured per unit cost of the robot system currently under conceptualization and design. This estimate includes purely material and labor costs to assemble and offer for sale a single such robotic abatement unit. Current estimates cause this number to lie somewhere between $50,000.- and $75,000 each.

- *L_r: Robot Life/Amortization Time; [yrs]*

The cost of the robot is amortized over the expected life of the robot itself, as measured in years. Currently a 5-year timespan has been allocated, which compares favorably with the life-span of other small-scale equipment of the same scale and frequency of usage, such as pipe-crawlers. Through a proper maintenance and repair schedule, this time-span could be increased, directly affecting the bottom-line profits for a contractor operating such a machine.

- *O_r: Abatement Operating Hours per year; [hrs]*

In order to calculate an hourly operating cost for the robot, on needs to determine the available hours per year, that this machine could be available to perform an abatement jobs. We use a standard of 2,080 hours per year in this category.

- *U_r: Percentage of time robot is in use per year; [%]*

Since the robot will not be operating each working hour every year due to scheduling, job availability and transport, a factor needs to be applied to the annual working hours to determine the true number hours per year this machine will really be in operation. Current estimates, based on contractor and DoE feedback, bracket this number between 15% and 30%. If properly scheduled and operated, these numbers could increase drastically, which would make the hourly operating cost decrease in direct proportion.

- *P_{rh}: Productivity of robot and tender at hangers; [hr/ft.]*

The current robot concept has the robot straddling the hanger, and giving access to the intricacies of the hanger to the assisting tender. The tender is expected to remove the lagging around the hanger (should there be any), and then perform a final hand-held pressure-jet cleanup of the intricate surfaces on the hanger, before the robot proceeds locomoting past the hanger on its own and continues to abate insulation past the hanger.

The time currently estimated for the tender to be present at the hanger and aid in abating that section, lies at around 15 minutes or about 0.25 hrs/ft. (we are assuming a 1-foot section around the hanger needs to be abated with human assistance).

- P_{ro}: *Productivity of robot and tender at obstacles; [hr/ft.]*

In the case of obstacles, we account for the tender (and possibly the operator) to abate that obstacle using conventional glovebag methods, while the tender needs to physically remove the robot off the pipe, and re-emplace it on the pipe beyond the obstacle for continued abatement of straight-run piping.

In order to be conservative, we have set this number at about 15 minutes (large overestimate) or about 0.5 hrs/ft., since we are assuming an obstacle of about 2 feet in length. In reality we expect this number to be much smaller.

- $R_{rp\%}$: *Percentage of per unit cost needed as annual parts cost; [%]*

In order to determine the annual replacement parts cost of the robot system, we use a flat percentage figure based on the per-unit cost to determine the actual parts cost. A good number to use, based on our experience and discussions with commercial robotic systems manufacturers, is a flat rate of 5%.

- $M_{rp} = E_r R_{rp}$: *Annual robot replacement parts cost; [$/yr]*

As mentioned above, the annual cost of replacement parts is based on a percentage of the capital equipment costs.

- R_{ml}: *Number of weeks per year spent maintaining the robot; [wks/yr]*

In order to maximize the life-expectancy of the robot, it should be put on a regular maintenance cycle. Based on our estimates, we believe that a bi-monthly week-long (at most) maintenance and repair cycle should be more than sufficient to keep the system operating optimally. These conditions set this number then at 6 weeks per year.

- M_{rl}: *Annual robot maintenance labor costs: [$/yr]*

Based on the number of maintenance weeks per year, the fact that there are 5 working days per week and 8 hours per working day, and we assume a machine-shop level hourly-wage of $18.- per hour, one can compute the actual annual maintenance labor costs.

- $A_r = O_r U_r$: *Annual robot availability [hrs/yr]*

Based on the number of hours per year and the percentage availability/usage per year, one can compute the actual number of hours per year that robot system will be in operation on a pipe.

- $M_r = (M_{rp}+M_{rl})/A_r$: *Hourly BOA Maintenance Costs (Parts & Labor); [$/hr]*

The hourly maintenance costs for the robot, can be simply computed by adding the annual parts and labor costs, and dividing by the time the robot is in actual abatement operations.

- $W_r = M_r + E_r/(A_rL_r)$: *Hourly robot Operating Cost; [$/hr]*

  The actual hourly operating cost, or 'wage-cost' of the robot, is simply computed by adding the hourly maintenance cost (parts and labor) to the hourly capitalized cost of the robot itself (dividing the capital cost by the annual robot availability figure.

•*Site Description*

- H_s: *Average Hanger Spacing; [ft.]*

  Based on review of construction guidelines and site-visits, we determined that the lowest average hanger spacing is about 10 feet. Some hangers are as closely spaced as 8 feet, but some go as far as 20 to 30 feet.

- O_s: *Average Obstacle Spacing; [ft.]*

  Average obstacle spacing depends largely on the type of installation one works in, but we determined a good average number to be no less than 20 feet, with 50 feet being a high-end on the estimate.

- L_{shc}: *Characteristic Hanger length; [ft.]*

  Characteristic hanger length relates to the length of insulation left around a hanger for the robot to remove in a tender-assisted manner. Our current design would place this number at about 1 foot.

- L_{soc}: *Characteristic Obstacle Length; [ft.]*

  A characteristic obstacle length which the tender/operator would be required to abate using standard glovebag techniques, depends on the type of obstacle and the size of the pipe. We believe that a good average number, allowing the worker to use a single 3-foot glovebag, lies around 2 feet. Most junctions and bends can really be cleaned to within 6 inches of the obstacles by the robot (leaving 12 inches to be cleared), but some valves can be rather large (but less frequent) and thus a 2-foot estimate seemed reasonable.

- $L_{so} = L_{soc}/O_s$: *Cumulative obstacle length as percentage of piping-runs; [%]*

  In order to determine the percentage of hanger-length per straight-run of piping, one can simply compute the average footage taken up by hangers through a ratio of the characteristic hanger length and its spacing along a pipe.

- $L_{sh} = L_{shc}/H_s$: *Cumulative hanger length as percentage of piping-runs; [%]*

  In order to determine the percentage of obstacle-length per straight-run of piping, one can simply compute the average footage taken up by obstacles through a ratio of the characteristic obstacle length and its spacing along a pipe.

- C_s: *Percentage of corroded piping-runs; [%]*

  Since know that human workers slow down if they have to brush a pipe clean should it be corroded and have entrapped fibers, we need to quantify the percentage of piping that might be corroded to properly account for manual productivity slowdowns. In the case of the robotic abatement system, corrosion has no effect, as it operates on the premise that it always has to clean the pipe surface irrespective of its state.

- R_{sl}: *Average level of on-site high contamination radiation levels; [mRem/hr]*
Certain sites might have high levels of contamination which figures directly into increased abatement time and accruing exposure costs. The level of radiation of additional exposure costs is linearly dependent on this figure and is thus case-sensitive.

- $R_{\%l}$: *Percentage of piping with low contamination levels; [%]*
In order to properly account for radiation effects in terms of manual productivity slow-downs and potential exposure cost increases, it is necessary to describe a site or case with an average figure of how much of the site is contaminated with low-level radiation. The bracket of radiation that describes low-level is currently set between 0.1 to 2.5 mRem/hr.

- $R_{\%h}$: *Percentage of piping with high contamination levels; [%]*
In order to properly account for radiation effects in terms of manual productivity slow-downs and potential exposure cost increases, it is necessary to describe a site or case with an average figure of how much of the site is contaminated with high-level radiation. The bracket of radiation that describes high-level is currently set at any contamination level above 2.5 mRem/hr.

Example Calculation

In order to illustrate the results of the proposed model, we have run a fictitious variable set for a non-contaminated DoE-site (see Table 9.4: on page 126), where the variables are all non-zero and set to average levels, based on our knowledge of the range on these variables. The resulting tabular representation is shown in . Note that the important result relates to the relative percentage savings in labor costs per linear foot, which in this case is ~\$9.^{30}.-/ft., or about 40% of the manual removal labor cost. Additionally, if the robot system competes with full-containment, an additional savings of about \$29.^{50}.-/ft. can be added to the overall savings. These figures could now be applied to the total linear footage within a building or a site and thus total savings calculated rather easily. As shown in ,

Example Savings calculation for average DoE piping abatable by a robotic system

CATEGORIES	Glovebagging		Containment	
Manual Removal Labor Cost	23.^{02}	\$/ft.	23.^{02}	\$/ft.
Robotic Removal Labor Cost	13.^{73}	\$/ft.	13.^{73}	\$/ft.
Relative Case-study Labor Savings	9.^{30}	\$/ft.	9.^{30}	\$/ft.
Addt.'l Savings due to lack of encl.	-	\$/ft.	29.^{50}	\$/ft.
Total Labor Savings	9.^{30}	\$/ft.	38.^{80}	\$/ft.
Total piping footage within site	155,000	feet	145,000	feet
Total realizable savings on site	1,441,500	\$	5,626,000	\$
TOTAL SAVINGS	**\$7,068,000.-**			

the current robotic system design could save as much as $7,068,000.- in abatement labor costs for glovebag and full-containment scenarios, which is the rough breakdown of piping within the DoE that are within the size-range of the robot and also reachable by the robot (clearances, etc.). Not included in this estimates are the costs of disposal nor post-treatment of the removed insulation.

	MANUAL ABATEMENT		ROBOTIC ABATEMENT	
Removal Costs (AWs only)	12.45	$/ft	1.70	$/ft
Set-Up Costs (Carp. & Laborers only)	18.96	$/ft	18.96	$/ft
Radiation Exposure Costs (AW & Carpenters ONLY)	0.00	$/ft	0.00	$/ft
Operator Costs	-		3.04	$/ft
Tender Costs [assisting BOA at hangers(abatement) & obstacles(handling)]	-		2.77	$/ft
Total Labor Costs: Asbestos Workers, Carpenters and Laborers	31.41	$/ft	26.47	$/ft
Total: AW Manhours/foot	0.34	man-hrs/ft	0.11	man-hrs/ft.
Percentage Manhour Savings (Manual vs. Robotic)	-		63	%
Additional labor costs due to longer manual job	24.10	$/ft	-	
Additional Exposure Costs due to longer manual job	0	$/ft	-	
TOTAL COST	**55.51**	$/ft	**26.47**	$/ft
TOTAL SAVINGS	**N/A**		**29.04**	$/ft.
TOTAL PERCENT SAVINGS	**N/A**		**52**	%

MANUAL	CONST/VARS		COMPUTED	
Prevailing Hourly Wage (Asbestos Worker - AW)	24	$/hr	36.88	$/hr (incl. mat)
Prevailing Hourly Wage (Carpenters - Carp)	21	$/hr	-	
Prevailing Hourly Wage (Laborer - Lab)	14	$/hr	-	
Prevailing Hourly Wage (Support Personnel - Sup)	24	$/hr	-	
Prevailing Hourly Wage (Project Manager - Prj.)	40	$/hr	-	
Manual Straight-Run Productivity	3	ft/man-hr	-	
Manual Brushing - Production Reduction Factor		-	-	
Obstacle - Productivity Reduction Factor		-	-	
Radiation Exposure Cost (Comm. Nuclear)	2,000	$/ManRem	-	
High Radiation Contamination Levels (Comm. Nuclear)	1.5	mRem/hr	-	
Low contamination (LC) Manhour Increase Factor (DoE)	30	%		
High contamination (HC) Manhour Increase Factor (DoE)	100	%		
Carpenter Wage (16/21 of AW cost - ratio of avg. %s at K-25 job)	76	%	28.10	$/hr
Laborer Wage (16/21 of AW cost - ratio of avg. %s at K-25 job)	76	%	28.10	$/hr
Support Pers. Wage (1/4 of AW cost - K-25 estimate)	25	%	6.00	$/hr
Project Manager Wage (1/7 of AW's hrs. - Means Const. Estimating Guide)	14	%	5.71	$/hr
Carpenter Labor effort reduction due to mechanized system	0	%	-	
Addt'l material costs per AW man-hr ((4 resps+tyvex suit)/8 hrs)	-			$/hr
ROBOTIC				
BOA Abatement Productivity on straight-run piping	40	ft/hr	-	
BOA Equipment Cost	75,000	$/unit	-	
BOA Ammortization Time	5	yrs	-	
Abatement Operating Hours per year	2,080	hrs/yr	-	
Percentage of time BOA is in use per year	25	%	-	
Productivity of BOA & Tender at hangers	0.25	hrs/ft of hanger	-	
Productivity of BOA & Tender at obstacles	0.5	hrs/ft of hanger	-	
Annual BOA Replacement parts cost	3,750	$/yr	5	%
Annual BOA Repair Labor	4,320	$/yr	6	wks/yr
Annual BOA Availability	-		520	hrs/yr
Hourly BOA Maintenance Costs	-		10.90	$/hr
Hourly BOA Equipment Costs	-		39.75	$/hr
SITE				
Average Hanger Spacing	10	ft	-	
Average Obstacle Spacing	20	ft	-	
Characteristic Length of Hanger	1	ft	-	
Characteristic Length of obstacle	2	ft	-	
Cumulative obstacle length as % of entire pipe-run	-		10	%
Cumulative hanger length as % of entire pipe-run	-		10	%
Percentage of corroded Pipe	0	%	-	
Average Level of HC radiation	0	mRem/hr	-	
% of piping with LC (DoE)	0	%	-	
% of piping with HC (DoE)	0	%	-	

Table 9.4: Example model calculation based on average DoE case study

Appendix C - Case Study Data and Images

This appendix contains the individual case studies used to describe the 'typical'[1] job sites for asbestos abatement. The individual case studies are sequentially numbered and serve as reference to Section *4.0 Case Studies* on page 53. Notice that only pertinent data needed to describe the different conditions is listed for each case study, with the remaining parameters assumed to be the average/medium figures shown in Table 3.5: on page 44.

The list of cases as shown in this appendix are the following:

Department of Energy

- **Indoors**
  - Case Study I - Indoor Heating Steam Lines, Administrative Setting - Fernald, Ohio
  - Case Study II - Indoor Heating Steam Lines, Maintenance Bldg. - Fernald, Ohio
  - Case Study III - Indoor Process Lines, Bldg. 2/3 - Fernald, Ohio
  - Case Study IV - Indoor Process Steam Lines, K27 Bldg. - Oak Ridge, Tennessee
  - Case Study VII - Indoor Process Steam Line, Bldg. 109-N - Hanford, Washington
  - Case Study VII - Indoor Steam Process Line, Bldg. 221-U - Hanford, Washington

- **Outdoors**
  - Case Study VII - Outdoor Interbuilding Steam Lines, Site Roadways - Fernald, Ohio
  - Case Study VIII - Outdoor Building Steam Lines, K33-Bldg. - Oak Ridge, Tennessee
  - Case Study IX - Outdoor Interbuilding Steam Lines, K25-Site - Oak Ridge, Tennessee
  - Case Study X - Outdoor Building Steam Lines, Outside 109-N - Hanford, Washington
  - Case Study X - Outdoor Intersite Steam Lines, Along Reservation Roadways - Hanford, WA

Industrial

- **Indoors**
  - Case Study X - Boiler Room, Steam Generator Plant, Pittsburgh, PA

- **Outdoors**
  - Case Study X - Oil Refinery, Oil/Steam pipes on face of Distillation Tower - Oahu, Hawaii
  - Case Study X - Oil Refinery, Crude-oil Pre-heater Feeder Pipes - Crocket, CA
  - Case Study X - Chemical Processing Plant, Steam Heater Feeder Gallery - Niagara, NY

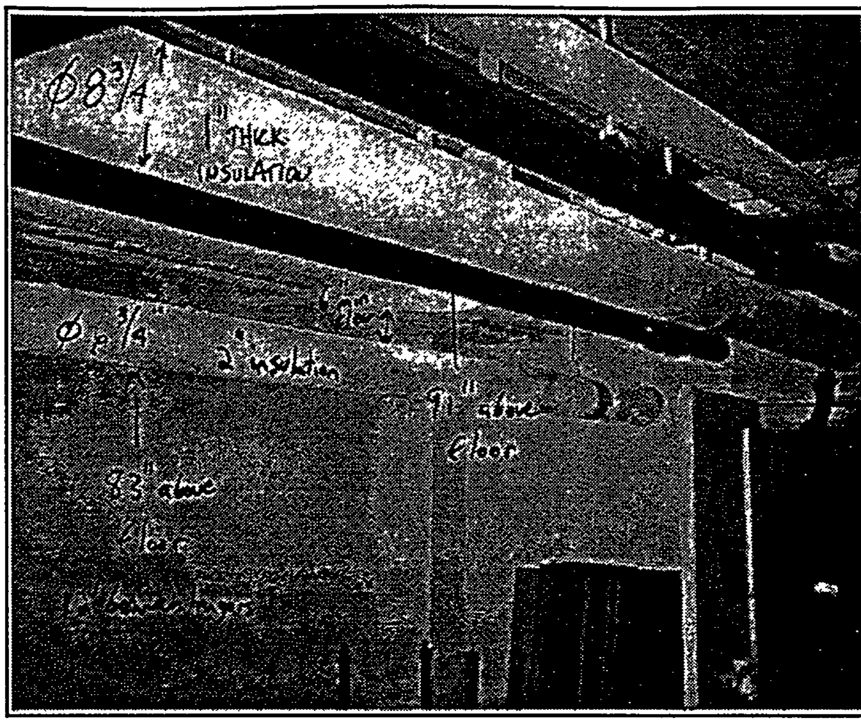
1. in the abatement industry every job is different, but for overall sizing of markets and costing figures, typical runs of piping had to be defined in order to gain at least a rough idea.

Case Study I

Indoor Heating Steam Lines

Site Description

- Site: Fernald, Ohio (DoE)
- Location: Administration Building Cellar
- Access: Double doors; no traffic
- Total Pipe Length: 150 ft.
- Pipe Height: 7 ft.
- Pipe Runs: Horizontal
- Pipe Sizes: 4 to 6 in. pipe O.D.
- Insulation: Aircell, rock-wool and block
- Lagging: none
- Hangers: Internal
- Obstacles: Valves, wall-penetration
- Clearances: 6 to 8 in.



Analysis Parameters

MANUAL	Const./Vars	
Manual Straight-Run Productivity	2	ft/hr
Carpenter Labor effort reduction due to mechanized system	0	%

ROBOTIC		
BOA Abatement Productivity	40	ft/hr.

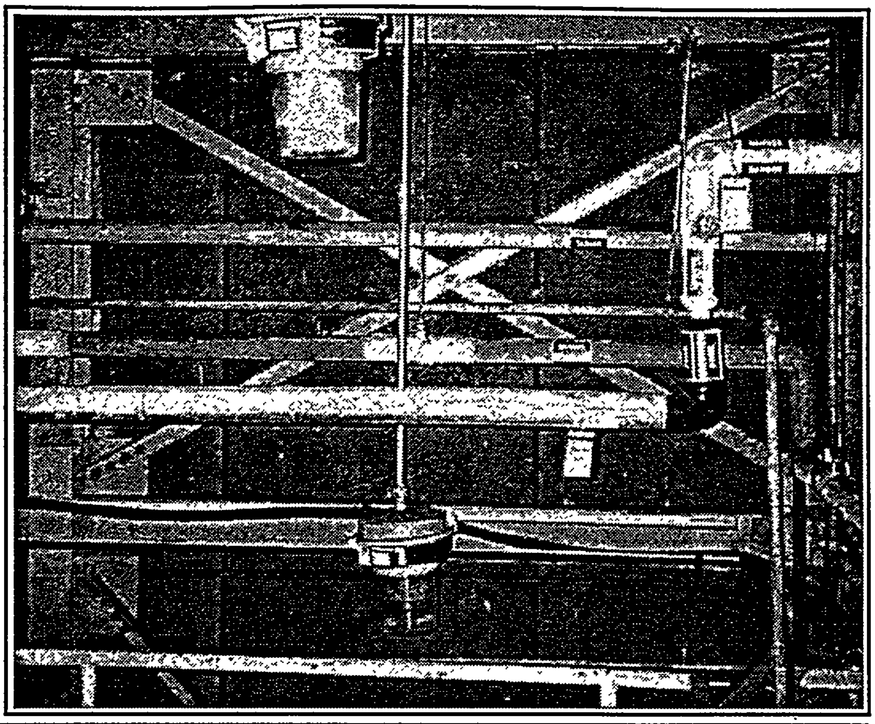
SITE	Const./Vars	
Average Hanger Spacing	10	ft/hanger
Average Obstacle Spacing	30	ft/obstacle
Characteristic Length of Hanger	0.5	ft
Characteristic Length of obstacle	2	ft
Percentage of corroded Pipe	0	%
Average Level of HC radiation	0	mRem/hr
% of Pipe-run with low contamination	0	%
% of Pipe-run with high contamination	0	%

Case Study II

Indoor Heating Steam Line

Site Description

- Site: Fernald, Ohio (DoE)
- Location: Maintenance Building
- Access: Highbay, min. traffic
- Total Pipe Length: 480 ft.
- Pipe Height: 40 ft.
- Pipe Runs: Horiz. (90%), Vert. (10%)
- Pipe Sizes: 4 to 6 in. pipe O.D.
- Insulation: Unknown
- Lagging: Aluminum w. clamps
- Hangers: Internal
- Obstacles: I-beam supports, other pipes
- Clearances: 6 to 12 in.



Analysis Parameters

MANUAL	Const./Vars	
Manual Straight-Run Productivity	3	ft/hr
Carpenter Labor effort reduction due to mechanized system	10	%

ROBOTIC		
BOA Abatement Productivity	40	ft/hr.

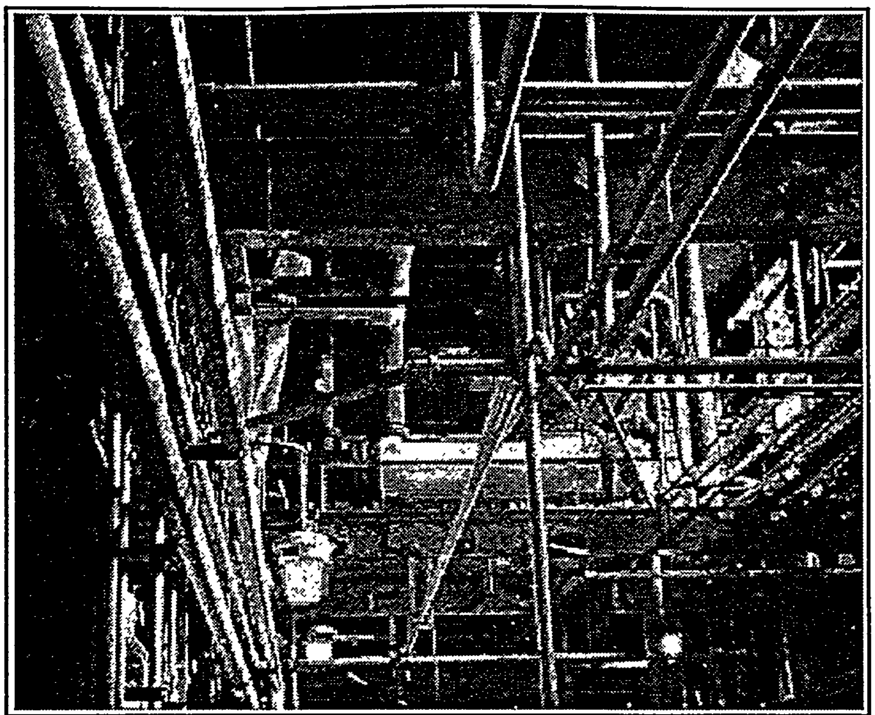
SITE	Const./Vars	
Average Hanger Spacing	20	ft/hanger
Average Obstacle Spacing	40	ft/obstacle
Characteristic Length of Hanger	0.5	ft
Characteristic Length of obstacle	1	ft
Percentage of corroded Pipe	0	%
Average Level of HC radiation	0	mRem/hr
% of Pipe-run with low contamination	0	%
% of Pipe-run with high contamination	0	%

Case Study III

Indoor Process Line

Site Description

- Site: Fernald, Ohio (DoE)
- Location: Building 2/3
- Access: Process Bldg., Catwalks
- Total Pipe Length: 5,500 ft.
- Pipe Height: 8 to 40 ft.
- Pipe Runs: Horiz. (85%), Vert. (15%)
- Pipe Sizes: 4 to 6 in. pipe O.D.
- Insulation: Unknown
- Lagging: Aluminum (90%), None (10%)
- Hangers: Internal, External supports
- Obstacles: I-beam supports, other pipes
- Clearances: 3 to 5 in.



Analysis Parameters

MANUAL	Const./Vars	
Manual Straight-Run Productivity	3	ft/hr
Carpenter Labor effort reduction due to mechanized system	0	%

ROBOTIC		
BOA Abatement Productivity	40	ft/hr.

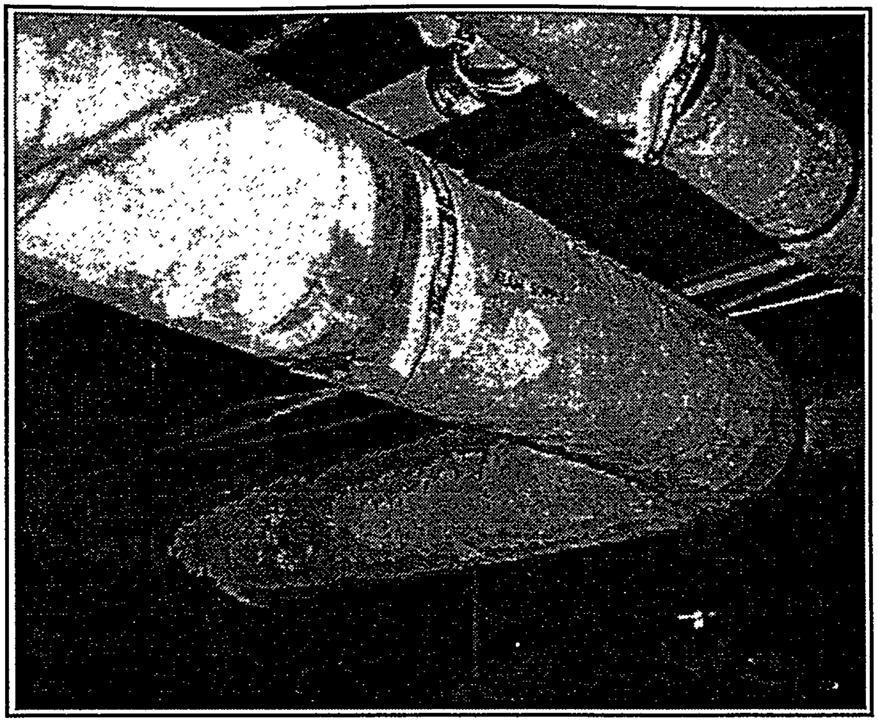
SITE	Const./Vars	
Average Hanger Spacing	25	ft/hanger
Average Obstacle Spacing	40	ft/obstacle
Characteristic Length of Hanger	1	ft
Characteristic Length of obstacle	1.5	ft
Percentage of corroded Pipe	10	%
Average Level of HC radiation	5	mRem/hr
% of Pipe-run with low contamination	20	%
% of Pipe-run with high contamination	5	%

Case Study IV

Indoor Process Steam Line

Site Description

- Site: Oak Ridge, TN (K25-complex)
- Location: Bldg. K-27
- Access: Catwalks, Floor-level
- Total Pipe Length: 8,500 ft.
- Pipe Height: 6 to 12 ft.
- Pipe Runs: Horiz. (90%), Vert. (10%)
- Pipe Sizes: 6 to 8 in. pipe O.D.
- Insulation: Unknown
- Lagging: None; clamps
- Hangers: Internal, External supports
- Obstacles: I-beam supports, other pipes
- Clearances: 3 to 15 in.



Analysis Parameters

MANUAL	Const./Vars	
Manual Straight-Run Productivity	3	ft/hr
Carpenter Labor effort reduction due to mechanized system	0	%

ROBOTIC		
BOA Abatement Productivity	40	ft/hr.

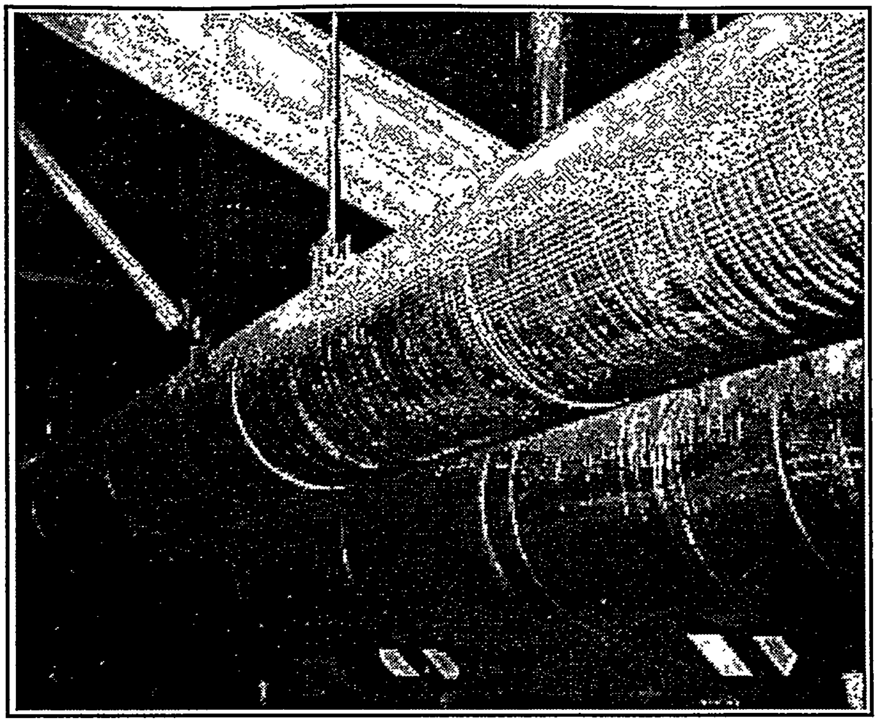
SITE	Const./Vars	
Average Hanger Spacing	15	ft/hanger
Average Obstacle Spacing	40	ft/obstacle
Characteristic Length of Hanger	1	ft
Characteristic Length of obstacle	2	ft
Percentage of corroded Pipe	10	%
Average Level of HC radiation	3	mRem/hr
% of Pipe-run with low contamination	25	%
% of Pipe-run with high contamination	0	%

Case Study V

Indoor Process Steam Supply Line

Site Description

- Site: Hanford, WA
- Location: 109-N
- Access: Open
- Total Pipe Length: 15,000 ft.
- Pipe Height: 8 to 24 ft.
- Pipe Runs: Horizontal
- Pipe Sizes: 6 to 8 in. pipe O.D.
- Insulation: Unknown
- Lagging: Aluminum; clamps (10%), PPT
- Hangers: External and welded supports
- Obstacles: I-beam supports, other pipes
- Clearances: 6 to 15 in.



Analysis Parameters

MANUAL	Const./Vars	
Manual Straight-Run Productivity	3	ft/hr
Carpenter Labor effort reduction due to mechanized system	0	%

ROBOTIC		
BOA Abatement Productivity	40	ft/hr.

SITE	Const./Vars	
Average Hanger Spacing	15	ft/hanger
Average Obstacle Spacing	20	ft/obstacle
Characteristic Length of Hanger	1	ft
Characteristic Length of obstacle	2	ft
Percentage of corroded Pipe	0	%
Average Level of HC radiation	0	mRem/hr
% of Pipe-run with low contamination	0	%
% of Pipe-run with high contamination	0	%

Case Study VI

Indoor Steam Supply Line

Site Description

- Site: Hanford, WA
- Location: 221-U
- Access: Open
- Total Pipe Length: 12,000 ft.
- Pipe Height: 8 to 10 ft.
- Pipe Runs: Horizontal
- Pipe Sizes: 6 to 12 in. pipe O.D.
- Insulation: Unknown
- Lagging: Aluminum; clamps, PPT
- Hangers: External and welded supports
- Obstacles: I-beam supports, other pipes
- Clearances: 3 to 6 in.

Analysis Parameters

MANUAL	Const./Vars	
Manual Straight-Run Productivity	3	ft/hr
Carpenter Labor effort reduction due to mechanized system	0	%

ROBOTIC		
BOA Abatement Productivity	40	ft/hr.

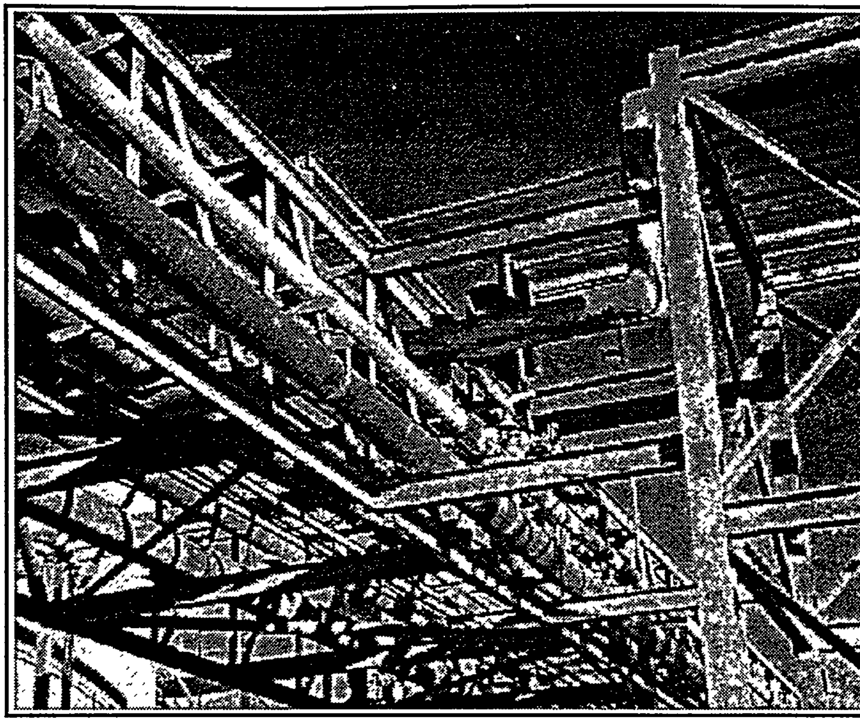
SITE	Const./Vars	
Average Hanger Spacing	10	ft/hanger
Average Obstacle Spacing	25	ft/obstacle
Characteristic Length of Hanger	1	ft
Characteristic Length of obstacle	2	ft
Percentage of corroded Pipe	0	%
Average Level of HC radiation	1.5	mRem/hr
% of Pipe-run with low contamination	25	%
% of Pipe-run with high contamination	0	%

Case Study VII

Outdoor Interbuilding Steam Supply Line

Site Description

- Site: Fernald, OH (DoE-FERMCO)
- Location: On-site Interbuilding Roadways
- Access: Open; outdoors
- Total Pipe Length: 105,000 ft.
- Pipe Height: 35 to 40 ft.
- Pipe Runs: Horizontal
- Pipe Sizes: 6 to 8 in. pipe O.D.
- Insulation: Unknown
- Lagging: Aluminum; clamps
- Hangers: External and welded supports
- Obstacles: I-beam supports, other pipes
- Clearances: 6 to 15 in.



Analysis Parameters

MANUAL	Const./Vars	
Manual Straight-Run Productivity	3	ft/hr
Carpenter Labor effort reduction due to mechanized system	20	%

ROBOTIC		
BOA Abatement Productivity	40	ft/hr.

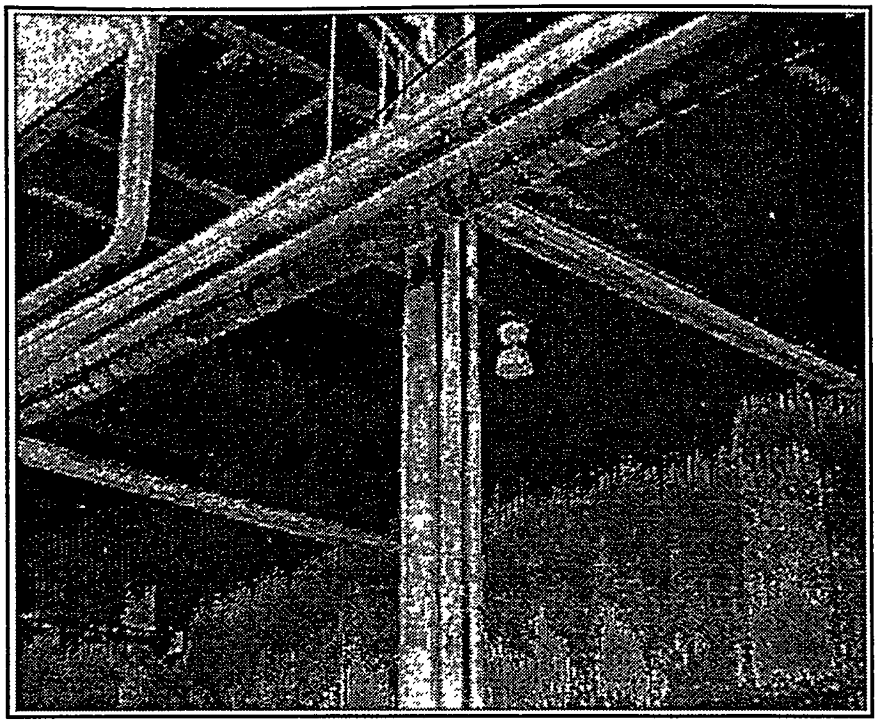
SITE	Const./Vars	
Average Hanger Spacing	10	ft/hanger
Average Obstacle Spacing	40	ft/obstacle
Characteristic Length of Hanger	2	ft
Characteristic Length of obstacle	0.5	ft
Percentage of corroded Pipe	10	%
Average Level of HC radiation	0	mRem/hr
% of Pipe-run with low contamination	0	%
% of Pipe-run with high contamination	0	%

Case Study VIII

Outdoor Building Steam Line

Site Description

- Site: Oak Ridge, TN (K25-Site)
- Location: Outside K33
- Access: Open; outdoors
- Total Pipe Length: 10,500 ft.
- Pipe Height: 35 to 40 ft.
- Pipe Runs: Horizontal
- Pipe Sizes: 6 to 8 in. pipe O.D.
- Insulation: Unknown
- Lagging: Aluminum; clamps
- Hangers: External
- Obstacles: I-beams, other pipes
- Clearances: 3 to 15 in.



Analysis Parameters

MANUAL	Const./Vars	
Manual Straight-Run Productivity	3	ft/hr
Carpenter Labor effort reduction due to mechanized system	20	%

ROBOTIC		
BOA Abatement Productivity	40	ft/hr.

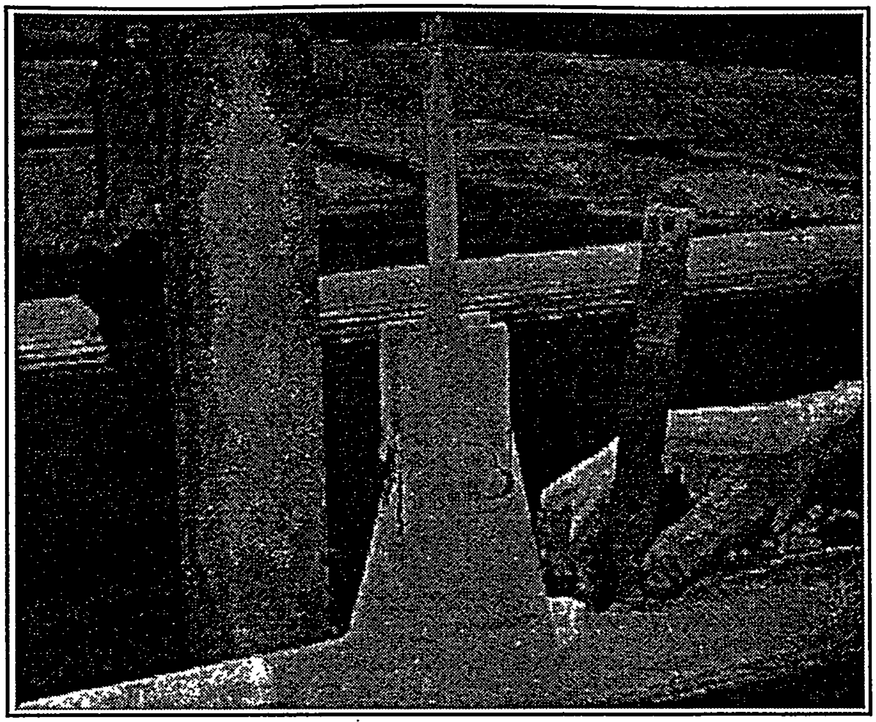
SITE	Const./Vars	
Average Hanger Spacing	20	ft/hanger
Average Obstacle Spacing	40	ft/obstacle
Characteristic Length of Hanger	1	ft
Characteristic Length of obstacle	2	ft
Percentage of corroded Pipe	25	%
Average Level of HC radiation	0	mRem/hr
% of Pipe-run with low contamination	0	%
% of Pipe-run with high contamination	0	%

Case Study IX

Outdoor Interbuilding Steam Line

Site Description

- Site: Oak Ridge, TN (K25-Site)
- Location: Inside of K25-site
- Access: Open; outdoors
- Total Pipe Length: 175,000 ft.
- Pipe Height: 3 to 10 ft.
- Pipe Runs: Horizontal
- Pipe Sizes: 4 to 8 in. pipe O.D.
- Insulation: Unknown
- Lagging: Aluminum; clamps
- Hangers: Welded Tops and Supports
- Obstacles: Other pipes
- Clearances: 6 to 24 in.



Analysis Parameters

MANUAL	Const./Vars	
Manual Straight-Run Productivity	3	ft/hr
Carpenter Labor effort reduction due to mechanized system	0	%

ROBOTIC		
BOA Abatement Productivity	40	ft/hr.

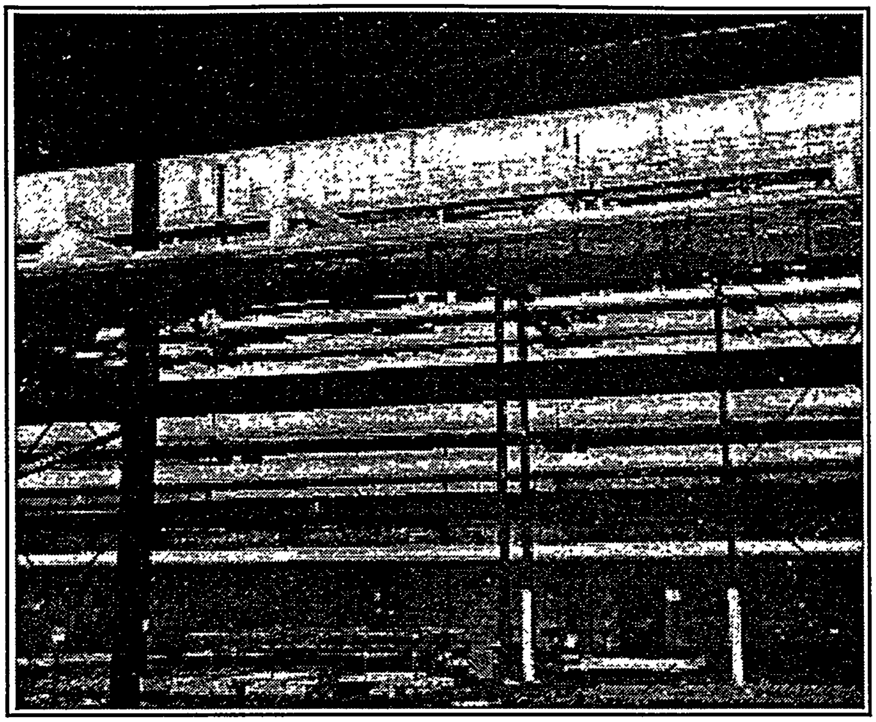
SITE	Const./Vars	
Average Hanger Spacing	40	ft/hanger
Average Obstacle Spacing	N/A	ft/obstacle
Characteristic Length of Hanger	1	ft
Characteristic Length of obstacle	N/A	ft
Percentage of corroded Pipe	0	%
Average Level of HC radiation	0	mRem/hr
% of Pipe-run with low contamination	0	%
% of Pipe-run with high contamination	0	%

Case Study X

Outdoor Building Steam Lines

Site Description

- Site: Hanford, WA
- Location: Outside 109-N
- Access: Open; outdoors along bldg. wall
- Total Pipe Length: 12,000 ft.
- Pipe Height: 8 to 24 ft.
- Pipe Runs: Horizontal
- Pipe Sizes: 6 to 36 in. pipe O.D.
- Insulation: Unknown
- Lagging: Aluminum; clamps
- Hangers: Welded Tops and Supports
- Obstacles: Other pipes, rack
- Clearances: 6 to 12 in.



Analysis Parameters

MANUAL	Const./Vars	
Manual Straight-Run Productivity	3	ft/hr
Carpenter Labor effort reduction due to mechanized system	0	%

ROBOTIC		
BOA Abatement Productivity	40	ft/hr.

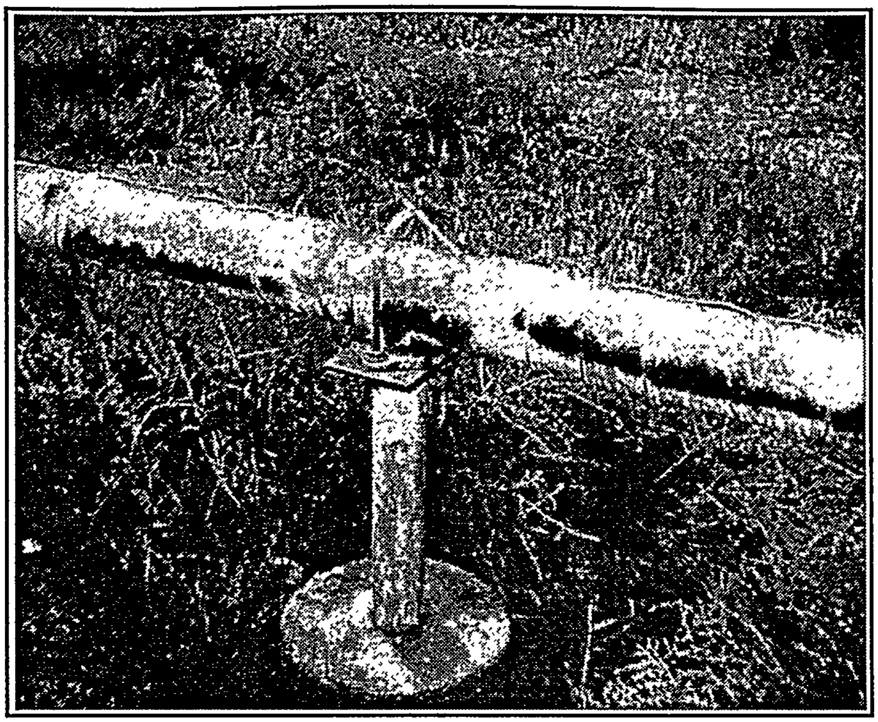
SITE	Const./Vars	
Average Hanger Spacing	N/A	ft/hanger
Average Obstacle Spacing	30	ft/obstacle
Characteristic Length of Hanger	N/A	ft
Characteristic Length of obstacle	2	ft
Percentage of corroded Pipe	0	%
Average Level of HC radiation	0	mRem/hr
% of Pipe-run with low contamination	0	%
% of Pipe-run with high contamination	0	%

Case Study XI

Outdoor Interbuilding Steam Lines

Site Description

- Site: Hanford, WA
- Location: Across the complex, along roads
- Access: Open; outdoors
- Total Pipe Length: 100,000 ft.
- Pipe Height: 2 to 4 ft.
- Pipe Runs: Horizontal
- Pipe Sizes: 4 to 36 in. pipe O.D.
- Insulation: Unknown
- Lagging: Aluminum/clamps, tar-paper
- Hangers: Welded Tops and Supports
- Obstacles: Supports & Hangers
- Clearances: 2 to 3 feet



Analysis Parameters

MANUAL	Const./Vars	
Manual Straight-Run Productivity	3	ft/hr
Carpenter Labor effort reduction due to mechanized system	0	%

ROBOTIC		
BOA Abatement Productivity	40	ft/hr.

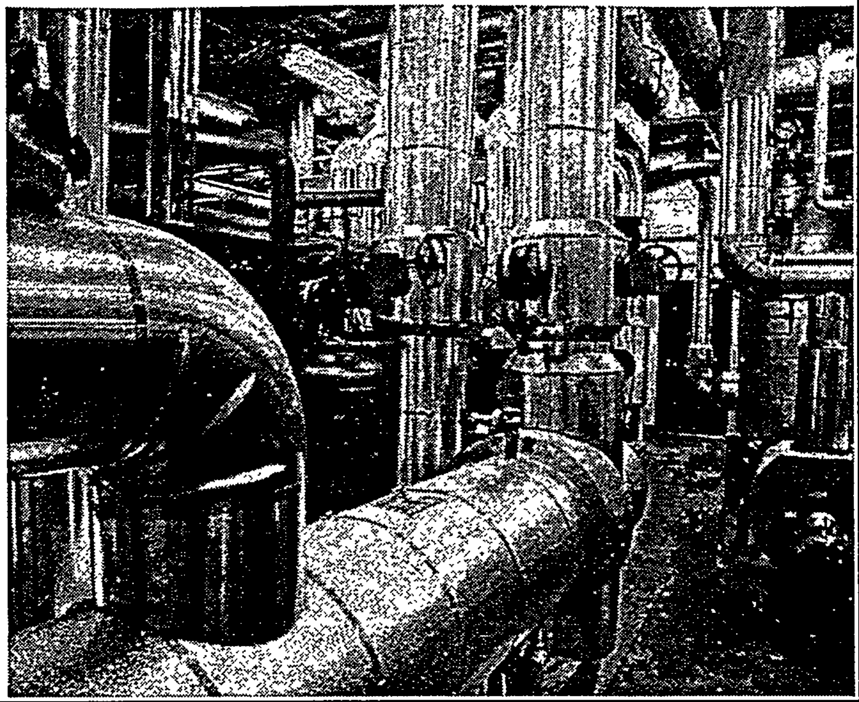
SITE	Const./Vars	
Average Hanger Spacing	N/A	ft/hanger
Average Obstacle Spacing	30	ft/obstacle
Characteristic Length of Hanger	N/A	ft
Characteristic Length of obstacle	1	ft
Percentage of corroded Pipe	0	%
Average Level of HC radiation	0	mRem/hr
% of Pipe-run with low contamination	0	%
% of Pipe-run with high contamination	0	%

Case Study XII

Indoor Steam Lines

Site Description

- Site: Boiler Room, Steam Plant
- Location: Pittsburgh, PA
- Access: Constrained, indoors
- Total Pipe Length: 1,000 ft.
- Pipe Height: 2 to 8 ft.
- Pipe Runs: Horizontal & Vertical
- Pipe Sizes: 4 to 12 in. pipe O.D.
- Insulation: Unknown
- Lagging: Aluminum/clamps
- Hangers: Welded Tops and Supports
- Obstacles: Supports & Hangers
- Clearances: 0.5 to 2 feet



Comments

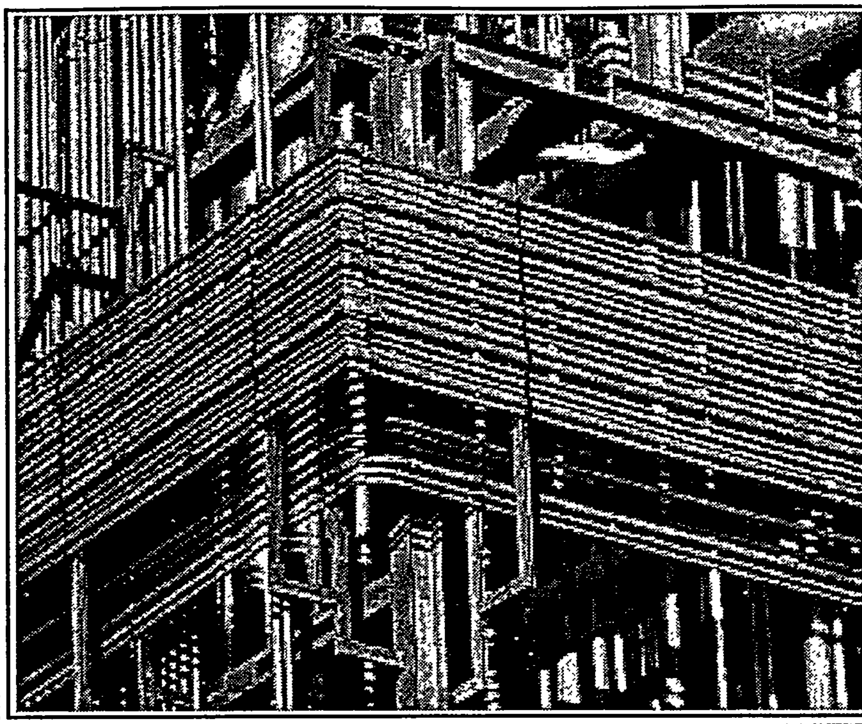
This picture illustrates the conditions of typical indoor steam piping, where most, if not all, piping is within the appropriate size-range, but due to an excess of obstacles and very short straight runs, this piping would not represent a very beneficial situation in which a BOA-like system would be used.

Case Study XIII

Outdoor Steam & Oil Lines

Site Description

- Site: Oil Refinery, Distillation Column
- Location: Oahu, Hawaii
- Access: Outdoors; Building outsides
- Total Pipe Length: 5,000 ft.
- Pipe Height: 0 to 100 ft.
- Pipe Runs: Vertical
- Pipe Sizes: 1 to 8 in. pipe O.D.
- Insulation: Unknown
- Lagging: Aluminum/clamps
- Hangers: Welded Sides and Supports
- Obstacles: Supports & Hangers
- Clearances: 0.1 to 1 foot



Comments

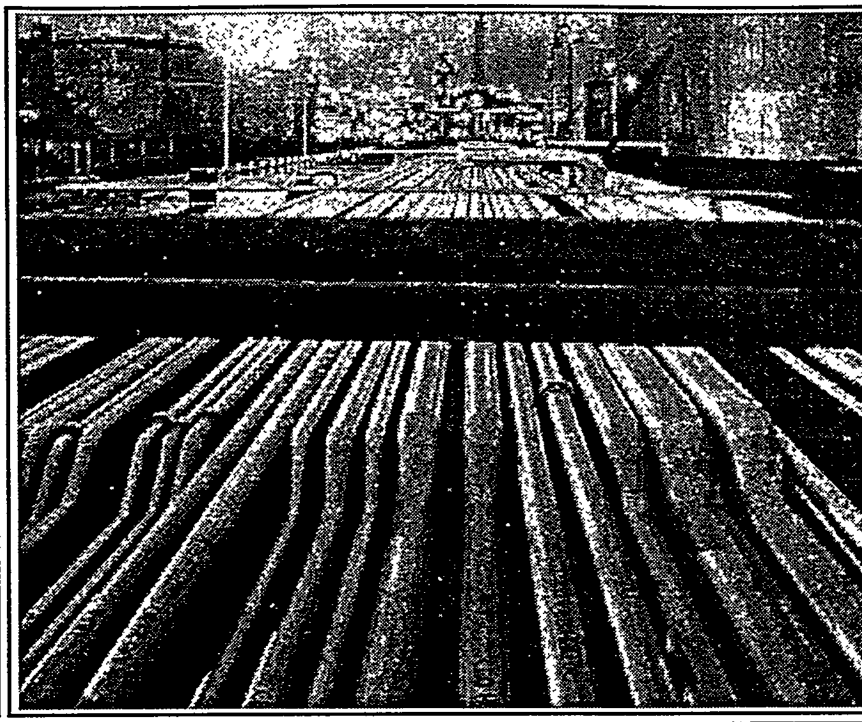
This picture illustrates the conditions of tightly packed outdoor piping that is not necessarily within the robot's range, and is hence termed 'spaghetti'. Access to the smaller piping is unrealistic, but the larger piping running along the face of the distillation column, might be promising, as long as access is made from the floor-level and vertical progress is not inhibited by too many obstacles.

Case Study XIV

Outdoor Crude-oil Lines

Site Description

- Site: Oil Refinery, Pre-heater feeders
- Location: Crockett, CA
- Access: Outdoors; free access
- Total Pipe Length: 35,000 ft.
- Pipe Height: 2 to 6 ft.
- Pipe Runs: Horizontal
- Pipe Sizes: 4 to 12 in. pipe O.D.
- Insulation: Unknown
- Lagging: Aluminum/clamps
- Hangers: Welded Bottom Supports
- Obstacles: Supports
- Clearances: 0.5 to 1 foot



Comments

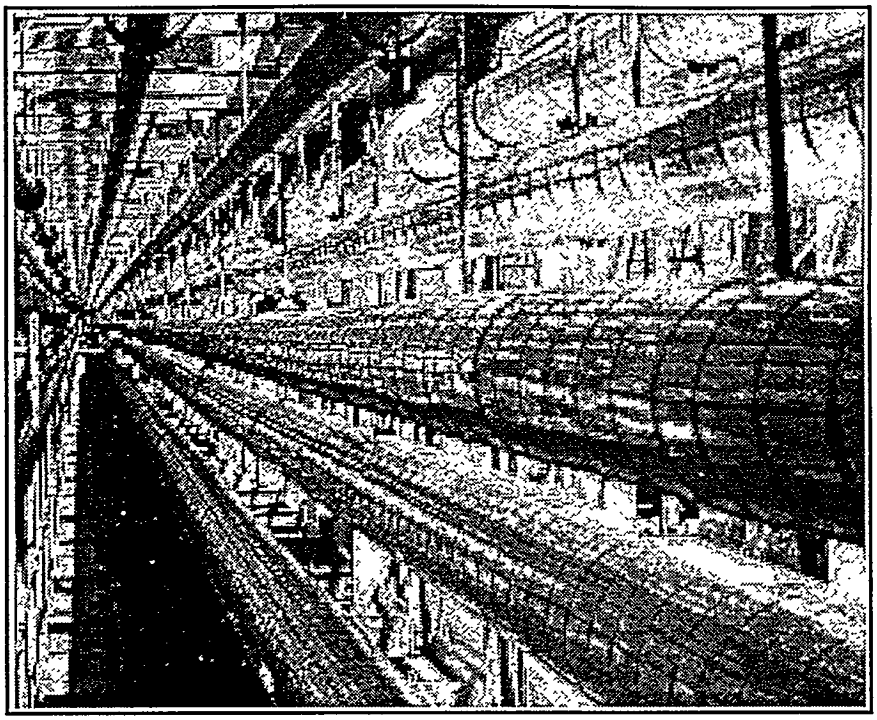
This picture illustrates the conditions of piping ideally suited for the application of a robotic system. Clearances and pipe size match the use of the system, and it would most likely favor robotic removal, since it represents perfectly straight runs with minimal and infrequent obstacles where it could replace manual glovebagging and/or full-containment abatement techniques.

Case Study XV

Outdoor Steam Lines

Site Description

- Site: Chemical Plant, Steam Lines
- Location: Niagara, NY
- Access: Outdoors; catwalk access
- Total Pipe Length: 18,000 ft.
- Pipe Height: 1 to 8 ft.
- Pipe Runs: Horizontal
- Pipe Sizes: 4 to 12 in. pipe O.D.
- Insulation: Unknown
- Lagging: Aluminum/clamps
- Hangers: Welded Side Supports
- Obstacles: Supports
- Clearances: 1 to 3 feet



Comments

This picture illustrates the conditions of outdoor steam piping feeding heaters for chemical processes inside buildings, whilst contained within a pipe-gallery. Access is straightforward, with minimal obstacles and substantial clearances for a robotic system to provide good abatement productivity.

Appendix D - Industrial Contractors Survey Forms & Results

Asbestos Contractor Survey Form

A total of 20 contractors were surveyed by mail using the form shown below. All contractors insisted on anonymity before they would share certain information with us, and hence no contractor names are listed either here nor in *Appendix D - Contacts by Market Segment & Industry.*

- **How many asbestos removal jobs does your company do in a year?**

  _____*jobs/year*

- **What is the length of time it takes to complete the average asbestos removal job?**

  _____*days* _____*weeks* _____*months*

- **How many asbestos removal workers are employed by your company?**

  _____*workers*

- **What is the percentage of glove bagging work which you do?**

  __________*%*

- **What is the rate of removal for glove bagging straight runs of pipe which are easily accessible? (This rate of removal should not include set-up and clean-up)**

  _____*feet/man-hour*

- **What is the most common range of pipe OD in industrial settings?**

  __________*in.*

- **What percentage of pipe in industrial settings is covered with aluminum lagging or aluminum jackets?**

  _____*%*

- **What is the percentage of 'live' steam pipes as compared to all pipes?**

  _____*%*

- **Removing insulation from a straight run of easily accessible 'live' steam pipe cuts production rates by**

  _____*%.*

- **The average rate of pay for a worker is**

  $_____/hour (hourly cost of the worker without fringe benefits, not the amount charged for the worker).

- **What is the most expensive piece of equipment which your company owns and uses in asbestos abatement?**

  ____

- **How much did this piece of equipment cost?**

  $__________

- **What are some important features or suggestions you can make regarding a robotic device for removing pipe insulation?**

Contractor Survey Result

	# Jobs/Yr.	Avg Lgth/Job (in weeks)	# Workers	Glove bagging	Removal Rate (ft/hr)	OD (inches)	Aluminum Lagging	% of Live Steam pipes	Live Steam Removal Rate Reduction	Pay Rate (no fringe)	Most Expensive. Equipment	Equipment Cost
	200	4	40	30%	5.625	3	3%	50%	30%	$11.00	vac loader	$100,000
	65	2	45	50%	7.5	4-8	75%			$27.00	water laser	
	200	1	25	25%	6.25	6-8	5%	25%	35%	$9.50	vac loader	$30,000
	125	2	125	10%	7	2-6	50%	0%		$19.25	guzzler unit	$150,000
	10	6	4	15%	8	6	50%	25%	50%	$21.00	negative air m	$2,000
	445		20	35%	12.5		5%	5%	65%	$12.50	decon trailer	$15,000
	150	4	35	40%	5	6-8	80%	50%	50%	$22.00	blast track	$25,000
	400	3	175	10%	5	6	50%	15%	15%	$10.00	decon trailer	$100,000
	400	3	25	20%	8.125	2	70%	10%	60%	$13.00	vac loader	$25,000
	3000	24	800	20%	6	12	85%	0%		$18.00	vac track	$85,000
	55	0.6	6	10%	9.375	6-8	70%	75%	50%	$14.50	vac loader	$70,000
	85	24	350	25%	6.25	4	90%	1%	75%	$10.00	negative air m	$1,500
	20	2		50%	10	6-8		40%	50%	$12.50	bead blast	
	6	8	15	6%		2-6		20%	40%	$17.00	pressure wash	$6,000
	300	0.6	180	8%	2.625	2	70%	5%	33%	$13.00	vac loader	$8,000
	1000	0.6	25	0%	9.375	2	30%	90%	40%	$14.00	vacuum&gener	$40,000
	650	3	150	25%	9.375	3-6	10%	10%	60%	$9.50	vacuum system	$200,000
		2	550	20%	8.125	2	10%	10%	30%	$10.00	guzzler	$130,000
	25	4	15	15%	4	8-10			50%	$19.00	vacuum truck	$40,000
	100	4	150	25%	6.25			50%	50%	$12.00	vac loader	$75,000
Avg.	381	5.15	144	22%	7.18		47%	27%	46%	$14.74		$61,250
Max	3000	24	800	50%	12.5	12	90%	90%	75%	$27		$200,000
Min	6	0.6	4	0%	2.625	2	3%	0%	15%	$10		$1,500

Appendix E - Contacts by Market Segment & Industry

This appendix lists the contact names, addresses and phone numbers of contact people we gathered during the performance of our cost/benefit analysis. Data and information was exchanged between CMU and these individuals, and we would like to acknowledge their substantial contributions to the content and thoroughness of this report. The names are structured based on the particular market segment and its internal make-up, as well as by the asbestos abatement contractors that would be doing the work for the different customers within these market segments.

Department of Energy

• Fernald

Rick Heath (FERMCO) - (513) 648-6291, Rick.Heath%em@mailgw.er.doe.gov
Brad Thompson (Wise Construction) - (513) 738-6372

• Oak Ridge

Roy Sheely, Asbestos Abatement Project Manager (Martin Marietta) - phone: (615) 576-7742, pager: (615) 873-9850, fax: (615) 241-2533
Paul Larson, Asbestos Abatement Project Engineer (Martin Marietta) - (615) 574-9905
Sylvia Parsons, Engineering Assistant to Roy - phone: (615) 241-4810, pager: (615) 873-6185
Julian Daniel, Documentation (Martin Marietta) - phone: (615) 241-2307, general: (615) 576-8082
Scott Anderson, Radian Corp. (surveying) - phone: (615) 483-9870. -9061 fax, 220-8168 direct

• Hanford

Mark Janaski, Program Mgr for asbestos abatement, Washington, DC (DOE) - phone: (301) 903-7428
Jeff Bruggeman, Program Mgr for asbestos abatement @ Hanford (DOE) - phone: (509) 376-7121, fax: (509) 376-4360
Bradley Mewes, Asbestos Project Manager (Bechtel Hanford Inc.) - (509) 373-5496

• INEL

Neil Allen, Asbestos Coordinator (Lockheed) - (208) 526-5007
George Clark, Rad. Con. Supervisor (Lockheed) - phone: (208) 526-3565, fax: (208) 526-8959
John Epperson, Estimating - (208) 526-2998, -5474 fax

• Savannah River

Ms. Pat Stone(DOE) - (803) 725-1192
Mr. L.P. Singh, (DOE OSHA) - (803) 725-3962
Caroline Burns, Asbestos Coordinator- (803) 952-7154
Paul McDonagh, Asst to Ms. Bruns- (803) 952-7157
Murry Angvall, Estimating - (803) 952-5733

• Rocky Flats

Peter Sanford, (SAIC) - (303) 966-2762
Tom Grethel, Dir of Occ. Health and Safety (DOE) - (303) 966-7632
Dero Sargent, Dir. of Stds, Performance, and Assurance (DOE) - (303) 966-6222
Sally Higgins, Asst. to Tom Grethel, (DOE) - (303) 966-9730

Industrial

- **Phone and Personal Interviews - Week of February 27 to March 3, 1995, March 30, 1995**

6. Mr. Larry Horvat, PDG Environmental, 300 Oxford Dr., Monroeville, PA 15146, 412-856-2200
7. Mr. Charles Johnson, Luse Asbestos Removal Company, 2050 N. 15th Ave., Melrose Park, IL 60160, 708-681-2600
8. Mr. Brian Sargent, Sargent Contracting Inc., P.O. Box 193, Jim Thorpe, PA 18229, 717-325-8000
9. Mr. Scott Turnbull, BLT Contracting, Inc., 1718 Mt. Nebo Rd., P.O. Box 401, Sewickley, PA 15143, 412-741-7725
10. Mr. Chad Rittle, Department of Environmental Resources, Air Quality Control, 400 Waterfront Dr., Pittsburgh, PA 15222-4745, 412-442-4329
11. Ms. Linda Raymont, Gateway Environmental Contractors, 122 Kerr Rd., New Kensington, PA 15068, 412-337-6220
12. Mr. James Stanko, Allegheny County Health Department, Bureau of Air Pollution Control, 301-39th St., Pittsburgh, PA 15201
13. Mr. Donald Horgan, Allegheny County Health Department, Bureau of Air Pollution Control, 301-39th St., Pittsburgh, PA 15201
14. Mr. Joseph Yakubisin, Allegheny County Health Department, Bureau of Air Pollution Control, 301-39th St., Pittsburgh, PA 15201

Appendix F - List of References and Documents

8. "*Asbestos Abatement Contracting Industry Report, 1993,*" The Jennings Group, Inc., Columbia, NJ, Copyright 1993
9. Analysis of Contractor Asbestos Abatement Data Base, by The Jennings Group, Inc., May 10, 1995.
10. "*Oak Ridge K-25 Site, Building K-27 Asbestos Survey,*" Radian Corporation, Oak Ridge, TN, December 1993
11. "*Oak Ridge K-25 Site, Building K-31 Cell Floor Asbestos Survey,*" Radian Corporation, Oak Ridge, TN, September 1994
12. "*Asbestos Survey Report, Hanford Site, Richland, Washington,*" prepared by Bechtel Hanford Inc., 1995
13. "*DEI Asbestos Survey, Fernald Site,*" supplied by the Fernald DoE site
14. "*Summary of Chemical Processing Plant Asbestos Survey, INEL Site,*" Pickering, Inc., Memphis, TN, April 1995
15. "*Savannah River Site Asbestos Abatement Activities Report,*" prepared for the U. S. Department of Energy by Westinghouse Savannah River Co., Aiken, SC, 1995
16. "*Request of Information - Asbestos Materials, Rocky Flats Site,*" prepared by EG&G Rocky Flats, Golden, CO, 1995
17. Revisions in NIOSH guide to manual lifting, by Putz-Anderson, V., & Waters, T., April 1991
18. "*The Asbestos Agenda*", Civil Engineering, by Tarricone, Paul, vol. 59, Oct. 1989, p. 48-51
19. "*Occupational Exposure to Asbestos: Population at Risk and Projected Mortality - 1980-2030*", American Journal of Industrial Medicine, by Nicholson, Selikoff, and Perkel, vol. 3, 1982, p. 259-311
20. "*Charting the Asbestos Minefield*", Nejmeh, G.A., et al, Shearson Lehman Brothers, Inc., Jan. 20, 1992

Appendix G - Commercialization Assessment Data

Asbestos Abatement Contractors in 1993 by Revenue and % Industrial Work[a]

1993 Revenue	Percent Industrial
100	25
75	15
36	
25	10
22	40
21.7	30
17	25
10.1	10
8	10
8	35
8	20
7.5	40
7	
7	10
7	20
6	20
6	30
6	5
5.2	15
5	20
5	30
5	0
5	
4.7	15
4	70
4	0
4	
4	10
4	
4	5
4	10
4	20
3.4	15
3.2	5
3	20
2.7	8
2.7	60
2.3	30
2.2	10
2.2	45
2	40
2	65
2	20
2	90
2	10
2	0
2	20
2	20
2	10
2	20
2	15
2	30
2	40
2	
1.8	10
1.7	50
1.6	30
1.5	20
1.1	70
.8	60
.7	10

a. Analysis of Contractor Asbestos Abatement Data Base, The Jennings Group, May 10, 1995

Asbestos Abatement Contractors in 1993 by Revenue and % Industrial Work

1993 Revenue	Percent Industrial	Industrial Revenue	Companies w/ Industrial Revenue Greater than $10m
2	0.9	1.8	
4	0.7	2.8	
1.1	0.7	0.77	
2	0.65	1.3	
0.8	0.6	0.48	
2.7	0.6	1.62	
1.7	0.5	0.85	
2.2	0.45	0.99	
2	0.4	0.8	
22	0.4	8.8	
2	0.4	0.8	
7.5	0.4	3	
8	0.35	2.8	
5	0.3	1.5	
2	0.3	0.6	
6	0.3	1.8	
21.7	0.3	6.51	
1.6	0.3	0.48	
2.3	0.3	0.69	
100	0.25	25	25
17	0.25	4.25	
1.5	0.2	0.3	
5	0.2	1	
2	0.2	0.4	
6	0.2	1.2	
2	0.2	0.4	
2	0.2	0.4	
3	0.2	0.6	
2	0.2	0.4	
8	0.2	1.6	
4	0.2	0.8	
7	0.2	1.4	
3.4	0.15	0.51	
2	0.15	0.3	
75	0.15	11.25	11.25
5.2	0.15	0.78	
4.7	0.15	0.705	
2.2	0.1	0.22	
10.1	0.1	1.01	
1.8	0.1	0.18	
8	0.1	0.8	
2	0.1	0.2	
0.7	0.1	0.07	
2	0.1	0.2	
4	0.1	0.4	
25	0.1	2.5	
7	0.1	0.7	
4	0.1	0.4	
2.7	0.08	0.216	
3.2	0.05	0.16	
4	0.05	0.2	
6	0.05	0.3	
2	0		
4	0		
5			
4			
36			
4			
7			
2			
5			
Total			36.25