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System Analysis: Developing Tools for the Future

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System Analysis: Developing Tools for the Future

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Abstract Follows

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Abstract

This report introduces and evaluates system analysis tools that were developed, or are under development, for the Robotics Technology Development Program (RTDP). Additionally, it discusses system analysis work completed using these tools aimed at completing a system analysis of the retrieval of waste from underground storage tanks on the Hanford Reservation near Richland, Washington.

The tools developed and evaluated include a mixture of commercially available tools adapted to RTDP requirements, and some tools developed in house. The tools that are included in this report include:

- a Process Diagramming Tool,
- a Cost Modeling Tool,
- an Amortization Modeling Tool,
- a graphical simulation linked to the Cost Modeling Tool,
- a decision assistance tool, and
- a system thinking tool.

Additionally, the importance of performance testing to the RTDP and the results of such testing executed is discussed. Further, the results of the Tank Waste Retrieval (TWR) System Diagram, the TWR Operations Cost Model, and the TWR Amortization Model are presented, and the implication of the results are discussed.

Finally, the RTDP system analysis tools are assessed and some recommendations are made regarding continuing development of the tools and process.

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Executive Summary

This paper describes the task and results of the Robotics Technology Development Program (RTDP) system analysis effort under the Cross Cutting and Advanced Technology (CC&AT) program for fiscal year 1995. These efforts focused primarily on the development of a set of system analysis tools with an initial focus on the Tank Waste Retrieval (TWR) program at the Hanford Reservation near Richland, Washington. The paper discusses activities in developing tools for customers' needs, applications of these tools to the TWR program, and closes with conclusions and recommendations for the future development of system analysis tools.

Developing Tools for Customers' Needs

Several tools were developed, reviewed, or are under development for use in the system analysis and cost benefit arena for RTDP personnel conducting analyses. These tools are still under development, and their use has been limited to the developers. The tools under consideration within RTDP follow:

- the Process Model,
- the Cost Modeling Tool,
- the Amortization Modeling Tool, a graphical simulation linked to
- the Cost Modeling Tool, and
- the DECIDE (DECISION Definition and Evaluation) tool.

Three external tools were also used or reviewed. The graphical modeling tools QUEST (QUEuing Event Simulation Tool), and IGRIP (Interactive Graphical Robot Instruction Program) were reviewed and used occasionally as well as *ithink*®, a system scenario devising tool.

RTDP Tools

Four tools were considered and are discussed below.

- The Process Modeling Tool provides a graphically based method to diagram system operations. Its major advantage is that it describes pictorially the operation of a system at a level of detail useful to the analyst or customer. The primary disadvantage of this tool is its difficulty of use. Automating this tool would provide much more utility for an analyst and customer.
- The Cost Modeling Tool (CMT) provides a very detailed accounting of the costs of operating a system. It allows an analyst to provide as much detail as he/she desires and then, through calculations, to express this detail at a high level as

the duration of operations, or cost of operations. A major disadvantage of the CMT is its user interface, which is primarily a numerically oriented text, both for input and output. A graphical means of conveying information between the tool and the analyst, or customer, would be helpful.

- The Amortization Modeling Tool (AMT) was initiated late in June of this fiscal year by SNL staff. As such, it is the least developed of all the tools. The AMT provides a system level shell of the proposed system in operation. The key premise of the tool is that a system can be used for more than one application. As a system is reused, the initial costs to develop and build it are allocated across applications. The tool helps an analyst determine the incremental costs for each use of the system and how the initial development costs are shared. Concerns about this tool are that it needs additional information and, for accuracy, that it requires validation.
- The DECIDE Tool was initially developed by JBF Associates in cooperation with ORNL to provide a facilitated forum for collecting and analyzing information regarding development and/or deployment of robotic systems. A considerable advantage of this tool is that it analyzes and collects information providing visual indications of optimum choices through graphs based on the collected information set. A significant concern is the lack of resolution in the outputs due to uncertainty in the information. An analyst or customer may be confused by current presentations of the DECIDE analysis because it does not seem to provide a clear outcome except when most of the information about the problem has been collected.

External Tools

- The *ithink*® system modeling and thinking tool provides the analyst with an easy to use graphical method for modeling systems. This software tool provides a very powerful capability by allowing the user to graphically create a system representation, which can simulate operation of the system. The analyst provides graphical inputs to the system via diagrams of the operations within the system. From these inputs an *ithink*® model can be executed, providing output in graphical or numerical forms.
- The IGRIP tool is a comprehensive 3-D robotics modeling package which includes device modeling capabilities and work cell layouts. The software includes many built-in libraries of robots, common production equipment, etc. The system analyst can use these libraries to provide input to other analytic tools previously discussed.

- The QUEST tool can be used to provide input to other analytic tools. As a discrete event simulation tool, QUEST serves as a platform on which overall systems (robotic and other) may be simulated in a cooperative environment. The discrete event portion of the tool can be used to estimate amounts of equipment costs which can then be converted to processing costs such as transportation , overhead costs, repairs, etc. These cost factors can then be factored into other analysis tools.

Applying the Tools

Three of the previously mentioned tools were used in analyzing the proposed Hanford TWR system for removal of waste from the underground storage tanks at the Hanford Reservation near Richland, Washington.

Early in the TWR effort, several options were considered as means of waste retrieval. Most of these options used a long reach manipulator of some variety because of the probability of success and potential acceptance. The option upon which planning and design efforts seems to have settled is the operation of a Long Reach Manipulator System (LRMS) through a 42-inch central riser.

To assist in the analysis of this option, the following tools produced the following results.

- The Process Modeling Tool resulted in the "TWR System Diagram."
- The Cost Modeling Method Tool yielded the "Operations Cost Model (OCM)."
- The Amortization Modeling Tool produced the "TWR Amortization Model (TAM)."

The TWR system diagram and the OCM focus on the problem of tank waste in a similar fashion. The diagram and model both bound the problem at the tank wall with modeled operations beginning when the Tank Waste Retrieval System (TRWS) is ready to enter a tank prior to retrieval.

Looking more closely at the TWRS diagram, its primary results are questions and insights. While reviewing the system diagram, one process reveals that one system operation may drop cut pieces of hardware to the waste surface. The question then arises, "Is leaving hardware on the waste surface desirable?" In another operation, questions were raised about the strategies for remediating a tank. For example, "Should waste or hardware be removed first?"

The OCM provides numerical data for the analyst regarding the operations represented. The most surprising result of the OCM is that hardware retrieval costs account for 63 percent of the total operations costs. By increasing the allowable size of hardware removed from the tank from 6 to 12 inches overall costs dropped substantially (by nearly 29 percent). Varying waste retrieval operations, on the other hand, only marginally affect the overall cost of operations.

While the previously discussed models focused on operations in a single tank, the TWR Amortization Model focuses on a single waste retrieval system operating sequentially in several tanks. This model reveals that as the number of applications for a particular system increase, the capital purchase, development, and installation cost per application drops dramatically.

Recommendations

While these tools and applications of the tools are still under development, and in some cases exploratory, they have been helpful for the analysis. Still, additional tools will be helpful in providing system analysis and cost justification assistance by providing the casual users and customers with a new and flexible method of analysis. The *ithink*® software should be explored further because it seems to have a high potential to be most useful. Other cost justification tools are being surveyed for potential use. It is recommended that the survey continue.

Additionally, performance testing is highly recommended because even though some teleoperational aspects of hardware retrieval have been accomplished, many remain. Further, a general procedure should be developed and adopted to assist RTDP personnel who are conducting system analyses. Such a procedure would help in the execution of analyses by providing suggestions for data collection, justification strategies, and decision making.

System Analysis: Developing Tools for the Future

1.0 INTRODUCTION

This report describes system analysis tools that are under development for the Robotics Technology Development Program (RTDP). It details the development completed thus far and then discusses methods of use for these tools. This paper reviews the use of tools in system and cost analysis of the Tank Waste Retrieval (TWR) systems at the Hanford Reservation near Richland, Washington. Additionally, suggestions are provided for future direction in tool development.

The programming of sufficiently detailed analytical models ("tools" in this report) for analyzing the costs and merits of possible robotic activities necessarily requires the programmers to gain a detailed understanding of the various options available to the activities which the tools are intended to analyze. Consequently, the development of the tools inherently provides the programmers with an in-depth understanding of the impacts of potential options and the relative merits of those options. Therefore, the process of developing the tools is as important as the results obtained from using the tools. Consequently, this study emphasizes the generic development process, not the results from specific models.

The report incorporates two major research related sections and two concluding sections. The first research section focuses on developing tools and techniques for the system analysis needs of the RTDP. This section begins with a discussion of an interpretation of the needs of the system analysis customer. Then it launches into a discussion of each of the tools developed, under development, or being explored for potential development. These tools include the following:

- a Process Diagramming Tool,
- a Cost Modeling Tool,
- an Amortization Modeling Tool,
- a graphical simulation linked to the Cost Modeling Tool,
- a decision assistance tool, and
- a system thinking tool.

It concludes with a discussion of performance testing in the RTDP.

The second major research section focuses on the RTDP effort to retrieve waste from the Underground Storage Tanks (USTs) at Hanford. First, it reviews some of the background of the challenges at Hanford, and it discusses some of the previously

proposed solutions. The analysis is then discussed. It focuses on the "Reference Concept" as discussed in Section 5.3.3 which used three of the tools explored in the Section 2.0. This examination yielded results in the form of a system diagram, an operations cost model, and a TWR amortization model.

In the concluding two sections, an assessment of the RTDP system analysis tools is made and some recommendations regarding continued development of them and related processes are discussed.

1.1 Benefits and Concerns of Using System Analysis Tools

Because the direction of this effort is set toward computer based system analysis tools, it seems appropriate to discuss the benefits or capabilities, as well as the limitations and concerns of such tools.

1.1.1 Capabilities and Benefits of Using Computer Based Tools

While each tool or technology described has its own capabilities and benefits, there are some benefits in using a system analysis tool that will be more or less independent from the tool chosen. System analysis tools can help conduct an inquiry into a problem or system by focusing the analyst's thinking while drawing on previous experience, providing a communication medium, and doing for the analyst much of the tedious repetitive work.

- *Focuses Thinking* By providing a framework into which data can be placed, tools have eased the burden on the analyst by allowing him or her to focus on the system of interest, rather than what data to collect. This focus allows the analyst to gain a better understanding of the system earlier. The analyst is allowed to place attention on the modeled system, the problem, their interaction, and the potential means to help the system perform its tasks better.
- *Draws on Previous Experience* The analyst can also benefit by using system analysis tools to learn from the experience of others. An appropriate tool provides a starting point for both the novice and experienced analyst. By using previous models, wholly or in part, an analyst can adopt insights gained from previous users of the tool, even if the he/she was the previous user. These insights make the building of a system analysis representation easier for new applications and allow cross checking of a new model with previous models.
- *Provides Communication Medium* System analysis tools can also assist an analyst when he/she is working with others to develop a mutual understanding of the investigated problem or system. An analytic tool can assist both customers

and analysts to see the problem they are attempting to understand from multiple views. Further, as options are considered and either discarded or retained for potential use, a tool can keep a history of decisions. This history helps in recalling which options worked and which did not.

- *Eases Tedious Work* Other benefits of analysis tools include those that ease calculation and visualization chores for the analyst. A good system analysis tool (or a combination of tools) will allow the user to complete complex calculations quickly and help to display visual graphical results from a set of data. Such tools can help the analyst visualize the problem, displaying a graphical rendition and analysis of that vision and sharing that vision with the customer. Additionally, it may prove useful for a tool to allow easy variation of a baseline option, or inclusion of stochastic processes, in a model to compensate for the natural variation in most systems.

These benefits have been found in a wide variety of tools, unfortunately not all in the same tool. To make use of them, an analyst will need a work bench on which he/she can use a variety of tools.

1.1.2 Concerns with Computer Based Tool Use

Similar to benefits and capabilities for the class of tools labeled “analysis” tools, there are limitations and concerns that exist simply because of the use of tools. The concerns that will be discussed primarily comprise the overall newness to system analysis of specific tools, the unstructured environment for analysis, and the presumed correctness of data.

- *Infancy of Computer Based System Analysis Tools* As stated, the introduction of tools to system analysis is relatively new. There have been some tools such as spreadsheets that look at a small part of an analysis, but an overall analysis of a system has normally been a long painstaking effort that an analyst completed by hand.
- *Unstructured Environment* The primary reason analysts completed such analyses manually was the unstructured environment into which they were thrust. In such an environment, where human perception contributes significantly to the analysis, computer based tools are very limited. Tools such as the process diagram provide the human assistance that is needed and ensure that powerful insights are included in the analysis. However, a computer based tool which can help structure the environment and account for these human inputs is not likely to appear until some time in the future.

- *Actual vs. Presumed Correctness* In order for a computer completing a quantitative analysis to produce accurate results, its input data must be “correct,” or as near correct as possible. In a system analysis, finding these numbers can be a major challenge. Tools that are to be used for general analysis will need to take this challenge into account and allow some forms of qualitative input or a range of numerical inputs.

Finally, a discussion must be initiated about computer models and/or simulations that are presumed to be correct. Computer based tools often lull humans into a false sense of confidence. With a lot of polish and shine, simulations and the accompanying details can “wow” customers and analysts to the point where errors are not noticed. The prevailing assumption, that computers must be right, needs to be checked at the door. Analysts and customers alike must scrutinize the results from computer based tools to ensure they are getting what they need from the tools and that what they receive matches their perception of reality.

2.0 DEVELOPING TOOLS AND TECHNIQUES FOR CUSTOMER NEEDS

In this section the needs of RTDP customers about system analyses are explored. Then, several analytical tools that have been developed and others that are under development are discussed. Performance testing as it has been used by RTDP staff is also discussed.

2.1 Customer Needs - An Interpretation

Before discussing the tools, it is important and necessary to give a quick summary of our understanding of the potential customer's needs in relation to system analysis tools. The customers, as understood by the system analysis team, include both analysts and the customers of the analysts. The customers need people who can bring skill and expertise in conducting system analyses to provide information that will determine if the expenditures of large capital sums are appropriate in developing robotic systems that retrieve waste and dismantle and decontaminate facilities in the Department of Energy (DOE) complex.

Proposed tools to meet these needs should have the following characteristics.

The method should be able to support the justification of technology options which include the following requirements.

- The reports should relay information in an easy-to-understand format that contains substantial accurate background research and that helps document the facts involved in decision making and justification.
- They should be flexible enough to incorporate requirements from the analyst's environment.
- Further, they should be easy for the analyst to use by providing well organized, useful reports for the analyst's customers.

A tool should provide an easy-to-follow representation of the problems and systems that analysts and customers are researching.

- The analysts would like to be able to see and show what work is required to develop systems to solve problems; and, further, how such systems will solve these problems; what benefits the systems will yield; and the costs they will exact.
- Also, analysts and customers want to know what would happen if the system is changed, or if the problem changes.
- Analysts need to know what effects changes on a proposed system may have on the results of a justification.

- The tools are also useful if they can answer questions about differing scenarios based on changing input parameters to the system.

Tools need to be flexible and usable in many applications for many systems.

- Flexibility and usability are especially helpful so that the analyst is not required to start from a “blank sheet” each time.
- Tools that allow him/her to utilize parts of previously collected models will be helpful.
- Finally, both the customer and analyst prefer tools that give them the correct answer, and that suggest the decision they should make.

Each of the tools described below meets some, or most, of the requirements stated above. The extent to which this effort meets those needs will be discussed later.

2.2 Tools Under Development

Through the course of the effort, several tools have been explored that could assist in a system analysis endeavor. There have been tools developed by the staff involved in RTDP, as well as tools found in the commercial sector that could help in the execution of system analysis. These tools are discussed in the following sections.

Groups under the auspices of RTDP have explored two cost based tools, one process oriented tool, and one decision oriented tool. These tools have undergone some development and may continue to evolve as the needs arise.

2.3 Process Modeling Tool (PMT)

The following section discusses the Process Modeling Tool (PMT), a graphical based diagramming tool, its potential uses, and it serves as a review of its capabilities and limitations. [SQNL 1995]

The tool, although similar to a traditional software flowchart, has some differences. It shows the various activities, decision points, and options available at those decision points during the completion of a system's waste retrieval tasks. Through the use of graphical symbols, the model allows the user to see the impact of decisions.

The process tool was developed to provide an easier method for non-technical users to understand the activities behind any process that is being documented or

developed. In this case, the process is environmental restoration and waste management through the use of robotics.

Using this modeling tool, the analyst and customer execute manual exploration of project options through path tracing with the addition of values to each of the process steps. The values used are associated with individual tasks or activities that comprise the system's operation.

2.3.1 Using the PMT

A process, or flow, model is a graphical (or schematic) tool that is similar to the software flowchart that software developers use to complete the documentation of their products. In this case, the tool, intended for decision assistance and documentation, has been used to show the logic and flow of logic behind the potential activities and decisions that will be made during the execution of RTDP efforts.

2.3.2 PMT Components

The process model is a visual device used to assist analysts and their customers in understanding how a system works. The current version of the tool is primarily a manual device with some links to a calculated model. The process modeling tool uses symbols similar to software, organizational, and business modeling programs. Figure 1 on the next page shows these symbols with labels. When blended into the overall schematic diagram, they provide the user with insights that other detailed methods of modeling leave obscure.

Figure 1 Process Modeling Symbols and Explanations

The module start and the result, or goal, symbol bound a process, whether it is the overall process or a sub-process. The start symbol indicates where the flow begins. The goal symbol shows what the analyst or customer expects to be the result of completing a process.

A diamond shaped symbol, the decision point, shows a point in the process where a decision is to be made. The decision diamond allows for several potential outcomes of the decision.

The action block shows an activity or task that may be completed during the system's operations. When the action block in the process diagram is associated with a sub-process symbol, it refers to a more detailed breakdown of the sub-processes. The sub-process (which consists of its own series of action blocks and decisions) provides more detail for understanding the overall set of activities needing completion.

The option block provides a description of a decision's potential outcome. As the action block may decompose, so the option block may explode to a series of processes, decisions, and options which provide a greater level of detail.

2.3.3 An Assumption

The underlying assumption of the process model is that more than one option exists for solving a proposed problem. With any system, a decision maker may be faced with many decisions as he/she traverses a path to determining the most correct, or most feasible option among several. The process diagram tool allows the decision maker to see where those decisions could provide the most impact for the least effort. The tool can also indicate resource intensive operations which need special attention, where questions need to be resolved, or operations where the choice of options represents the difference between success and failure.

2.3.4 What an Analyst Needs to Know

While building a system's process model there are several things an analyst must remember. The primary knowledge of the system usually resides with the customers, users, or staff maintaining or developing the system. From these primary information sources, the analyst must establish a high level working knowledge of the system under investigation.

As the diagram/model is fleshed out, questions naturally arise, and they must be resolved. The analyst should feel free to include such questions in the diagram, potentially with notes on how they might be resolved. These questions are important because they raise the awareness of the analyst as well as those with whom he/she is working. The analyst also needs to know of options available for each decision. By knowing the options, he/she is more likely to be able to understand some of the implications of each option. To strengthen the analysis, a working technical and economic knowledge of the background of the options, as well as potential political reasons to choose the options, is valuable information.

As stated earlier, the analyst needs access to persons knowledgeable of details in the sub-processes of the current or proposed system. Information from these knowledgeable people can provide insight on how the sub-tasks are completed, or how a system works. They can provide comments on the diagrammed system to help improve the analysis.

2.3.5 Analyzing a Problem or System

[SQNL1995] describes the effort required to solve a problem in the following manner.

First, identify the elements of the system that are expected to complete a set of tasks.

Second, identify the set of tasks.

Third, determine how the system elements will complete the tasks.

In the process diagram, the analyst must also identify decisions that will need to be made while completing the tasks.

The process diagram is initiated by determining the scope of the system under investigation. The study is more likely to succeed if the process flow has distinct boundaries. The next task is to analyze what is known about the system being studied. Then, the analyst develops a high level diagram of the problem and the proposed system operation, which includes the tasks it must complete. During this initial analysis the analyst places indicators in the model showing where questions exist and where decisions are expected to be made or have been made.

As more information is gathered, the modeling tool adds successive detail beneath higher level tasks in a decomposition, or top-down, definition of the system or problem being studied. The analyst who has developed a high level model will take a component of that high level model and distill it into more detail. This decomposition will provide more information about how the activities or tasks are completed. Figure 2 provides an example of how this decomposition is formulated. One advantage of these sub-models is that they allow the analyst or customer to see, or show, only as much information as is needed to understand the process.

As mentioned earlier, questions are appropriately placed in a process diagram. They serve to point out where information is lacking and where a better understanding of the system and its associated tasks is needed. To provide a more complete understanding of the system, measurable values can be assigned to activities in the tool regarding task duration, costs, or whatever is important for the analyst and customer.

For example, a process value of time to complete tasks could be assigned to an activity, or set of activities. Additionally, costs, whether in dollars, radiation dose, or other units could be assigned to activities in a process. Benefits, perhaps less

measurable, could also be assigned. Then, using an appropriate function, these values would be grouped to provide some measure of the worth of particular options.

2.3.6 Capabilities and Benefits

This process diagram tool provides several capabilities. It allows an analyst to share with his/her customers a pictorial or schematic understanding of a problem or system being investigated. This schematic modeling of a system provides a better communication medium than does the written word. As such, misunderstanding of system operation, boundaries, and interfaces is lessened. The flow model allows users, customers, analysts, and others with differing view points to see the system and its tasks from a similar perspective and allows them to identify any tasks, activities, decisions, processes, etc. that need further clarification or correction.

Finally, a modeled system can be decomposed to the necessary level of detail required to provide the analyst and the customer with an understanding of the system, or problem, and any proposed alterations or solutions.

2.3.7 Limitations and Concerns

Currently, there are some aspects of the graphical schematic model that reduce its usefulness. Foremost, the process diagram development is a manual effort. As such, it is a very slow and tedious process. During the creation of the model described in Section 10.3, "TWR System Diagram," various processes and their interactions could be disturbed, but during a "walk through" of the modeled process activity, task values were manually altered and tracked. Automating the model building and execution would enhance the usefulness of the schematic charts and the model.

Another limitation is that it is not a one person effort. The analyst, without the assistance of knowledgeable people, must know the activities or tasks very well to complete a process model. The development of a process model for a system works best with multiple people. One person developing such a model can miss some important issues that other people could notice.

2.4 Cost Modeling Tool (CMT)

The Cost Modeling Tool (CMT), which was developed by Sandia National Laboratories (SNL) staff, and it examines a look at a system, process, or problem from a view of cost and time to complete activities.

2.4.1 Purpose of the CMT

The CMT primarily focuses on operations to complete waste retrieval or similar activities. It is currently specific to a series of tasks associated with the retrieval of waste from storage tanks using some form of remote manipulation under some range between teleoperational and telerobotic control.

The continuing purpose of this tool is to associate operations with their completion times as well as the cost of those operations. There are components of this tool that could be used in models of other processes. Operations such as mapping a particular space, attaching an end effector, moving an end effector along a surface, and inserting and removing a system into a hazardous environment are a few of the modeled tasks that could prove useful in other operational models.

2.4.2 Description of the CMT

The CMT is a workbook made from Microsoft Excel™ spread sheets that provides a very detailed look at a process or problem. It provides aggregate and/or detailed time and cost values into which the analyst may place values which will be used to calculate effects on a modeled system. For example, in the TWR Operations Cost Model, which is discussed in detail in Section 7.0, the insertion and removal times have been aggregated into two numbers from the several components of that sequence. The waste retrieval process, however, is decomposed into greater detail, such as the time to attach an end effector, time to map a layer of waste, etc.

2.4.3 The Structure of the Cost Model

The CMT is the first attempt at modeling operations associated with RTDP by Sandia. As such, it has been evolving over the time it has been used. It began very simply and has evolved to reveal a complex system.

The CMT is designed in an hierarchical structure. It has a very general representation of the problem under study at its upper levels. From this general representation an analyst can delve into detail regarding a particular operation or activity. Figure 3 shows the upper level structure of the CMT, and Appendix B has all of the structural details as applied to a TWR problem. As the model is developed for a spread sheet application, all of the tool's detail is held in a main calculation sheet. However, there has been some attempt to insulate the analyst and his/her customer from much of the calculation detail through the initial development of a user interface and through the partitioning of detail so that the user sees only what is needed.

Figure 3 High Level Structure of the Cost Modeling Tool

The partitions allow the analyst to look only at the activities of interest. Figure 4 shows an initial screen.

	A	B	C	D
1	Model Summary Statistics			
2				
3	Total Costs to Remove Waste from a Tank			
4		Total Cost to Remove Waste	\$1,203,620.26	
5				
6	Costs to Insert TWRS (1)			
7		System Insertion Cost	\$57,152.00	dollars
8		Total System Insertion Time	320.00	hours
9				
10	Costs to Complete Primary Waste Retrieval by Manipulator (88)			
11		Primary Waste Retrieval Cost	\$191,383.34	dollars
12		Manipulator Retrieval Time	1,386.53	hours
13				
14	Costs to Complete Residual Waste Retrieval by Manipulator (89)			
15		Cost to Remove Residual Waste	\$67,918.14	dollars
16		Time to Remove Residual Waste	492.05	hours
17				
18	Costs to Retrieve Hardware			
19		Hardware Retrieval Costs	\$439,091.38	dollars
20		Time to Retrieve Hardware	3,286.61	hours
21				
22	Costs to Remove TWRS Time (3)			
23		Total System Removal Cost	\$71,440.00	dollars
24		Total System Removal Time	400.00	hours

Figure 4 An Example Screen of the CMT

For example, if the analyst is studying the impact of changing the application environment in which the system will operate, he/she need only look at the sheet of environmental parameters. Similarly, if changes to the robotics system or personnel parameters are being investigated, they have their own special worksheet in which their values can be altered. Of these three, the robotics system parameters are the most detailed. Additionally, a summary sheet showing the upper level results is available.

2.4.4 Overview of the CMT

The CMT examines a single variation of a proposed system in five different phases of operations. They encompass most of the RTDP activities including system insertion into the waste retrieval and decontamination and dismantlement environments through the removal of the system from the environment and decontamination of the system.

The CMT tracks three general operations after entry into the environment. These operations can happen in any order as deemed necessary. One operation includes retrieving hardware from the environment. There are several sub-operations also included, ranging from cutting the hardware to placing a cut piece of hardware into a basket (or bucket) for removal from the environment.

The CMT accounts for two types of waste retrieval operations in the tank world environment. The first operation, primary waste retrieval, allows the robotics system to quickly remove most of the waste found in the environment. The proposed system will be designed to retrieve waste efficiently because it can maintain some distance from obstacles in the environment. Thus, the operator of such a system would not need to be concerned about coming into contact with obstacles or damaging some component of the remote manipulation system.

The remaining operation is the residual waste retrieval (the second mode of waste removal). In the model, the CMT allows for the modeling of slower, more precise operations for waste retrieval around obstacles, near walls, or near the retrieval equipment itself. The tool allows for a predicted reduction in speed of the operations of the retrieval equipment, thus accounting for additional costs as a result of the additional time required to complete operations.

2.4.5 Environmental Parameters

The CMT also supplies the capability to analyze various environments based on constraining factors within those environments. Whether the environments are tanks or facilities designated for decommissioning, the various components of the CMT can be incorporated into a model allowing analysis of the system being

examined. The tool can be adjusted to reflect the amount of hardware in a system, if there is any waste in the system to be removed, and the amount of that waste. This section can also reflect safety concerns, or issues, by allowing a set percentage of residual waste. This percentage will provide an indicator to the system that waste retrieval efforts should be adjusted when a certain level of "cleanliness" is reached. This percentage also indicates when costs will be altered for each unit of waste retrieved.

2.4.6 Personnel Parameters

The system can also be configured to permit varying personnel assignments. It will allow the analyst to adjust the number of workers and the number of supervisors assigned to the major tasks. It will also allow the variation of the hourly rate of supervisors and workers and the number of hours that employees spend completing the major tasks assigned to them. Recognizing that not all work completed during a day will make progress in achieving the goals of the system, the capacity for training, meetings, minor repairs, and other activities not directly contributing to the completion of the projects can be modeled. This allowance is currently expressed in terms of hours per day worked, that directly contribute to the project completion effort.

2.4.7 Operations Calculations

For the most part, the information just discussed enters into the calculations section and yields results with standard arithmetic and algebraic calculations in a relatively straightforward manner. The exception is the utilization of the random functions within the Excel worksheets to model stochastic processes inherent to the robotics and human operations. In this case, it is understood that the tasks taught to a robotic manipulator have an 80 percent probability of success. This figure leaves a 20 percent probability that the task must be retaught to the manipulator. The CMT has accounted for this discrepancy by using the "random" distribution from the Excel program and associating it mathematically with the manipulator reteaching as calculated within the tool.

2.4.8 Suggested Use of the CMT

The CMT allows the analyst to conduct sensitivity analyses to establish trends in performance data or to determine where minor changes in a task can improve the end result of the system. This style of using the tool does not produce a single answer, rather it gives a series of answers that provide a better understanding of the system, procedure, or product under analysis.

Because many factors contribute to changes in a system's ability to perform an analyst must be familiar with the operation of the system. If the system is not yet developed, it is necessary to understand the design and proposed method of operation. With this knowledge, the analyst will be able to gain more insight about the operation of the modeled product from the tool.

Some of the information necessary in using the model is data that establishes the scope of the problem under study. For example, what will the system do? Will it clean tanks or remove decommissioned systems from buildings? If a system is cleaning a tank, does the model need to encompass the flow of the waste beyond the walls of the tank?

After the scope has been determined, the parameters for operation of the system must be decided. For example, what system operations will the CMT model? In a system decommissioning, are there concerns with how components of the system are decontaminated? Will these components need to be cut into multiple pieces to facilitate disposal? In a tank waste problem, what type of a waste retrieval end effector will be utilized? What are its characteristics?

As the analyst investigates the system's cost and operations, the data requirements of the CMT need not be totally fulfilled. Estimated nominal values within a model can provide valuable insights to the operation, and, hence, the costs of the system. A host of information can be derived by using sensitivity analyses of several variables of interest in the model. As alluded to earlier, a sensitivity analysis conducted using CMT involves several runs of a model in particular configurations. The analyst alters selected parameters of the modeled system, ideally one at a time, noting how the end results of the model will change. Analyzing these end results allow the analyst to determine which factors provide the most response for the changes made.

Through the study of the modeled product or system, the analyst should be able to estimate which factors have the most impact. If there are a tremendous number of unknowns for the system, a sensitivity analysis can provide insights concerning the variables that have the most impact on completing the tasks. By using sensitivity analyses to determine which operations have the greatest impact on the outcome of the process, an analyst can seek data for those operations first. Collecting the high impact data first, the analyst can use CMT to produce results early in the analysis.

It is very important to have data for the model that mimics the operation of an actual or a similar system. The more accurate the parametric data entering the CMT, the more realistic the results will be. The CMT has available stochastic or random elements to replicate some of the uncertainty found in all systems. If used, it is best to execute the sensitivity analyses several times without changing the parameters and then determine the distribution of results. By incorporating a

distribution, the results of the model can approximate occurrences in the actual system. From the results, an analyst should determine the mean of the results as well as the standard deviation. This additional analysis will provide indications of either the costs or time involved in conducting an actual waste retrieval process. Key variables, as determined earlier, should also be studied to provide some insight concerning the results of the model runs.

2.4.9 Capabilities

The CMT provides a method of relating the operations of a system to its cost more easily than the process model. The relationship between cost, time, or other factors can be defined by the analyst as he/she deems appropriate. CMT assists in conducting sensitivity analyses which point out the operations in the model most susceptible to change as a result of changes to the input. The results of the sensitivity analyses provide the analyst an indication of where it is most important to have the most correct information for the model.

Some additional strengths of this tool are that the model is very detailed. This detail provides the analyst with options in the creation of similar models in the future. He/she can take sub-operations as shown in a model, rearrange, duplicate, or alter their structure slightly for use in models of other operations. The relationships between these sub-operations will need to be reestablished to ensure a correct model. However, the individual operations will have been established for consideration in new models, and, in some cases, performance data have been collected for the individual operations.

For example, the tool with its current application of the TWR operations, can be leveraged for use at several sites of interest to RTDP. In one instance, the general operations at Hanford's waste tanks and Oak Ridge's Gunnite tanks are similar, so the model could, with minor alterations, be used in studying the operations of both locations. Using these leveraging details, this modeling tool is capable of making rough predictions of the operational times of various tasks based on the input from knowledgeable people or actual performance data.

Another advantage of the CMT is the potential inclusion of stochastic factors. Using random distributions, approximation of the actual randomness of natural and human processes can be included.

To assist the analyst, there are several groupings into which the model segregates the detail. First, all of the calculations are completed in one location. To avoid unintentional alterations of the calculation sections, there are three input sections. Information concerning the system being investigated is placed in one section, data on the environment in another section, and personnel data in a third section. A

summary section shows the results of the current execution of the tool, with some detail as needed to give an overall impression of the system's operation.

2.4.10 Limitations

Just as this tool has several important capabilities, it also has some limitations that need to be discussed. The most noteworthy is its inability to easily show a "big picture" view of the system being studied. Some reasons for this limitation include:

- the tool's focus on operations of a system during its duty cycle makes it easy to get lost.
- the detailed view only shows numerical indicators at one point in time, with one setting of input parameters.

This single point estimate methodology obscures trends of system performance. In the operation of a system, trends are important because they provide insight about the future performance of the system. Because CMT only shows the values associated with operations at the completion of tasks, it does not allow for observing or changing of the trends during a "run" of a model. It also does not allow reaction to, or changing of, these trends. Consequently, CMT's flexibility in predicting the operational characteristics of a particular system is reduced. Unless a person is intimately familiar with the modeled system operations, predicting future system performance based on changes to system, environmental, or personnel parameters will be very challenging.

The operational cost model does track costs associated with a system completing the activities to fulfill its mission. A capital cost model (or amortization model as described in the next section) can allocate costs over the life of the system to give a much better system view of one time or periodic costs.

While obscuring information about trends, the amount of detailed information can make the tool seem unwieldy and it can obscure some important information. Further, the detail can also hide potential errors. The combination creates a challenge in finding errors or determining the reasons modeled scenarios "just don't make sense." These errors can be very difficult to find because of all the information that must be verified.

The CMT at the present time does not have an integral visual representation of the results from the execution of the model. A visual aid resulting from the tool's execution would be a great help in understanding the effects of changes on an overall system instead of the effects on a component or two.

Finally, the tool requires accurate input data to provide a reasonable representation of the system. In the case of robotic systems, experimental evidence is highly desirable. With such experimental data collected for the modeled system components, future models or robotic processes using similar components will be much more accurate.

2.5 Amortization Modeling Tool (AMT)

The Amortization Modeling Tool (AMT), which was developed by SNL staff, allows an analyst to determine the effects on overall project costs using robotic components for applications beyond the initial use of the system.

2.5.1 Purpose of the AMT

The AMT addresses several factors affecting the overall costs for the development of a robotics system. The model is designed to spread costs over the life of a system rather than applying all of the costs to the first application. The model provides for two types of project cost, those that do not repeat when additional applications are completed, and those that repeat (by some percentage) as a recurring cost when each application is completed.

2.5.2 Applying the AMT

The AMT addresses the amortized cost considerations derived from sources of cost estimates for human/teleoperated systems in a particular application. An AMT application would in all likelihood have the data elements with the associated considerations described in the following paragraphs. It should be noted that, although this initial version of the tool does allow for multiple systems, effects of the potential impacts on a human operator in a repetitive environment will need to be factored into future models as that information becomes available. These considerations are important, but information on the effects have not yet been incorporated to allow additional differentiation between teleoperational and telerobotic environments.

2.5.3 Data Elements

This initial version of the AMT has a limited set of data elements. These elements of the information base provide a representation of the type of behavior expected of a typical robotics system. A more detailed analysis might reveal additional elements of data that were appropriate for consideration as well. For now; however, the following general elements are used in the model.

- Unit Cost Estimate - This data element represents the total projected cost of a single system unit that will be used to accomplish the required tasks.
- Number of Applications - This data element represents the number of applications of a single system unit and its associated technology to complete the required tasks. Adjustment of this element affects both the " Amortization per Application " and " Total Recurring Costs for All Applications."
- Amortization per Application - This data element represents those costs that are "one time" costs and that are essentially not required to be repeated for additional uses of the system. This cost amortizes with a decreasing amount on a per application basis.
- Recurring Costs per Application - This element represents costs that will occur with the initiation of each application of the system. In this case, the AMT aggregates the cost to increase total project costs for each application of a system.
- Total Recurring Costs for All Applications - This column represents the total recurring costs for all uses of a system. It is computed as either:
 - (a.) Some fixed percentage multiplied by "Number of Applications," for costs that aggregate for all uses of a system (e.g., replacement parts costs) added onto the original capital expenditure for purchase or build; or
 - (b.) Some fixed percentage multiplied by ("Number of Applications" entry minus 1), for costs that will aggregate for all applications done after the initial use.
- Total All Applications - This data element represents the *total* capital cost estimate. Since the individual line amounts extracted from the source of cost data may be either an amount that is amortized, or a recurring amount (or split to both types), this data element should be computed by using the formula:

$$\text{Total All Applications} = [(\text{NumberOfApplications}) * (\text{AmortizationperApplication})] + (\text{TotalRecurringCostsforAllUnits})$$

This equation formally addresses the fact that the original cost estimates of system units from the cost data sources may be replicated in whole or part by either the "Amortization per Application " or "Recurring Costs per Application" data elements.

- Other data elements that may be included in the model, but are not required include:
 - Descriptions of the items that make up the cost estimates, be they single units, maintenance costs, utilities, personnel, etc.
 - Remarks reflecting the assumptions made concerning values assigned to other data elements.
 - Information on the source of the individual estimates that were placed in the model.

2.5.4 Capabilities

The AMT gives a general overview of the system to build or project to fund. It supplies the analyst with a tool that can show the effects of changes to various parameters within the system. AMT also provides a framework in which a customer, manager, or analyst can try out various system application scenarios.

The AMT allows the analyst to study factors that affect all system applications and allocates cost effects to all of the applications. Using this tool, the set-up, fabrication, research, and other one-time costs can be allocated to each system application. This allocation provides a more accurate cost picture of individual applications and shows how the initial set up costs for each system decrease as a system unit is reused over the course of time.

The AMT can provide information on the true savings (or costs) of systems as the production unit is developed, deployed, and reused. For example, an application of the tool could include factors such as research, requirements definition, design, site preparation costs, capital equipment and supply purchase, as well as maintenance costs. The tool could also include the costs of human or environmental exposure to hazardous materials, radiation, or other undesirable substances.

For each additional user in RTDP, more knowledge about the cost of robotic dismantling and retrieval systems can be gathered. The framework is easily alterable so that any new information acquired can be placed in a model. Data elements that do not apply to a specific system can be removed from consideration.

The AMT's simplicity is also a benefit. A model that can be seen on a single page, allows the analyst and customer to easily see the interactions of the system. Additionally, the effects on the costs because of the reuse of a system are more easily seen.

2.5.5 Limitations

Because AMT is new, there are still many information needs that must be met, as well as validation of the tool that requires completion. As this use of the tool was a limited study to determine its potential utility, there is some concern about the lack of information on costs that occur with the re-application of a system unit. At the present time, there is no guidance provided by AMT on how much of a cost will be incurred with each application for spare parts, maintenance, system installation, deployment, etc. The analyst will need to collect this information as the tool is used.

As with the Cost Modeling Tool, accurate data are required. Without accurate input data, the singular point estimate of the model does not provide the analyst or the customer useful information. Also, a limiting feature is the lack of graphical representation of output data. At the present time there is only a limited method to show trends of the data over the re-application of systems. Given a set of assumptions and input data, the AMT presents a final number to the analyst and he/she will need to provide some interpretation of how that number was derived and how it can be used.

2.6 DECIDE

The DECIDE (DECISION Definition and Evaluation) tool was designed by JBF Associates in cooperation with Oak Ridge National Laboratory (ORNL) to provide assistance for managers studying the differences between robotic and human options in completing environmental waste management tasks. The tool is designed to help a decision maker balance the need to make a decision with the availability of information. The purpose of this effort was to provide a tool to compare options for decontamination and dismantlement.

2.6.1 Description

DECIDE, a software based tool, was initially developed to assist decision makers at the Idaho National Engineering Laboratory (INEL) to determine an appropriate method to decontaminate a high radiation "off gas" cell on site. Managers at INEL requested assistance in choosing the best of four options. As such, the methodology behind the tool, as well as the tool itself have been alpha tested. The current version of the tool is being used at the Argonne National Laboratory to assist in the clean up of its CP-5 reactor.

The tool assists an analyst by recording facts gathered from a facilitated meeting to gather information in making of a decision. The software (as specified in [GUTHR 1994]) follows a general ten step approach to identify the best

alternative to solve a problem using the minimum amount of information which allows discrimination between options proposed. The steps are similar to approaches used in system analysis except they have been partially automated.

2.6.2 Capabilities

The advantage of using a computer and a facilitator trained in this approach is that important steps are less likely to be skipped during the course of the decision making process. The computer also assists by scoring results through weighting options.

The DECIDE tool supports the analyst and customer in several ways. First, the tool and the approach for using it are simple and easy to understand. This simplicity allows the decision maker to focus on the problem at hand. Both bring together a group of people and facilitate communication of ideas and concerns that will affect the outcome of a decision. This process is an iterative one where the goal is group consensus. This facilitated approach often leads to better decisions because the concerns and ideas are expressed and documented. Because the tool is easy to use, a decision maker inexperienced with it can make an informed choice of one option from several proposed options without extensive training. The tool helps by indicating through visual cues, which option would be the best choice given the current information base. These visual cues also signal through the use of graphs where additional data would be best collected to help discriminate between the options.

DECIDE uses a library of facts from previously studied systems to assist in the decision making process for a current problem. Then attributes of the current problem are placed in the library because similar problems may arise and better solutions are often found to challenges when the library of stored information is considered. Using these libraries, the tool can accommodate as many decision factors as the user wants to incorporate into the decision making process.

In other aspects, the tool tolerates uncertainty in the knowledge of the decision maker and those who have information to add to assist the decision maker. Additionally, assumptions and justifications or reasons for pursuing a particular path can be included in the DECIDE model. This information helps later in the explanation of the material presented by the decision maker. The software assists in this documentation by making presentation of information concerning the decision less cumbersome.

2.6.3 Limitations

When the input to DECIDE contains uncertainty, however, it produces uncertainty in the output. It requires an extensive collection of information to discriminate adequately among options.

Figure 5
Options
Comparison
Chart from
DECIDE

Figure 5 shows the results of the analysis of four technological alternatives to solve a particular problem. For each alternative, there is a "most likely" score; for example, 7 for Alternate 1, 10 for Alternate 2, and so on. Surrounding this nominal score is a range in which the score could actually fall; for example, for Alternate 1 the score could be 2 or 10 with some probability, more likely falling near 7, and so on. To reduce this uncertainty range in the current version of DECIDE, more data must be collected moving the ranges closer to their nominal score.

Without a great deal of data, DECIDE yields a wide range of uncertainty around each nominal score as shown in Figure 5. As uncertainty of data clouds the decision making process, so it clouds the ability for DECIDE to present a clear choice. Often the nominal score of one option is bounded by uncertainty limits which overlap other scores significantly. This overlap causes a clearly superior option to be rendered invisible to the untrained eye. Figure 5, [GUTHR 1994] shows this limitation in pictorial detail. If this limitation is mitigated and DECIDE can provide a more discerning analysis with less data, it could be a very powerful RTDP decision tool.

3.0 COMMERCIAL TOOLS

In the next sections, two commercial tools used to some degree in the RTDP are described and some capabilities listed.

3.1 *ithink*® - A Process Modeling Tool

The tool, *ithink*®, is a system analysis tool in the most general sense. It is designed to help describe how a system works so that an analyst's customers can better understand the decisions they are facing and the options they have.

3.1.1 *Description*

The software provides the analyst with a graphical method to model systems. A model is developed in an hierarchical environment which allows an analyst to build and interact with graphical models. The graphical component of the model assists the analyst in getting information from customers and explaining the system which he/she is studying. The environment consists of two major levels,

- the "High Level Mapping and I/O layer" and
- the "Model Construction layer".

From each of these levels the analyst can move to deeper levels of detail through the use of sub-models which pass information back to the mapping level through the construction level. The *ithink*® modeling tool and the modeling process use layering to control the complexity to which the users of the tool (analysts or others) are exposed. In order to build a system model, an analyst focuses his/her efforts on the most important aspects of the system. This approach to modeling, the top-down approach, is strongly encouraged by the *ithink*® development environment. A system map, (in the high-level mapping & I/O layer) provides a method to direct customers as well as analysts toward sources of information. The detail of a system model which describes how a system operates and how it interacts with other systems is located in the Model Construction Layer. Finally, more detail can be found in a micro-detail level of sub-processes and sub-models.

3.1.2 *Capabilities*

As mentioned earlier, the *ithink*® software provides a very powerful capability as a graphical analysis tool that can help in decision making processes through information layering. The models developed by an analyst using the modeling process promoted by High Performance Systems (the *ithink*® vendor) allows him/her to show as much detail as necessary to explain the operations of a system being studied without overwhelming the customers. Another advantage of this top-down

development environment is the maintenance of a clean and simple diagram. By keeping it simple, the customer of the analyst is less likely to be overburdened with detail.

The authoring version of the tool adds one other capability through its graphical "flight simulator." [JOHNS 1994] states that the simulator allows those persons not intimately involved in the detailed development of the system to "create and experience the dynamics of the system" the analyst has modeled. Through the use of the flight simulator other people than the analyst can vary selected inputs to the model and determine the effects of these variations.

Another important capability of this tool allows a user to provide input by graphical functions. The system permits the user to provide the input by sketching the behavior of a particular function based on his/her interpretation of how that input will cause the system to behave. No longer does an analyst or customer need to provide a complicated formula describing the characteristics of a particular input of a system.

The tool can also conduct sensitivity analyses by varying selected inputs automatically. The input and output features of this tool are some of the easiest to master for any simulation the authors have seen. As the analyst is allowed an easy way to describe inputs, he/she is given similar options in the generation of the output information. Graphs, tables, and numeric display devices allow the user to pick and choose which information needs to be displayed for the consumer of the project data.

A distinctive characteristic of the tool, not to be overlooked, is its ability to investigate intangible properties of a system. For example, in a model which studies the efforts to decontaminate and decommission a nuclear facility, there may be some effects due to negative (or positive) publicity that the customer wishes to model. Finding or developing an explicit function for a numerical simulation would be difficult, if not impossible. However, a customer can tell an analyst that there is an effect that he/she wishes to achieve. They can even specify how that effect manifests itself in terms of funding, or other characteristics that may be very important to the system simulation as a whole. The customer might be concerned, for instance, with the intangible area of fatigue in an operator and how that factor effects safety as he/she operates a robot arm to retrieve hardware or waste from some site. The customer might not have an idea of the explicit details of a function that represents the effect of fatigue on safety, but he/she could graph the effects with this system.

In short, *ithink*® appears (in comparison to others) to be an investigative tool that is just starting to be used in RTDP for analysis of systems. The investigation of its capabilities needs to continue.

3.2 IGRIP Modeling Tool

The Interactive Graphical Robot Instruction Program (IGRIP) is a comprehensive 3-D CAD package which includes device modeling, including kinematics capabilities and workcell layout generation. [Davis 1995B] and [Deneb 1995] provide insight into the use of this tool.

The IGRIP 3-D graphics-based simulation software package provides an interactive environment in which to verify production concepts, workcell designs, and manufacturing processes before implementing them on the shop floor. IGRIP provides interactive program debugging for increased production reliability, human/computer safety, and productivity. The software includes built-in libraries of robots, common production equipment, and application-specific options that include tooling such as spot weld guns.

Within IGRIP, the user can create any kind of 3-D object using the CAD package or import objects drawn with other CAD packages (IGES, DXF, CATIA, etc. formats). The objects are then connected together to form devices. Once devices are generated, they are placed in a workcell. The devices in the workcell (such as a robot) can be programmed to move to certain locations, grab other objects, etc. IGRIP allows the user to create any kind of device to perform tasks.

Robotic workcells can be simulated to demonstrate and analyze automation capabilities, check for potential collisions, and negotiate requirements with Sandia's Intelligent Systems & Robotics Center's (IS&RC) customers. The IGRIP/ERGO option can simulate manual activities needed to help compare robotic and manual operations. Such items as safety and radiation exposure comparisons can then be made.

Certain optional IGRIP features can be purchased in addition to the base product. These include spot welding, arc welding, finishing, painting, calibration, dynamics, cabling, stereoscopic viewing, low-level telerobotics interface, ergonomics and virtual reality.

3.3 QUEST™ Modeling Tool

The QUeuing Event Simulation Tool (QUEST™), which was invented by Deneb, Inc., is a discrete event simulation product that serves as a platform to model overall systems which potentially have robotic and other components. [Davis 1995B] and [Deneb 1995] provide insight into the use of this tool.

QUEST™ has features that are found in most simulation tools plus a few extras. Some of the similar features include activity based accounting, graphing, and simulation language tools. The activity based accounting tools include mechanisms to measure the costs of processing, raw materials, transportation, repairs, scrap material, and overhead. To display these costs the simulation tool uses the standard tables of numbers, or it can use comparative graphs in bar, line or pie formats.

Further, the simulation language provides a high level, structured language to solve problems unique to a customer's situation. At present, QUEST™ provides 3-D figures which other products do not. QUEST™ goes further by providing three dimensional figures of items such as forklifts, cranes, work process, and even robots. If these models don't meet the criteria of the customer or analyst, other 3D figures can be created. Finally, with these figures, physical properties such as speed, length dimensions, and facility layouts can be assigned which can help in the modeling of tasks using QUEST™.

4.0 RESULTS OF PERFORMANCE TESTING USED AS A TOOL TO INCREASE UNDERSTANDING

Reliable methods for estimating the costs and benefits associated with telerobotic devices deployed in environmental restoration and waste management missions would serve as useful tools for policy makers within the U.S. Department of Energy (US DOE) and for other stakeholders. Unfortunately, performance data that would be useful to evaluate the robotic devices used for these missions is lacking.

RTDP, as part of US DOE Office of Science and Technology (OST), is developing methods for gathering telerobotic system performance data. This work is being performed by ORNL, SNL, and Pacific Northwest Laboratories (PNL). To support performance and cost modeling, a series of experiments were proposed to investigate interesting variables as they relate to the following issues:

- telerobotic system performance,
- waste retrieval, and
- in-tank hardware handling (ITH).

4.1 High Level Description of the Technique

The goal of the proposed experiments was to provide realistic TWR task performance data. To that end, realistic tasks and situations have been identified for completion by remote control operators. Because the data were integrated into a task network simulation and the operation cost model, it was adequate to collect sub-task data in some cases. This use of sub-task data enhances the efficiency of the experiments.

Dependent variables, or performance criteria of interest, include efficiency, effectiveness, and ease of use. Specific methods for measuring these variables are described later.

Data gathered was employed to enhance previous research using task network models and cost benefit models for evaluation purposes. The realistic data gathered under the testing plan can be used to validate task network and cost/benefit models in previous and future analysis simulation studies.

In addition, the discovery of novel scientific detail related to the scope of the project is a positive by-product of performing realistic research. As the TWR testing progresses other benefits now unforeseen may be derived.

Selection of tasks for the testing program were based on the task network models produced in recent simulation studies. Thus, task time estimations for selected tasks were derived from measurement of human-machine performance of representative tasks, preferably using existing manipulators or, if necessary, interactive simulations. Allowing "hard" data to replace opinion data of somewhat less reliability enables a robust analysis of the efficiency, effectiveness and ergonomic impact of the TWR robotic system. This section of this report describes the first attempt at such a testing program.

4.2 Detailed Description of the Test Task

This experiment used the Dual Arm Work Module (DAWM) to evaluate four factors.

- the impact of cutting tools and the level of control on pipe cutting task performance efficiency,
- work quality,
- collisions with the environment, and
- ease of use.

Data collection used a multi-measure approach to adequately describe system performance. Variables measured during the test program included:

- a.) **Task efficiency** - the time required to complete tasks. Task efficiency was measured as the time required to complete a task in seconds. Time measurements might be taken by any convenient instrument.
- b.) **Collisions** - number of collisions with walls or surfaces. Collisions with the wall or with other surfaces in the task area were recorded by a test observer as they occurred. Walls were simulated using cardboard, Plexiglas, or other material. Task repetitions might be videotaped to allow these data to be captured with more accuracy.
- c.) **Ease of use, workload, and fatigue** - ease of use, workload, and fatigue were measured using the NASA TLX workload measurement system. The NASA TLX is a computer administered workload rating scale that assesses how hard it is for a human to perform a task. These data may be combined with other data to evaluate the risks of human errors associated with workload and fatigue. Ease of use measurement might include an evaluation of the degree of "immersion", "telepresence", or "flow."

The test task consisted of six sections of stainless steel pipe mounted on the pipe cutting mock-up in the Robotics Technology Assessment Facility (RTAF). Each

section of pipe was 3 feet long. The participants' task was to cut the first 2 feet of each pipe into 6-inch lengths using the cutters provided for the DAWM under continuous manual control. The task was performed without direct viewing of the work site by the participant.

4.3 Capabilities and Benefits of Conducting System Analysis - Performance Testing

4.3.1 Benefits of Conducting System Analysis - Performance Testing

There are many benefits to the successful development of performance analysis methods.

- 1) They will allow informed decisions to be made about the specific application.
- 2) They will provide methods for assessment of robotic systems in environmental remediations.
- 3) They will identify technological challenges within the application.
- 4) They will promote more efficient technology development by providing a means for comparing the impact of technological options on mission performance.
- 5) They will allow cross-validation and calibration of computer simulations by providing task-based performance estimates against which graphic simulations may be compared.
- 6) They will allow assessment of the generalizability of robotic performance data.
- 7) They will allow analysis of the impact of errors and unexpected events, particularly human errors.
- 8) They provides a general approach to robotic and telerobotic performance assessment that researchers across the country may use to generate mutually compatible data.

4.3.2 Concerns about Performance Testing for System Analysis

This section lists some concerns that performance testing must overcome. These concerns often color the assessment of the return on the performance testing investment.

concept demonstration, for instance. However, this planning and execution must be completed to establish a set of experiments that can gather the information required to determine the performance characteristics of the system.

By determining which information to collect prior to testing, two concerns can largely be mitigated. First, experimenters and analysts will be able to accurately translate test results to field conditions. Second, planning allows completion of experiments and translation of their results to be executed correctly the first time thereby reducing the expense of the work.

- *Uncovering Undesired Information* The best thing that performance testing can do is to reveal unexpected or unplanned performance constraints. Uncovering these constraints will help in the overall quality of the system, if repairs are made, or the results are incorporated into the system. Performance testing can uncover undesirable information concerning the operation of the system in the experimental configuration. The hypotheses of the system designers may not have been precise, or the system capability may not be as robust as advertised. When unexpected results occur during experiments, they can be a blow to the ego of the system designers. They may also breed a certain amount of frustration that is directed toward the performance testing program, resulting in a degradation of the program. The situation will need to be managed to avoid such an occurrence.

4.4 Summary

In summary, limitations exist in every tool. Using these ranges, it is possible to conduct sensitivity analyses which can still provide useful information to the analyst and customer. By being aware of the potential limitations in a class of tools, analysts and customers will be able to compensate in the analyses for these limits and may find methods to circumvent the short comings.

5.0 BACKGROUND INFORMATION FOR AN ANALYSIS OF TWR

During the course of the year, Sandia was asked to conduct a system analysis of proposed TWR systems as an initial step in the decommissioning of the underground storage tanks (USTs) at Hanford. The previously discussed tools and processes were developed or reviewed, and, in some cases, tested during the course of this analysis. Results of this usage, lessons learned, future suggestions, some background information, and sample usage of the tools described earlier are discussed in the following sections.

5.1 TWR History

Since about 1944, the DOE Hanford site in southeastern Washington state has produced high level radioactive waste as a major byproduct of processing spent nuclear fuels. The waste from these processes still are stored in USTs. Negotiation among the DOE, Washington State Department of Ecology, and the US Environmental Protection Agency (EPA) resulted in the 1989 *Hanford Federal Facility Agreement and Consent Order*. This order provides for a 30-year cleanup program of the underground storage tanks and the surrounding area at the Hanford Site. Information in this background section was compiled and summarized from a variety of published documents including [KLEM 1991], [KRIEG 1990], and [WELLN 1991].

5.2 The Environment

The following paragraphs describe the characteristics of the tanks, their contents, and hazards inside the tanks that a waste retrieval system must negotiate while removing waste and hardware from such an environment.

5.2.1 SST/DST Overview

Between 1944 and 1969, 149 "single-shell" waste storage tanks (SST) were constructed at Hanford. Although no wastes were added to the SST after 1980, water is regularly added to one tank for evaporative cooling. Of the 149 SST, 133 are 75-foot-diameter cylindrical tanks constructed of steel reinforced concrete with steel liners, a dome shaped top, and a flat or dished bottom, with capacities varying from 500,000 gallons to 1,000,000 gallons. The other 16 SST are all cylindrical 20-foot-diameter tanks with capacities of 55,000 gallons.

Since 1944, four major chemical processing operations were conducted. Three processes (the bismuth phosphate, Reduction-Oxidation (REDOX), and

Since 1944, four major chemical processing operations were conducted. Three processes (the bismuth phosphate, Reduction-Oxidation (REDOX), and Plutonium-Uranium Extraction (PUREX) plant processes) were designed for plutonium extraction. The fourth (tributyl phosphate) process was designed to extract relatively large amounts of uranium remaining in the bismuth phosphate waste.

These major chemical processing operations resulted in wastes that contained most fission by-products with small quantities of uranium and plutonium. Where feasible, pumpable liquid wastes have been removed and transferred to double shell tanks (DST), a "tank-in-tank" design placed into service beginning in 1971. The DST construction was completed in 1980, after which all new wastes were transferred to DST for storage. High level radioactive waste varies by volume from about 5% to about 95% of individual SST capacities and varies in consistency from pumpable liquids to sludge to hard salt cake. A majority of the 500,000-gallon and 750,000-gallon capacity SST are built in three to four tank "cascade" formations, with pipes leading from one tank to another allowing waste transfer from the first SST to overflow into successive tanks within the cascade. As of August, 1995, 60 of the 75-foot-diameter SSTs and 7 of the 20-foot diameter SSTs were considered to be "leakers." [HANLO 1995]

Figure 6
Typical 75 foot
Diameter SST

5.2.2 Waste Description

Although early separation processes resulted in large volumes of dilute, lower-heat waste products, the later REDOX and PUREX processes resulted in wastes that contain much more highly concentrated heat producing radionuclides, particularly ^{137}Cs and ^{90}Sr , capable of causing self-boiling within the liquid waste. This form of waste was reprocessed, reducing but not eliminating the heat producing conditions. Further, a large part of the original liquid waste volumes underwent evaporation (later evaporation-crystallization) processes to reduce the volumes by producing thicker slurry. There is also an indication that some 17 of the SST may have a hydrogen gas build-up located in the waste, creating potentially flammable or explosive gas mixtures within the SSTs.

5.3 1991 Decision Analysis

Jenkins describes the results of a Kepner-Tregoe decision analysis performed to select from among a total of 11 options for SST hardened waste removal [JENKI 1991]. The analysis addressed each of the 11 options against all of the [KRIEG 1990] "must" criteria on a pass/fail basis, with the passing options then being scored against 28 "want" criteria. The "want" criteria are spread among the categories of system features, operating features, set-up and removal characteristics, exposure and contamination characteristics, and other evaluation criteria. The analysis results noted two outer elements (one top and one bottom) with the remainder of the options grouping around two points. The "top five" option analysis results (descending order) and options descriptions from [JENKI 1991] were the "top off" concept (high value outer), large hole concept, reference concept, contained sluicing - pump out concept, and contained sluicing - air conveyance concept.

5.3.1 Top Off Concept (Option 7)

Analysis of this option scored an aggregate 1338 in the Kepner-Tregoe decision analysis and was noted to be considerably higher than the other options. The major feature of this concept is the removal of a large (approximately 48 feet in diameter) portion from the top of the 75 ft diameter SST. The Top-Off Concept (see Figure 7) is the only concept that enables direct viewing of the waste retrieval operations. However, the distance between operator and end effector (ranging up to about 75 ft) is judged to be too great to enable operation without the control system that is planned for all other concepts.

Figure 7 - Top-Off Concept

The benefit that can be gained in both safety and productivity by general viewing (and close up viewing when necessary) is a positive aspect of this concept.

5.3.2 Enlarged Hole Concept (Option 6)

Analysis of this option scored an aggregate 1193 in the Kepner-Tregoe decision analysis. The enlarged hole concept (see Figure 8) provides additional space for inserting the arm and perhaps other equipment such as lighting systems, air conveyance hoses and control cables.

Figure 8 - The Enlarged Hole Concept

The key feature is the additional space that would be available, if needed, to provide an arm with maximum rigidity. With a very rigid arm, the number of end effectors (or smaller articulated arms with end effectors) at the end of the arm can be increased, thus minimizing end effector change outs.

5.3.3 Reference Concept (Option 4)

Analysis of this option scored an aggregate 1144. The "Reference Concept" (see Figure 9) has the key feature of the arm being able to operate through a 42 inch diameter hole in the center of the tank dome. Approximately one half of the single-shell tanks have such an opening. Therefore, tank preparation operations might be minimized by use of the center hole. If additional openings were required, they would be limited in this concept to a maximum diameter of 42 inches.

Figure 9 - "Reference Concept"

5.3.4 Contained Sluicing - Pump Out (Option 9)

Analysis of this option scored an aggregate 1107. This concept (see Figure 10) is a variation of the "Reference Concept." One notable characteristic of this concept is that all water added to the tank is contained by the equipment inside the tank. For example, some components of this concept are the end effector (clam shell bucket) and a small tank that collects waste from the clamshell bucket, water is added and mixed with the waste to form a slurry, and the slurry is pumped to the surface. Therefore, no further water needs to be added to the SST.

Figure 10 - Contained
Sluicing -
Pump Out

A key feature is that the waste is prepared for transport before it leaves the tank (assuming that a slurry is a desirable form of waste when transporting it to its destination).

5.3.5 Contained Sluicing - Air Conveyance (Option 8)

Analysis of this option scored an aggregate 1097. This concept (see Figure 10) can be considered a variation of the "Reference Concept" which can operate through 42 inch diameter holes in the tank dome. A key feature of this concept, as with that of Contained Sluicing-Pump Out, is that all water that is added to the tank is contained by the equipment inside the tank. Other key features of this concept are the end effector (clam shell bucket) and the water injected hopper attached to the air conveyance system. It should be noted that all air conveyance concepts under evaluation included water injection into the suction nozzle to assist in conveying the drier sludge like materials. However, this concept also includes water injection into the hopper to break up the material as required to "feed" the nozzle without plugging at the inlet.

5.4 Focused Study and Peer Review Results

A study [WELLN 1991] focused on three conceptual approaches derived from the work in [JENKI 1991], two of which were mechanical (the large opening/hole and the central arm concepts) and one hydraulic. This study underwent peer review by a team consisting of the following individuals:

- L. M. Martinson, Westinghouse Idaho Nuclear Company,
- B. L. Burks, Oak Ridge National Laboratory,
- M. S. Evans and L. A. Strobe, Pacific Northwest Laboratory,
- R. W. Harrigan and S. Thunborg, Sandia National Laboratories, and
- F. E. Boyd,
- J. A. Eacker,
- L. E. Thomas,
- M. J. Klem,
- B. E. Opitz,
- L. C. Stegen,
- J. A. Yount, Westinghouse Hanford Company.

The review results were reported in a memorandum [KLEM 1991], and they are summarized from Section 5.5 through 5.8.

5.5 Large Opening Concept

In the [WELLN 1991] study, one group focused on the large opening (hole) concept, referred to in the [JENKI 1991] Kepner-Tregoe decision analysis as the "top-off" concept and found to be the high-end outer concept for waste retrieval from the SSTs. This approach would result in an opening to a tank similar to that depicted in Figure 11.

Figure 11 -
SST with
50-foot
Diameter
Top Removal

5.5.1 Key Design Features

The [WELLN 1991] study identified key features of the large opening concept to be:

- Size of the opening
- Type of end-effector delivery equipment
- End-effector deployment and changeout
- Waste retrieval method
- Maintenance activities

5.5.2 Size of Opening

In considering opening size, the study group specified retention of a shoulder on the upper part of the tank to assure SST structural integrity. The group believed that a 50-foot to 60-foot diameter hole would not present a structural integrity problem for the 75-foot-diameter SST. The study group found the large hole concept to be much more complex than first envisioned because of the existence of "numerous pipes, conduits, pump pits and other structures above the tank that will have to be removed" (depicted in Figure 12). Also, the group expected that there will be significant radiation fields in some tanks so that operations will have to be done remotely. The group concluded that "a 50-foot diameter opening in the top of the tank is the maximum that should be considered" because of the limits required for structural integrity. See [WELLN 1991] for further details.

Figure 12 - Above Ground SST Considerations

5.5.3 End-Effector Delivery, Type, and Change-Out

For delivery of the end-effectors to the work area within the SST, the study group considered two types of gantry mechanisms (bridge and polar) and concluded that "the need to remove the crane equipment from above the SST and provide a clear opening for installing or removing a cover from the 50-foot opening" constituted primary considerations in choosing a gantry robot with a telescoping arm as the better option. This results in a concept similar to that shown in Figure 13.

Another group in the [WELLN 1991] study examined whether it was desirable to tether end-effectors, or to use a remote changeout plate, and they concluded that tethering the end effector through the center of the tank with changeouts outside the tank was the preferred option. However, concerns were raised regarding radiation exposure during changeout. Additionally, the issue of tethering lines interfering with any force feedback was raised and not resolved. [KLEM 1991]

Figure 13 - Large Hole Concept (Side View)

5.5.4 Large Opening Concept Summary

The study group [WELLN 1991] which focused on the large opening concept for waste retrieval from the single-shell tanks (SSTs) determined that it should include the following features:

- A 48-foot diameter opening cut in the top of the 75-foot-diameter SST (the 20-foot diameter SST were not addressed).
- A robotic arm to be used to manipulate tools (end effectors) inside the SST to dislodge, size reduce and remove the waste and debris.
- Tools (end effectors) for:
 - (1) Cutting metal parts (Abrasive Water Jet)
 - (2) Breaking up hard cake waste (Scabbler)
 - (3) Moving items in the SST (Grabber)
 - (4) Retrieving sludge and soft cake (Scarifier)
- An X-Y crane for moving the robotic arm.
- A large above ground confinement, tool change, maintenance, decontamination, and waste load-out facility.
- An air conveyance system for transporting the waste from the SST to load-out area in the aboveground facility."

The study group [WELLN 1991] estimated costs (non inclusive of engineering, design and/or development costs) for the large opening concept to be:

Facility and Equipment Fabrication	\$18,285,000
Site Preparation and Hole Cutting	\$41,000,000
Total Per Tank	\$59,285,000

The study derived facility and equipment costs based on a 1980 design that had a detailed cost breakdown, applying escalation factors and design differences to arrive at the 1991 estimate. The \$41,000,000 estimate made for site preparation and hole cutting was derived from a KEH study for a system that used hands-on means to remove soil and pipes above the tank and that also had a basis for comparison of costs to cut different sized holes in an SST.

5.6 Central Arm Retrieval Concept

In the [WELLN 1991] study, another group focused on the central arm retrieval concept, referred to in the [JENKI 1991] Kepner-Tregoe decision analysis as the compendium of four related concepts known as:

- Reference concept
- Enlarged opening concept
- Limited sluice-pump out concept
- Limited sluice-air conveyance concept

Each of the concepts uses a single central arm that is located vertically in the approximate center of the SST, with some form of extensor and end-effector, as depicted in Figure 14.

Figure 15 Central Arm Concept
(Side)

Figure 16 Central Arm Concept
(Top)

- *Scarifier* A tool used to break up salt cake or sludge with high pressure water or air jets, including a means to retrieve the waste and water through an integral air conveyance system. The scarifier would weigh about 1000 pounds excluding hoses.
- *Scabbler* An air-operated tool with reciprocating rods, used to break up hard cake, weighing about 500 pounds.
- *Grabber* A hydraulically operated gripping tool used to grasp and move items within the SST and weighing about 500 lbs, possessing about a 1500 pound lift capacity.

5.6.2 Considerations in Central Arm Study

The group that was focused on the central arm retrieval concept examined waste retrieval methodology, end-effector considerations, required size of tank opening, and in-tank hardware considerations, all taken in terms of the four related central arm concepts.

5.6.3 Waste Retrieval Considerations

The group found two different methods to be available among the four variations on the central arm concept, referred to respectively as "batch" and "continuous." In the batch method used by the limited sluicing variations, waste is first dislodged, then picked up and moved by a clamshell bucket to a hopper, where it is mixed with water

and removed from the tank by either a pump or air system. The study group found potential inefficiencies with the batch method as well as reason to question efficacy in handling the harder wastes. The group noted that the reference concept and enlarged opening concept used an end-effector to dislodge waste which was then immediately and continuously removed by an air conveyance system. The group concluded that the continuous methodology was the preferred approach.

5.6.4 End-Effector Considerations

The central arm concept group noted at least eight possible connections that would be required to be made by a tool changer plate effectively simultaneously and suggested that the number and conditions made this very difficult to achieve. The hostile SST environment further complicated use of an end effector plate change. The study group found that,

"Based on the number of utilities needed and the working environment, the tool changer plate is not considered practical for this application. A viable solution is to tether the utilities and end effectors. The utility cables will be directly attached to the end effector."

The study group presented further technical options analysis that concluded that the end effectors should be deployed through a center opening in the SST, with required changes being made outside the tank.

5.6.5 Considerations about the Required Size of the Opening

The central arm concept group noted that, although about 50 percent of the 75-foot-diameter SST has a central 42-inch riser, if this size were the limiting criteria, then the other half would still require a similar hole to be cut. The group found that the order of magnitude cost consideration was the same for risers in the 42-inch to 120-inch range. The group concluded that the opening should be the smallest practical to accommodate the central arm but that the opening should not arbitrarily be restricted to 42-inches-diameter.

5.6.6 In Tank Hardware Considerations

One requirement for the retrieval system was that it must be able to remove 98 percent of SST waste. Most SST's are believed to have some form of in-tank hardware (ITH), with most ITH assumed to have been contaminated with some amount of waste. Current end-effectors are not designed to be able to clean the ITH and, any ITH remaining in the SST would be anticipated to create some difficulties with general waste removal operations. The central arm concept group examined the implied requirement to remove ITH via three methods that took into account

removal systems that would require the least ITH handling and also time efficiencies among the ITH removal methodologies.

- (1) *Removal as a cut*, in which the ITH piece would be taken out of the SST as soon as it was cut, probably entailing retracing the arm from the tank so that it could deposit the ITH into a storage area.
- (2) *Hardware set-aside*, in which the arm moves the ITH piece to some set-aside area within the SST, with final stacking on the bottom of the SST when a space was cleared. This method requires handling the ITH pieces at least three times.
- (3) *Removal as a batch*, in which the arm transports ITH pieces to a bucket (or some other conveyance device). Once the "bucket" is full, it is removed from the SST. This method requires handling of the ITH pieces only two times and does not require the arm to be retracted after each cut.

Their analysis concluded that the batch removal method would be the preferred approach for ITH removal. This method is used as appropriate in the following cost analyses.

5.6.8 Central Arm Cost Estimate

The study group estimated the following costs in [WELLN 1991].

Total Fabrication Cost for the Manipulator System	\$19,185,000
Demolition Cost of the Central Arm System	10,000,000
TOTAL	\$29,185,000

5.7 Hydraulic Options

5.7.1 Past Practice and Limited Sluicing Methodologies

In past practice at the Hanford site, the supernatant was pumped from the SST to be sluiced to another tank for temporary storage, with approximately 35,000 gallons of the liquid being retained in a receiver tank. This liquid was then used as the sluicing medium, to be pumped through a nozzle in the target SST, impinging on the sludge surface. This action re-suspended solids, with the transfer pump returning the slurry to the sludge receiver tank. The liquid re-circulated in this process until about 2000-3000 gallons of sludge had been retrieved. Flocculent then was added, solids allowed to settle in the receiver tank, and the supernatant was recycled. The process is illustrated in Figure 17.

Figure 17 Past Practice Sluicing Methodology

The study group focusing on hydraulic concepts concluded that past sluicing methods, which relied on re-suspending water soluble sludges, would not be suitable for current wastes which contained a wide variety of waste types. They also examined limited sluicing, which is similar to the past practice sluicing method except for placing the sluicing nozzle closer to the surface and using multiple nozzles. They noted that the limited sluicing technology offers lower flow rates and higher pressures but concluded that it would share similar disadvantages with those found in past practice sluicing. Examination of related technologies such as commercial tank cleaning systems revealed that they did not have significant advantages.

5.7.2 Articulated Arm with Water Impact End Effector

The [WELLN 1991] study group also examined information and test data derived from feature testing of high pressure water and air jet technology on simulated waste. This technology uses the energy stored in water that is compressed to 55,000 pounds per square inch (psi) to generate a significant hydraulic shock on the target (Figure 18).

Figure 18 Articulated Arm with Water Impact End-Effector

The [WELLN 1991] study group concluded that a system using this articulated arm with water impact end-effector would be practical.

5.7.3 Hydraulic Barriers

The [WELLN 1991] group felt that the presence of a number of "leaker" SST's required that leakage barrier technologies be explored, if hydraulic retrieval was to be feasible. A major approach considered was the use of a cryogenic barrier (Figures 18 and 19, involving installing freezing pipes around the circumference of the SST.

The pipes consist of an outer pipe with a somewhat smaller pipe installed inside, with refrigerant being pumped down the outside pipe and returned through the inside pipe. The side pipes are installed at a slant, such that the bottom ends are relatively close together, with a second set of side pipes being installed about 20-30 feet outside of and parallel to the first set of pipes. The overall effect is to create a double wall of pipes, between which the earth is frozen. Injection pipes are used within the space between the two refrigerated walls to allow addition of water, silicates and/or other filler as needed to create a contiguous, strong barrier. The study group noted that ice barriers are common in civil engineering applications and mines for water control, allow *in situ* repair, and are self-healing. The group also examined consolidation and particulate grout injection methods and found that, although this technology appears promising, "no large scale test has been conducted to encapsulate a large underground structure" like an SST. They concluded that

there exists adequate barrier technology to support hydraulic methods of waste retrieval.

Figure 19 Cryogenic Barrier Field (Top View)

Figure 20 Cryogenic Barrier Field (Side View)

5.7.4 Hydraulic Option Conclusions

The [WELLN 1991] team concluded that hydraulic retrieval is practical but required barriers, for which technology is available and the use of which would obviate the

need for a leak detection system. They further concluded that a center mounted arm with a water impact end-effector could handle ITH and that, of available methods, air conveyance was preferred for waste conveyance.

The study group [WELLN 1991] estimated costs for the hydraulic concept to be:

• Total Fabrication Cost	\$19,185,000
• Demolition Cost	\$10,000,000
• Encapsulation Barrier	\$1,200,000
• Total Per Tank	\$30,385,000

5.8 Results of SST Waste Retrieval Concept Peer Review

The foregoing three concept studies were reviewed by the DOE multi-contractor peer review team in June 1991. Their recommendation was to proceed with the engineering design of the retrieval system based on the central arm concept and air conveyance system, noting several points that needed additional work including:

- The air conveyance system removes the dislodged and size reduced waste from the tank and transports it to an above ground facility. The above ground facility is used for air-solid separation and transport of the waste to the waste transfer system. The air conveyance system should be refined and other concepts evaluated. If hydraulic slurry is accepted as an alternate method of waste retrieval then a barrier around the tank maybe required.
- The waste transfer system was beyond the scope of this study. The information presented was for completeness of the retrieval concept. The retrieved waste form must be identified and integrated into the requirements for the transfer system, retrieved waste storage system, and waste partitioning facility to ensure compatibility and operational continuity.
- If closure is defined as removal of the tank steel liner and concrete shell then the large opening concept should be reexamined.
- The preliminary conceptual design did not adequately address site preparation, decontamination and maintenance of equipment, transport and storage of waste, seismic study, soil loading analysis, and tank selection criteria. The tank selection criteria need to balance retrieval difficulty and near term available technology. The selected tank needs to be evaluated for radiation level to establish requirements for radiation hardening of equipment and sensors that will be located inside the tank.

These considerations bear heavily on the analyses as described in succeeding sections where there is a focused effort on control arm concepts while other options are kept in mind.. The analyses studied the central arm concept and air conveyance system. Regardless of the option choice, the analysis methodology involved in investigating of the central arm concept could be used to study the option desired.

6.0 MODELING COMPONENT 1 - EMPLOYING THE PROCESS DIAGRAM TOOL TO STUDY THE TWR SYSTEM

The Process Diagram Tool was used to provide some understanding of TWR from a graphical, schematic point of view. An initial high level diagram was completed which became the foundation upon which the rest of the system diagram was created.

6.1 Analyze the Problem and the System to Retrieve Waste

The activities of the tank waste retrieval system were charted to develop a more complete understanding of the problems faced by the retrieval and tank operations staff. The analysis of the proposed system revealed that there were actually several sub-systems that will need to work together to complete the tasks of waste retrieval.

The high level diagram of the system operation revealed several questions before further analysis was begun. The set of process diagrams for this analysis are found in Appendix B. This analysis, while not complete, has yielded significant results as well as questions that remain to be answered. These issues will be discussed in the following paragraphs.

Figure 21 shows the upper level process diagram for the TWR effort. This problem is bound at the front by the tasks completed between the time the TWR system becomes operational and all construction has been completed. The end point of the problem as it was studied is the point where all waste has been retrieved, or before any waste reduction and treatment plans have been implemented.

The detailed process analysis begins the study at the point when the TWR system would commence operation as it is tested prior to insertion into the waste tank. The diagram then shows the insertion of the system which then consists of placing closed circuit television cameras into the tank. These cameras determine if clear access to the tank is available for the long reach manipulator system (LRMS). If the access is available, then the LRMS could be inserted into the tank either manually or telerobotically.

Figure 21 Upper Level Process Diagram - TWR

Then the system diagram focuses on the next retrieval phase, removal of the waste from the tank. See Figure 22. At this point, the process diagram shows that a choice of retrieval strategy is required.

- Will the system retrieve all the visible hardware first?
- Will the LRMS remove the hardware and waste in layers?
- Will the waste be removed first and then remove the hardware?
- Or, will the waste be removed leaving all of the hardware in the tank?

After the method of waste and hardware retrieval has been selected and executed, the diagram shows removal of the system from the tank environment.

The system diagram can provide indicators of areas of concern as well as initial insights into questions that may be asked.

Figure 22
Waste Retrieval
Process Diagram

For example:

- What are the benefits and disadvantages of each option?
- Is there something missing that needs to be answered?
- What must be considered in the execution of options?
- If this diagram is to be used in a quantitative manner, is there a method by which an equation or set of equations can be developed to represent it in a graphical animated model, a simulation, or in some computer code?

These questions as well as others discussed later can be addressed by building a graphical schematic model of the process. As mentioned in the general tool description of these modeling tools, there is much work that needs to be done to build a tool that can be used by many people. From usage thus far, it is very important to find or develop an automated method of building these schematic models. Additionally, a method to associate equations with such questions will also be a requirement of such a modeling system.

6.2 Assumptions for TWR

While developing the system design for TWR, it became clear that not all the information about the project is known. As such, assumptions about the

performance of the system, the tank environment, and the personnel had to be made. The assumptions follow:

6.2.1 General Operations

In this section and the three that follow it, certain operating assumptions are examined. For the sake of clarity, a tabular format has been employed to distinguish the assumption from its discussion.

Assumption	Discussion
The model makes an underlying assumption that retrieval of waste is possible from all tanks and that no errors are made during the operations.	There are a few points in the system diagram where questions arise concerning potential pitfalls regarding a potential failure of the system. In the initial application of the diagram, there is not enough knowledge of the system regarding the contingencies to deal with operational or system failure. Errors made during operations, are not accounted for in the model.
The diagram does not track radiation exposure, hazardous waste exposure, or task completion times for particular operations.	Because this system diagram is a first attempt for these waste retrieval operations, there have been data neglected in order to determine the feasibility of this approach.
A mapping system will be available and will make a surface map of the inside of the tank in a reasonable amount of time. It is also assumed that the mapping is completed using sensors on the end of the manipulator.	At the current time, a mapping system is available with the potential of scanning a tank from a fixed position (not manipulator mounted). Time to scan is dependent on level of detail. Minimum times for a coarse map (1 foot at extremes) would be 45 minutes. A more detailed map would require multiple views and higher resolution, several hours, and modification of the system.

6.2.2 Insertion/Removal from the Waste Tank

Assumption	Discussion
A long reach manipulator with a dexterous manipulator attached to the LRMS will enter the tank environment through a central riser.	The model at the highest level of abstraction shows the potential for two options for retrieving waste from a tank. In this model, these two options are shown because a contact group which studied the problem early gave both options a high vote of confidence. However, only one option is studied here, because the alternative options of study were unknown until recently. If the TWRS effort were to continue, these additional options may need to be studied in more detail.
<p>If no center opening of 42 inches, or greater, exists in a tank per section 7.3.2 and 7.3.3, an enlarged hole equal to, or greater than, 60 inches will be built to allow for use of the remote manipulator systems.</p> <p>Telerobotic operations to insert and remove the manipulator systems from the tank environment will be operational at the time of deployment.</p>	There are several choice points in the diagram where either teleoperational or telerobotic control of the remote manipulators is available. When choosing the options, the system diagram does not limit itself to the currently available technology. The model assumes that telerobotic control facilities will be available to an operator which will allow automated insertion and removal of the manipulator system.
There may be a need for three risers that end with their exit points a long distance away from the waste to accommodate closed circuit television (CCTV) cameras, the LRMS, and the structured lighting system.	No discussion.

6.2.3 Waste Retrieval

Assumption	Discussion
Telerobotic operations to retrieve waste and hardware from the environment will be operational at the time of deployment.	The diagram assumes that telerobotic control facilities will be available to an operator which will allow automated path planning. This path planning will allow the operators to select appropriate retrieval path strategies (e.g. spiral, circular, rectangular) while moving around obstacles.
<p>The primary tank waste retrieval operations will be halted when one of the following situations arise:</p> <ol style="list-style-type: none">1. The waste has been retrieved to the safety limits using the primary retrieval strategy and the residual cleaning operations must commence2. Decontamination and/or maintenance of the system is required due to radiation effects, exposure, hazardous waste exposure, or regular preventative maintenance must be completed.3. Further waste retrieval is prevented by hardware blockage.	Any one of these situations is projected to occur during the option of removing all the hardware visible in the beginning of the operations, prior to the initiation of primary waste retrieval.
The residual waste retrieval will begin after 80 percent of the waste in the tank has been successfully retrieved by the primary waste retrieval operations.	No discussion.

6.2.4 Hardware Retrieval

The following assumptions carry no discussion.

- The primary waste retrieval operations will reveal all of the hardware that must be retrieved from the tank.
- The retrieval option which retrieves all of the visible hardware from the tank prior to the commencing of primary waste retrieval operations will only find 75 percent of the total hardware in the tank. This leaves 25 percent to be found and removed during the waste retrieval operations.
- There will exist a device that will pull hardware from the waste and maneuver it to a disposal area. The device will cut the hardware into disposable sizes. This device is required for the retrieval option which retrieves all of the visible hardware from the tank prior to the commencing of primary waste retrieval operations implies
- The hardware pulled from the waste will not cause any damage to the walls floor or ceiling of the tank.
- There will be an end effector that has been designed to grip and cut the hardware such that the hardware does not fall into the waste.
- A disposal basket for hardware will be attached to the tool rack at the end of the long reach manipulator so that hardware retrieval and disposal can be completed independently.
- The disposal basket will probably not be large enough to hold all the hardware pieces from a single layer, therefore it will need to be emptied periodically.
- The "not retrievable" option has not been explored.

6.2.5 Tank Contents

The model assumes three different types of waste that must be retrieved from the tanks: liquid, a sludge similar to peanut butter in viscosity and pumpability, and a hard salt cake. The amount and proportions of waste will be compensated for by the speed of the end effectors.

6.3 Results of the TWR System Diagram

The most important kinds of information from the TWR System Diagram arise from the questions that it raises. In looking at the diagram, the following questions occur.

- What would happen if there were no riser in a tank on which a CCTV camera could be placed?
- In a tank that constantly "churns," what would the system operators do if the system deployment riser were blocked by waste or hardware?
- If a central riser were to be installed into a tank environment what would be the implications of building it larger than 42 inches?
- Will this installation create more waste in the tank to retrieve?
- What are the effects of radiation on the hardware, sensors, people who need to perform maintenance on a system, etc.
- Is it possible to automate the insertion and removal of the TWRS?
- In retrieving the hardware, during the cutting process, is it acceptable to drop hardware pieces to the waste surface?
- If not, does a new end effector need to be designed that will grip on both sides of a cut?
- Is maneuvering around risers in an underground storage tank technically feasible?
- If so, is it cost effective?
- On a more global note, if there are no entry risers in the tank for an LRMS, a riser will be built into the tank.
- How large an opening should the new riser have?
- What if an existing entry riser is blocked such that the LRMS cannot enter into the tank?
- Also, what are the effect of radiation exposure on the equipment and on the people utilizing the equipment?

In addition to raising questions, the system diagram also provides other insights. The diagram revealed the potential four strategies for retrieving waste from a tank that were partially investigated through its use. The operators could:

1. Remove all the visible hardware at once in the beginning of the operations.
2. Remove the waste and hardware in layers.
3. Maneuver around the hardware removing the waste, leaving the untouched hardware in the tank.
4. Maneuver around the hardware removing the waste, waiting until all of the waste has been removed before retrieving the hardware.

These options raise still more questions. In option 1, removing all the hardware first, these questions arise.

- Does the LRMS have enough power and structural integrity to remove long pieces of hardware from the varying waste substances that will be found in the tanks?
- If not all the hardware is found during primary waste removal operations, will it be acceptable to “discover” it later?
- What impact will later discovery have on the maintenance costs and speed at which waste retrieval end effectors will be operating?

If operating under option 2, removing the hardware and waste in layers, the question of dropping hardware into the waste becomes pertinent.

- If the hardware is dropped, is it appropriate to risk exposure of the hardware to the higher radiation levels near the surface of the waste?
- How close is too close for the end effectors that cut and grip hardware?

In options 3 and 4, sophisticated path planning will be required to move around the hardware.

- Is this path planning worth the potential benefits of removing the hardware at the end, or not removing it at all?
- Is the path planning even possible given the size of the LRMS and the number of obstacles in the tank around which the LRMS would need to maneuver?

Finally, other results of the model showed that joint usage of teleoperation and telerobotic operation of the LRMS should be considered, provided the technologies will support such operations. Also, during the course of planning the operations of such a system, is it true that the balance of teleoperation and telerobotic operations will require some management such that an automated graphical model may be required to simulate these operations? Such a simulation could help answer questions such as:

- When does it become impractical for teleoperation to retrieve waste?
- When is it better for telerobotic operation to halt in the retrieval and disposal of hardware?

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7.0 MODELING COMPONENT 2 - TWR OPERATIONS COST MODEL (OCM)

Just as the TWR System Diagram shows a graphical overview of the TWR, so the TWR Operations Cost Model (OCM) was designed to show the effect of various operations on the costs of operating either a teleoperational or telerobotic long reach manipulator in retrieving waste at Hanford. The OCM only accommodates operational costs, whereas the costs of purchasing equipment, maintenance, replacements, etc. are compiled in the amortization model which is described in Section 10.0, "TWR Amortization Model".

7.1 Results of Building the OCM

The OCM is a workbook of Microsoft Excel™ spread sheets which assigns costs to various tasks through the component of time. In other words, the model uses time as the varying component for all operations. The times are then compiled into an aggregate time. This time is multiplied by the normally static costs of personnel charges, utilities, and other charges that are accrued during a particular length of time (in the OCM, 1 hour).

The general discussion of this modeling tool provides a good description of the tool's usage in this particular case. As mentioned earlier, Appendix B shows the structure of the model, and Figure 3, High Level Structure of the Cost Modeling Tool, shows the upper level content of the model. The information that follows is a more specific description on the values of the parameters for the initial model.

The model has many parameters that are associated with the operation of a remote manipulator system in an underground storage tank. In the following paragraphs, some of the more interesting parameters will be described and their known effects.

7.2 A System Level View

At the higher level there are three types of information included in the model. The first consists of the system parameters which include the known characteristics concerning the operation of the remote manipulator system, regardless of environment. When these operational characteristics are linked with the second type of information, parameters of the underground storage tank environment, a more complete picture of the system in operation is revealed. The tank parameters provide information on the contents of the tanks.

The third type of information involves personnel parameters which provide a more significant link to the actual cost of the system. While there are some costs associated with operation of the system without personnel costs, it appears the costs of personnel are the most significant in the operation of the system.

7.3 The Modeling Detail

The following sections describe the contents of the OCM. The sections of the model representing the system parameters, tank parameters, and personnel parameters are discussed and explained.

7.3.1 TWR System Parameters

The system parameters section consists of component information including the distance the end effector travels in a given time, the time of travel, the time required to verify a correctly functioning CCTV system, etc. These components are then collected (in the calculations sections of the model) to create higher level information such as speed of the end effector.

The detailed information is collected into six basic operations that the system must perform:

- insertion into the tank,
- mapping of the waste surface including the hardware exposed,
- primary waste retrieval operations within a safety margin,
- retrieval of the residual waste (after the primary retrieval),
- retrieval of the hardware (if performed), and
- removal of the system from the tank.

Each of these upper level operations is then subdivided into component or sub-component operations.

The insertion of the system into the tank is decomposed into testing and adjusting both the CCTV system and the LRMS. After both systems have completed their initial checks, they are lowered into the tank in a series of steps. Some of the insertion detail has been included in the model if it was deemed important. The removal operations are assumed to be the reverse of the insertions operations, with the exception that the system must be decontaminated prior to its exposure to the environment outside of the tank.

The surface mapping operations are expected to be used in both the waste retrieval operations and the hardware retrieval operations. The mapping operations modeled include the attachment of the mapping end effector to the dexterous manipulator on

the LRMS, time to conduct the mapping sweeps based on experimental data from Sandia, and the time to review the map to ensure its correctness. Characterization of the waste is also included in this section of the model although it now appears to be completed in operations distinctly different from the surface mapping. As an example of how these tasks decompose in order to model the attachment of a mapping end effector, the analyst must provide information on the time to select, attach, and inspect the mapping end effector.

The primary waste retrieval operations decompose similarly to the mapping operations. There are tasks to attach the end effector to the manipulator and tasks to execute the retrieval of the waste. In this section of the model, the analyst's exposure to elemental parameters involves more familiar variables. For example, in the calculation of end effector speed, the model requires information on a test distance which the end effector travels and the time period required to travel that distance.

Additionally, the analyst is asked to provide information on the size of the area cleaned by an end effector. This information allows the model to calculate the area the end effector will clean over some distance. Likewise, there is an understanding that not all the actions taught in waste retrieval will be successful. Therefore, there is a parameter implying that some waste retrieval operations will need to be retaught. These are stochastic values so that they will be only used a fraction of the time.

The residual waste retrieval parameters are identical to the primary waste retrieval parameters. These parameters' values in the residual operations are allowed to vary from the primary waste retrieval operations. A variance could account for additional concerns regarding removal of waste from hardware and surfaces close to the sides of the tank. In this model, for example, the residual end effector operates at 90 percent of the speed of the primary end effector.

The hardware retrieval parameters of the model include information regarding the attachment of end effectors, teaching and adjustments of hardware cutting, as well as the disposal of the hardware piece that was cut. In this model, hardware retrieval and disposal permits the choice of two potential end effectors; however, as mentioned earlier, a third end effector may need to be designed to accommodate cutting and gripping the cut piece. The OCM is able to account for such changes in operating strategy, so the analyst can provide a realistic set of operational results for the customer in the event of such a change.

In addition to the system parameter times, data are also included about costs directly attributable to the operation of the system. These costs are allocated to each major stage of the retrieval operations. Some of these costs such as electricity

and water have easily calculable costs per hour. Other costs such as maintenance, parts costs, protective clothing, and service contracts are not so easily calculated. In fact, there is consideration of allocating these costs to a single system operating over several SSTs in the amortization model. With these pieces of information, the model provides a very detailed view of the operational characteristics of the system.

7.3.2 TWR Tank Parameters

The tank parameters describe the initial state of the environment in which the system will be placed. The tank parameters modeled include the diameter of the tank, the amount of waste in the tanks, the amount of waste that will remain as a safety factor prior to residual retrieval, and the number and sizes of hardware (modeled as risers ??) the system will encounter.

Regarding the percentage of waste left for the residual retrieval and the consideration of the hardware differences, there are several noteworthy elements. First, the percentage of residual waste is used as a signal that allows an adjustment of the speed of waste retrieval to change as the end effector comes into close proximity of the tank sides and floor. Second, because the hardware retrieval system handles various sizes of hardware differently, the model provides for hardware to be sized 6 inches or less in diameter and greater than 6 inches in diameter. To cut hardware of these two different sizes, different implements are used which have their own timing characteristics, and operational cost parameters.

7.3.3 TWR Personnel Parameters

The personnel parameters include the following:

- different categories of employees,
- hourly rates for each category,
- the number of workers from each category assigned to a major operation,
- the number of hours waste retrieval work is actually performed,
- the hours employees are paid, and
- the number of days per week that employees are working.

The two current categories, supervisors and operators of the LRMS, have modeled hourly rates adjusted for benefits as would be expected in the workplace. Also the operators are expected to have other duties which compete for their time. Therefore, the operators and supervisors will only be able to allocate a portion of their full day to waste retrieval operations. These options also allow a customer or analyst to determine the effect on the costs of waste retrieval operations of working more than one crew shift per system.

7.3.4 Cost Calculations

The calculations of the model are housed in the operational costs section. In this section, all of the above mentioned information is brought together to determine the costs of using the system. These calculations provide the model's final results based on the data values read from the previous sections. The calculations range from the highest level (e.g. Cost to Remove Waste from a Tank) to the lowest level (e.g. Time to Teach a Cut).

This amount of detail could be overwhelming to an analyst or a customer. As such, a "Summary Page" was created for the high level results of the calculations which a customer might need to know. These data include:

- the total costs to remove waste,
- the cost and time to insert and remove the system into the tank environment, and
- the cost and time to remove waste and hardware.

Additionally, the summary delineates the costs into labor costs and operations costs per hour.

7.4 Assumptions

In the development of the TWR OCM, it is clear there is still much yet to learn. However, in order to provide a model that might be used while still acquiring information, some assumptions were necessary. The following assumptions about the operation of the system were made.

7.4.1 General Modeling

There are only a certain small number of parameters within the model that are likely to vary with any regularity. These include, but are not limited to:

- end effector speed,
- number of risers (hardware pieces) to remove,
- length of risers to remove,
- amount of waste,
- time to characterize waste,
- waste area cleaned by a stationery end effector,
- the percentage of residual waste,
- times to teach operations (either hardware or waste retrieval),

- time to complete disposals,
- number of personnel that operate and supervise operations of the systems, etc.

It is assumed that there will be no shutdowns due to emergencies, accidents, or regularly scheduled maintenance. The system will remain in the tank environment until all of the retrieval has been completed. Upon removal of the system from the tank, any repair efforts will then be performed.

The model implies that the waste retrieval will be completed telerobotically. Teleoperation activities will center on the hardware retrieval and disposal, although there is the option for telerobotic hardware retrieval and disposal.

In telerobotic modes, some of the actions will need to be retaught. Because teaching operations in the telerobotic mode are complicated, it is assumed that some graphical programming will be available to the operators of the system, even though that is currently not the case.

Electricity and water utilities costs have been estimated on the basis of the costs incurred at Sandia National Laboratories during its 1994 operations.

7.4.2 System Parameters

Eight system parameters have been determined based on the following assumptions.

- 1) There are no deviations in speed of the end effector during either telerobotic or teleoperational waste retrieval operations once the speed has been set.
- 2) The waste retrieval end effector speed is variable, but the nominal rate for primary waste retrieval is 4 inches per second or 20 cm per second.
- 3) During residual waste removal, the end effector operates at 90 percent of the speed during primary waste retrieval.
- 4) The amount of waste retrieved from a certain location is determined by the depth to which the end effector retrieves waste.
- 5) The time to remove the system from the waste tank will take longer than the insertion of the system. Upon removal, the system will be decontaminated of radiation and hazardous waste. Periodic maintenance and any repairs will also be performed at this time. The projected time taken to perform these activities has been added to the removal time for the system.

- 6) There were two alternatives tried in the model for an end effector that retrieves the hardware. There was one option that used two end effectors at different times. The first end effector, a cutting end effector, was used to separate risers ?? or pipes into manageable sections. Then the piece that was cut was disposed of by a gripping end effector. The other option had the gripping end effector built into the cutting end effector. As a pipe/riser ?? was cut, the gripping end effector held the piece of hardware in place so that it would not fall to the waste surface.
- 7) Individual component times were not available in the deployment and insertion of the tank waste retrieval system. The suspected aggregate values for the total operations were placed into two of the available parameters, time to insert CCTV system, and time to insert retrieval system. Likewise, the aggregate removal time was placed in the parameters time to remove CCTV system and time to remove retrieval system.
- 8) The times to retrieve hardware are estimates because the timing studies have just been initiated for these operations. See Section 5.
- 9) Waste retrieval costs are based on estimates of telerobotic retrieval operations times. ITH retrieval costs are based on estimates of teleoperational retrieval operation times. These data represent the only currently available information. Planned experiments in the future could reveal data for automatic hardware retrieval operations. See Section 5.

7.4.3 Tank Parameters

Seven tank parameters have been determined based on assumptions.

- 1) The maximum dimensions of the hardware that can be disposed of is variable, but the nominal size is 6 inches or 30 cm in length, or diameter, or circumference.
- 2) The amount of waste represented by the model is variable, but the nominal amount is 200,000 gallons of waste in a tank.
- 3) The amount of waste remaining for residual retrieval is 15 percent.
- 4) There can be a varying number of hardware pieces with a varying size in the tank, but the nominal value is 20 risers of 25 feet length. Note that there may an average of ten metal measuring tapes at the bottom of any tank and that the analysis accounts for their retrieval by extending sizes of ITH. The analysis does not accommodate the potential threat to the end effectors.

- 5) The size and shape of the hardware in the tanks varies, however the model assumes a uniform size and shape of the hardware. By adjusting the number of hardware pieces of the modeled size and shape, it is assumed that the total amount of hardware to be retrieved will be adequately represented.
- 6) The model assumes that there will be only one type of waste. The model can be adjusted to allow for various types of waste by reducing the speed of the end effector and the amount of waste picked up by the end effector.
- 7) There are two categories of hardware: pieces less than six inches in diameter and pieces greater than six inches in diameter.

7.4.4. Personnel Parameters

It is assumed that the staff will only actively retrieve waste on an average of 6 hours during the work day. Other times during the day they will be involved in training, meetings, completing necessary forms, and non-retrieval related work activities. There are two operators required for waste retrieval operations. A supervisor is available, but is only actively associated with the operations a portion of a single day.

7.5 Results of the Model

The results of this model are best interpreted as a guide, or a way to determine trends. Regarding the waste retrieval system, it appears that hardware retrieval is the operation requiring the greatest amount of time to complete. At the initiation of sensitivity analysis the hardware retrieval required a larger percentage of the time used during the overall retrieval process. Figure 23 displays the impact on overall system performance of hardware retrieval for the initial set of assumptions and parameters analyzed.

Figure 23 Overall Impact of Hardware Retrieval on System Costs

To reduce this percentage, some experiments were conducted regarding the size of hardware retrieved, the time to conduct disposal activities as well as cutting times and mapping times. The parameter with the most pronounced effect on the waste retrieval operations was the size of the retrieved hardware. The model shows that a change from a six inch sized piece of retrieved hardware to a 12 inch reduced the hardware retrieval operations cost by 50 percent and the total operating cost by 29 percent. When retrieved sizes were changed to 36 inches, the total operations cost was reduced by nearly 50 percent. These cost savings were more dramatic than any other parameter in the system. Figure 24 shows this effect.

Figure 24 Impact of Hardware Retrieved Size on Overall Retrieval Time

Some of the results from the model presented below were determined as the outcome of sensitivity analyses. These analyses revealed several interesting facts, but perhaps the most interesting is that changing one parameter by a little bit can alter the outcome of the model significantly, and hence, the operation of the actual system if a similar parameter is altered during operation.

In conducting the sensitivity analysis, there were seven parameters tested of which four had a noticeable impact on the modeled systems. These parameters, in order of effect, were:

- maximum size of retrieval hardware,
- waste retrieval depth,
- speed of end effector for waste retrieval, and
- the surface area cleaned by a stationary end effector.

The results of testing the hardware retrieval factors that were hypothesized to impact the hardware retrieval cost are shown in Figure 25. See Figure 25 for more details of altering these parameters.

If, because of better hardware retrieval equipment and procedures, waste retrieval begins to impact the total system effort, there are functions where significant

system gain can be achieved with small adjustments. The parameters investigated were end effector speed, the end effector size (area) in one location, and the depth at which the end effector retrieves waste in one pass over the surface. The waste retrieval parameter that caused the most significant fluctuation was the depth of waste removal. By increasing the retrieval depth from 1 inch to 2 inches, the waste retrieval cost dropped over 50 percent. However, the total cost savings based on this change was approximately one percent. These savings are less than expected, however, because the component of hardware retrieval costs is so large, it is not surprising.

<i>Parameter Value</i>	<i>Percent Change in Parameter Value</i>	<i>Percent Change in Total Costs</i>	<i>Percent Change in Primary Waste Retrieval Costs</i>	<i>Percent Change in Hardware Retrieval Costs</i>
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Length of Retrieved Hardware Pieces (inches)

6	0%	0.00%	0.00%	0.00%
12	100%	-25.20%	0.00%	-49.97%
18	200%	-33.60%	0.00%	-66.63%
24	300%	-37.80%	0.00%	-74.95%
30	400%	-40.32%	0.00%	-79.95%
36	500%	-42.00%	0.00%	-83.28%

Depth of Waste Mined by End Effector (inches)

1.0	0%	0.00%	0.00%	0.00%
1.5	50%	-7.10%	-32.88%	0.00%
2.0	100%	-10.66%	-49.32%	0.00%
2.5	150%	-13.03%	-60.27%	0.00%
3.0	200%	-14.51%	-67.12%	0.00%
3.5	250%	-15.39%	-71.23%	0.00%
4.0	300%	-16.28%	-75.34%	0.00%

Speed of End Effector During Waste Retrieval (inches/minute)

75	-75%	+55.27%	+300.00%	0.00%
150	-50%	+18.42%	+100.00%	0.00%
225	-25%	+6.14%	+33.33%	0.00%
300	0%	0.00%	0.00%	0.00%
375	25%	-3.68%	-20.00%	0.00%
450	50%	-6.14%	-33.33%	0.00%
525	75%	-7.90%	-42.86%	0.00%
600	100%	-9.21%	-50.00%	0.00%

Surface Area Cleaned by End Effector (square feet)

1.0	0%	0.00%	0.00%	0.00%
1.5	50%	-7.13%	-33.33%	0.00%
2.0	100%	-10.69%	-50.00%	0.00%
2.5	150%	-12.83%	-60.00%	0.00%
3.0	200%	-14.26%	-66.67%	0.00%
3.5	250%	-15.28%	-71.43%	0.00%
4.0	300%	-16.04%	-75.00%	0.00%

Figure 25 Contributors to Retrieval Costs

Figure 26 Impact on Amplification by Modifying Waste Retrieval Depth

The return on investing in a higher efficiency end effector could be very high. Figure 26 shows the impact on waste retrieval costs of increasing the waste retrieval depth. Other parameters adjusted that yielded results as noticeable, but less significant were: increasing the end effector speed and enlarging the end effector to cover a greater area with each pass over the waste surface. The two had similar impact on waste retrieval cost, reducing it by 17 percent from the nominal case. Figures 27 and 28 show the impact of changing these parameters.

Figure 27 Impact on Cost of Modifying End Effector Speed

Figure 28 Impact on Cost of Modifying End Effector Size

It was felt that when the effects of these parameters were working in concert, there might be a compounding effect. This effect, it was hoped, would result in a better performance of the system. To this end, altering the depth of waste retrieval and the end effector area was compared with the time to clean a tank. See Figure 29. This experiment yielded a result of 66 percent of the waste retrieval costs when the depth of the retrieval was increased from one inch to two inches and the end effector area was increased from 1.0 to 1.5 square feet. Also, depth of waste retrieval and speed of the end effector were compared with waste retrieval time. This comparison showed a 56% reduction in waste retrieval costs when the depth was increased from one inch to two inches and the speed of the end effector was increased from 240 inches per minute to 300 inches per minute. See Figure 30.

Figure 29 Effects of Altering Parameters of Waste Retrieval Depth and End Effector Area

Figure 30 Effects of Altering the Parameters of Waste Retrieval Depth and the Speed of the End Effector

Further, alterations in the size of the hardware that can be retrieved and disposal time were compared with the time to retrieve hardware from the tank. In this case, the reduction in hardware retrieval cost was 56 percent when the size of the hardware was increased from six inches to twelve and the disposal time was reduced from 40 minutes to 26. See Figure 31 for the effect of altering these parameters.

Figure 31 Effects of Altering the Parameters of Disposal Time and the Size of Retrieved Hardware

Finally, the parameters with the most impact in the hardware retrieval and waste retrieval were altered simultaneously. Figure 32 shows the effects of improving the two factors improves system performance, but with diminishing returns. This experiment showed a decrease of 50 percent in waste retrieval costs, 50 percent in hardware retrieval costs, and 40 percent in overall cost reduction when the size of retrieval hardware was increased from six inches to 12 and the depth of waste mined was increased from one inch to two.

Figure 32 Effects of Altering the Parameters of Waste Retrieval Depth and Hardware Retrieval Size

The results of this model are based on some robotic software or hardware components or systems that have been proposed but the operational characteristics of this hardware (*e.g.* end effector) or software (*e.g.* path planning algorithm) when developed may have a profound impact on the results of the model. On the other hand, the results of this model might impact the software or hardware to be developed. The model can provide bounding requirements for the system under development. In the case of the current data the model seems to indicate the best place to improve a TWR system is in the accommodations for hardware handling and/or retrieval. In this portion of the retrieval effort, handling larger sizes of retrieval hardware indicates a large payoff. Then, development of an end effector that can tolerate deeper retrieval is indicated by the model. These conclusions could change with different input to the model, however, the results do provide some interesting insights that might prove useful in directing further research and development of robotic systems.

8.0 MODELING COMPONENT 3 - TWR AMORTIZATION MODEL (TAM)

The TWR Amortization Model (TAM) results from incorporating as many of the overall costs as possible regarding the problem of retrieving waste from the USTs at Hanford using a remote manipulator. The model then calculates the overall cost if the system is used to retrieve waste in more than one application (a single tank).

8.1 Description of this Model

The initial data for this model were gathered from estimates to develop a totally teleoperated system with little automated support. The data were then altered to take into account addition of intelligent robotics support. The model starts with a published (and assumed accepted) set of estimates from Krieg [KRIEG1990] regarding the aggregate time to retrieve waste (including hardware). This model also accounts for the costs of purchasing equipment, maintenance, replacement of hardware, components, etc. It does not account for operational and staffing costs which are discussed in Section 7.0, "Modeling Component 2 - TWR Operations Cost Model (OCM)."

8.2 Content of this Model

This particular analysis was an initial study of the amortized costs derived from the sources of cost data for systems that could be applied in the TWR effort at Hanford. This application of the amortization tool has data elements as described in Section 3.0 the "Amortization Modeling Tool." Here the model has been altered to directly associate it with the application to TWR.

As mentioned earlier, this model allows for multiple uses of a system. The model is focused on the potential use of a human teleoperated system for this initial study. However, it does not attempt to ascertain the potential impacts on a human operator in a repetitive teleoperated environment, nor does it reflect the resulting performance effects of such impacts on a human. Performance data about humans in a teleoperational environment, when they have been located, will need to be factored into this model.

8.3 Model Specifics Regarding Amortized Costs

When examining cost trade-offs for UST waste retrieval operations between a completely human teleoperated system with no, or very limited, automated support, and one in which significant intelligent robotic support is available, considerations

affecting the model arise with respect to both the efficacy of human operation and with respect to the impacts of human learning and error when multiple SST are involved.

Vladimir Lumelsky [LUMEL 1991] proposed several points bearing on human performance in situations similar to the problem of SST waste retrieval. His experimental data supported the view that, even in relatively simple tasks, the capability of human beings to accomplish space orientation and planning is limited. Further, the experimental data indicated that human motion planning skills did not execute the motion planning algorithms efficiently, nor did they improve greatly as they repeated the task. In fact, one experiment indicated human teleoperation took 3.5 times longer than a path planning algorithm executing on a sunset technology machine.

In addition to the studies discussed in Sections 10.3.1 and 10.3.2 several other analyses, factors and assumptions potentially affect a full cost model.

8.3.1 Time per SST

Krieg [KRIEG1990] estimates that a teleoperated extraction unit will require 16 total months to extract the waste from one SST, consisting of:

Months Duration	Activity
2	Initial system set-up and installation into tank
6	Waste extraction operations
4	Removal of extraction unit from tank
4	Extraction unit maintenance post-operation servicing

Figure 33 Time/Activity Table

8.3.2 Reducible Time

Therefore, according to Krieg, intelligent robot assistance can affect only the 6 month period in which actual waste extraction operations occur, so that [Krieg 1990] estimates a *minimum of at least 10 months is required per SST*, plus whatever time is required for actual waste extraction operations. Note that the original estimate on extinguishing all oil well fires in Kuwait was more than two years, while the

actual time to put them out took only a few months. Krieg may be off in some estimates. There is no "theoretical minimum."

8.3.3 Ten Year Project After Demonstration Phase

[EDENB1992] notes that, based on a tri-party agreement (US Department of Energy, US Environmental Protection Agency, Washington State Department of Ecology), the Robotic Five Year Program Plan developed jointly by Oak Ridge National Laboratory and Sandia National Laboratories anticipates initiating tank farm closure in 2004, with the first four years of the program being devoted to a demonstration tank farm closure. Note that TPA Milestone M-45-05, "Retrieve Waste for All Remaining SSTs," is set at September 30, 2018.

8.3.4 Tanks Remaining To Do After Demonstration Phase

There are 149 SST at the Hanford site, spread among a number of tank farms. The pilot demonstration effort has been designated for Tank TK-241-C-106 [WALLA1993], which is one of 12 tanks in the 241C tank farm. Although [WALLA1993] does not specify which tank farm would be the overall pilot, it is assumed that it would be the same farm and thus a total of 12 tanks would be done in the four year initial demonstration. *That leads to the assumption that 137 SST would remain to be done in the ten year period following the initial demonstration phase.*

8.3.5 Number of LRMS Required

[EDENB1992] estimated LRMS quantity required using a formula that can be generalized to Equation 1:

$$N = \text{Int} \left[\left(\frac{\text{Number_of_Tanks}}{\text{Available_Months_to_Clean}} \right) \times (10+T) \times (1+S) \right] + 1 \quad (1)$$

where,

- N is the number of LRMS required.
- "Int" is a function to return an integer rounded upward to the next higher value for any fraction.
- (Number of Tanks) is the quantity of SST remaining to be done.
- (Available Months) is the time allowed for completion.
- (10+T) is the total time in months to complete a single tank.
- T is the time in months required for completion of waste removal from a single SST and is a variable dependent on several factors (such as the level of human teleoperation vs. automated intelligent robotics support).

- $(1+S)$ is the factor to account for the whole unit plus some fractional unit allowed for spares (in [EDENB1992] and [KRIEG1990], $S=0.2$ but also may vary depending on human vs. intelligent robotics support ratios).
- "+ 1" end unit is added as a mock-up, troubleshooting, etc. as suggested by [EDENB1992] and [KRIEG1990].

Equation 1 points out that there are truly *two unknown independent variables*, T representing the time to complete a single SST (which is itself dependent on several factors) and S representing the number of spare systems, which also varies with T by similar factors.

8.4 Impacts of Human Teleoperation Error

Lumelsky's analyses [LUMEL1991] pointed out that humans tended to perform much more poorly than a path planning algorithm. However, such studies have not addressed two related factors potentially bearing on cost analysis for the Hanford SST project:

1. *Human error induced damage from repetitive work.*
2. *Human error increased time-to-complete in a repetitive work environment.*

When other factors are held equal, a human's mental state in a repetitive work environment is likely to tend toward less attention to detail, less alertness, and a lessening of capability. The adverse impacts on project completion could be severe, depending on the severity of the human error. For example, if human error should allow the LRMS to strike the side of the SST or some internal structure, the force could damage the LRMS requiring a major rebuild or complete replacement and could also severely damage the SST itself, with either event involving a delay. With over 100 SST to be done, a probability of occurrence of even 1% could lead to an expectation of at least one such accident over the duration of the project.

8.4.1 Error Impact on "Spare Unit" Considerations

Both the [EDENB1992] original equation and equation 2 assume that not *all* available LRMS units are to be placed into operation during the post-demonstration phase of the project. Efficiency and cost containment suggest that it might be appropriate to use all available LRMS simultaneously. This strategy recognizes the possibility of a declining number of LRMS available as systems are taken out of service permanently because of accidents, major failures, etc. This model assumes that all systems would be in operation from the beginning of the mass retrieval

effort and over time accidents would cripple (beyond repair) a number of systems. This strategy results in the following equations:

$$S_1 = \text{Num} - \text{Cleaned} \times \text{LRMS} \quad (2)$$

where:

- It is assumed that there are a set number of LRMS and a required time frame (one month in this case), during which some portion of the total SST will be cleaned.
- S_1 is the number of SST's completed per month.
- LRMS is the number of LRMS in operation at any one time.
- Num-Cleaned is number of SST's cleaned in one month by one LRMS.

If, at first, you assume that there are no failures of LRMS, the equation for the number of LRMS required to complete the project in the required amount of time is:

$$\begin{aligned} S_{Tot} &= (\text{Num} - \text{Cleaned} \times \text{LRMS})_1 + (\text{Num} - \text{Cleaned} \times \text{LRMS})_2 + \dots \\ &\quad + (\text{Num} - \text{Cleaned} \times \text{LRMS})_N \\ S_{Tot} &= \sum_{i=1}^N \text{Num} - \text{Cleaned} \times \text{LRMS} \end{aligned} \quad (3)$$

where:

- S_{Tot} is the expected total number of SSTs completed over the life of the project.
- i represents an elapsed month.
- N is the number of months to complete the Project.

When the possibility of system failures is introduced, the number of LRMS in equation 3 is no longer constant over time. The quantity, LRMS, is now time dependent. Equation 3 can now be rewritten as:

$$S_{Tot} = \sum_{i=1}^N \text{Num} - \text{Cleaned} \times \text{LRMS}[i] \quad (4)$$

where:

- $\text{LRMS}[i]$ is the expected number of LRMS in operation during month i .

$\text{LRMS}[i]$ can be described as:

$$LRMS[i] = LRMS[i-1] - Num_Failures[i] \quad (5)$$

where:

- $Num_Failures[i]$ is the expected number of failures in month i ,

and can be written as:

$$Num_Failures[i] = LRMS[i-1] * P[i] \quad (6)$$

where:

- $LRMS[i-1]$ is the number of available systems for waste retrieval at the beginning of month i .

This number is used because the probability of failure of a system at any one time is based on the number of systems available the previous month and how long the systems have been operating since the initiation of operations. It is assumed that all of the systems in operation during month i have been operating the same amount of time.

$P[i]$ is the probability of a failure of an LRMS in month i . This number is based on the Weibull probability density function which [WALPO 1978] and [HASTI 1975] state is the preferred choice for modeling complex system reliability behavior:

$$f(t) = \left(\frac{\alpha \tau^{\alpha-1}}{\beta^\alpha} \right) \varepsilon^{-\left(\frac{t}{\beta}\right)^\alpha} \quad (7)$$

where:

- α is the characteristic $0 \leq \tau$, $\alpha > 0$, $\beta > 0$ of the Weibull distribution that controls its shape and β is the scaling parameter, sometimes referred to as the characteristic life.

By means of computer experiments, the values $\alpha = 5$ and $\beta = 3$ seem to best fit an assumed TWR application. The probability density function using these values is shown in Figure 34

Figure 34 An Equipment Probability Density Function and the Resulting Probability of a Failure of an LRMS in Month i

Then calculate the probability of failure during each discrete month i as:

$$P[i] = P[(i-1) \leq t < i] = \int_{i-1}^i f(t) dt \quad (8)$$

Equations. 4, 5, and 6 give us:

$$\frac{S_{Tot}}{\text{Num_Cleaned}} = \sum_{i=1}^N (LRMS[i-1] - LRMS[i-1] * P[i]) \quad (9)$$

It would be preferable to solve for $LRMS[0]$. However, this may require an iterative process due to the number of unknowns in the equation.

8.5 Assumptions

In this initial development of the TWR Amortization Model, there is still much work to complete. In order to provide a model that could show the utility of such calculations, some assumptions were necessary. They were made about the waste retrieval problem, the system, and its operating characteristics.

- The total number of LRMS depends on the number of tanks that remain to be cleaned after the initial pilot projects. In this version of the model, it is assumed that 137 underground tanks would remain to be done in the ten year period following the initial demonstration phase.
- The number of systems that need to be purchased also depends on the available time to clean the waste from the tanks after the initial pilot projects. The model assumes that 10 years will be available as planned to complete the efforts for all tanks outside of the demonstration.
- The amount of time required to complete the waste retrieval from a single tank impacts the number of systems needed. A minimum of 10 months per tank is assumed to complete the waste retrieval in each underground storage tank.
- The model also assumes that some of the costs allocated to the initial system will occur with each system purchased.
- The model takes the Kaiser engineering estimates as the starting point for the overall costs of the initial system.

8.6 Model Results

Figure 35 shows that the number of SSTs completed per system decreases the cost per tank. The results of this modeling effort provides some insights to the TWR problem and some effects on cost of a proposed system. The graphs shown in Figures 35 and 36 give an idea of the information that this model can provide. Figure 35 shows the individual amortized costs versus the number of systems cleaned.

After the second application of a system, the cost drops between 17 and 25 percent from the cost of the first application. The chart shows a varying assumption of reusability. In this circumstance, reusability implies how much of the system used in tank A can be reused in tank B without purchasing or refurbishing. Of course, all components have a varying degree of reusability; however, the chart shows the

system's reusability factors combined. For example, reusable components would include the manipulator system, hydraulic system, the bridge structure, etc.

A more concrete example of non-reusable components that would need to be purchased, or built, for each tank include the concrete pilings on which the system rests, hardware disposal baskets, etc.

Figure 35 Retrieval in Number of Tanks vs. the Amortized Retrieval Cost

Figure 36 shows a representation of the total costs of utilizing a single system over several tanks with similar assumptions of reusability. The total cost of operating a system shows a smaller increase for the second application of a system, say, on the order of 72% to 83% percent when compared to the purchase of a completely new system. It shows, regardless of the assumed level of reusability, that the total system cost increases as the number of tanks completed increases. This rise is caused by the purchase of new components, maintenance costs, etc. required for each system deployed.

Figure 36 Retrieval in Number of Tanks versus the Total System Costs

This model when used in concert with the OCM can provide valuable insights and knowledge of overall utilization of multiple systems for the waste retrieval efforts at Hanford.

9.0 MODELING COMPONENT 4 - LINKING SYSTEM ANALYSIS AND SIMULATION

The final tool under development by the RTDP is the link between graphical simulation and the cost modeling tools. This work was initiated to link a graphical modeling package (IGRIP) to the Cost Model. The initial work has proven successful, providing a basis for operation duration information in the costs model from simulations. A primary benefit of this analysis strategy is that graphical simulation can directly provide some information regarding systems with the accuracy as derived by a simulation. The chief concern is that the data provided from the simulation is only as reliable as the data provided to the graphical model.

9.1 Graphical Simulation Model

Safe and efficient robot manipulation requires complete and accurate geometric information regarding the robot workcell and its environment. Constructing a graphics-based, geometric world model of the robot workcell provides an environment where robot programs can be verified, validated, and optimized prior to implementation in the actual robot workcell [MCDON1993]. Collisions between the robot and its workcell components in the simulated or virtual world model do not damage expensive equipment or compromise worker safety because they can be corrected and validated prior to operation in the real workcell.

The graphical world model is created using *a priori* CAD data (such as blueprints or other drawings) for the robots and workcell, and then is modified with sensor data (such as structured lighting scans, laser range finding scans, or visual targeting correlations) as it becomes available. Data from CAD models and sensors are then combined into a geometric database accessed by a robot simulation software package. Robot operators can then program and validate robot motion using a graphical user interface provided by simulation software or other high level user interface.

Currently, several different robot simulation software packages are employed. Generally, these software simulators run on sophisticated graphics workstations. The simulation packages are used to model robots, workcell, and robot/workcell interactions. Sensor data is acquired in real-time via multiple Motorola 68020 single-board microprocessors resident in VME backplanes running real-time operating system software. Data is passed to a host workstation from the VME and communicated to the graphics workstation to update the graphical world model as needed. Robot motion control is based on the world model, sensor subsystems, and operator inputs.

Inaccuracies in the world model may require the further integration of real-time sensing and control technologies to obtain sufficient correlation between the graphically simulated workcell and the actual workcell geometry. Real-time sensors implemented at Sandia include various force, proximity (both ultrasonic and capacitance based), and vision sensors.

Once the geometry of a robot workcell has been accurately modeled, robots can be programmed to accomplish various automated tasks and operations. Before robot motion is initiated, a graphical representation of the world model displays the motion sequence allowing approval or disapproval and correction by a system operator. Software interference checking, proximity checking, and sensor proximity checking can be integrated into the control system to provide additional layers of safety and reliability. Once the robot paths are accepted by the operator, they can be downloaded to the robot controller for execution.

Robot position sensors (encoders or resolvers) update the world model robot configuration in real-time. This information is used to drive the graphical representation of the robot so that it is in precise synchrony with the motion of the physical robot. Since the world model contains information regarding robot joint range of motion, joint speed limits, joint acceleration limits, and robot kinematics, the graphical representation of the robot workcell can be configured to warn of impending motion problems before the physical robot begins motion.

9.2 Purpose of Graphical Simulation in System Analysis

The world model not only contains geometric data regarding robots, but it also contains the geometric representation of all other devices and objects in the robot workcell. This information is used to graphically check intended robot motion for potential collisions of the robot with its surroundings, evaluate proximity of workcell components, evaluate task cycle times and evaluate task interactions and performance. The graphical world model contains algorithms for mathematically checking for collisions and measuring object proximity. The model also can be used to calculate cycle times during operation and measure other performance parameters of task operations. Thus, the simulation can provide estimates of time requirements and task performance using only models of the robot and its workcell.

As with any analysis or prediction of performance, the estimates are only as good as the information and assumptions employed by the models. The more accurately the world model and modeling algorithms reflect the actual robot and its workcell the better the estimates of cycle time and task performance parameters will be. With reasonable care taken to provide detailed models with realistic operating parameters, the models have proven to be reliable estimates of actual robot

performance. For instance, accurate representations of robot joint acceleration and velocity profiles can be obtained from robot manufacturers. Other details of the model, such as accurate estimates of geometry, payloads, maximum slew rates, joint ranges of motion, link masses and inertias, product tolerances, fixturing tolerances, etc. can further improve the accuracy of the model. Depending on the required accuracy of simulation estimates, some details may prove to be insignificant or even irrelevant in specific circumstances.

9.3 Graphical Simulation Used in General System Analysis

Relative to cleaning out hazardous waste tanks, a tremendous amount of critical information can be obtained from task simulation [CHRIS1992]. Much of the information can be used to drive the design of the robot arm remediation system and other associated subsystems. Good estimates of robot fabrication, setup, and operating costs can be obtained before the system is even designed or built. Additionally, operating modes can be compared and plans regarding use of robotic and teleoperation modes can be planned and optimized.

A hazardous waste tank was modeled and a model of a candidate long reach manipulator was placed in the tank and programmed to clean out portions of the waste. An analysis was performed that compared controlling the manipulator as a robot with controlling the manipulator as a teleoperated device during tank remediation operations. Simulated material removal rates were employed which approximate the remediation end-effector design material removal rates. The results of this simulation and analysis were discussed in preceding sections.

9.4 The Linking Program

As mentioned previously, a candidate LRM was modeled inside a tank and programmed to clean out portions of the waste. The model was instrumental during the retrieval process to gather data about the times of certain operations. These data were then converted from the IGRIP form to the OCM with the IGRIP conversion program. Figure 37 (IGRIP Conversion Program) shows the general flow of data in the context diagram of this Visual Basic program which links IGRIP and the EXCEL Workbook executing the OCM.

Figure 37 IGRIP Conversion Program

10.0 CONCLUSIONS

In the following sections, some understanding gained from this effort is brought to bear in an attempt at focusing on future efforts.

10.1 How to Meet Customer Needs

In Section 2.1, "Customer Needs - An Interpretation" (p. 3), the needs of the two potential customers, the analyst and the analyst's customer, were discussed. As discussed in the previous sections on tools and the usage of these tools, the operation of a system can be described in a graphical manner, or in a highly detailed spreadsheet of times and system operating costs. Accuracy and substantial background research was one of the stated needs. The tools are very accurate when the data input is known to be accurate, particularly the amortization modeling tool and the cost modeling tool. The models that were developed for the TWR system contain much background information and robotics component research that can be reused in future model development.

The component research can be used in other applications that have similar needs. This available research will help reduce analysis work, by allowing the analyst to use known robotic components in future system models as appropriate. In addition to this component reuse, adding operations utilizing existing models is possible. At this time, such an effort is highly labor intensive, but it could be completed successfully.

Once information about a system is modeled, analysis customers can be provided useful information to meet their needs. In some instances, it may take some exploration to reveal the information however. In working with the process modeling tool, a customer can use the graphical information directly without a tremendous time investment. The cost model requires a bit more effort. There is a significant amount of information available, but it requires some knowledge in how to retrieve it. The graphical simulations from IGRIP and QUEST linked to a cost model do or could provide another source of easy to understand information. The graphical simulations execute a set of operations. Currently, the results of these operations are a source of information for the cost modeling tool which then calculates the resulting costs based on the simulation information.

10.2 Tool Development

The RTDP system analysis group has been working extensively with three tools, and to a lesser extent a fourth, in development and use. These tools, the Process

Diagram, Cost Modeling Tool, and the Amortization Modeling Tool were the primary tools under development. The fourth, a link between the graphical simulation and the Cost Modeling Tool was a minor player in the work completed this fiscal year.

These tools are in their initial stages of development and as such, there is still a great deal of work required to develop these tools for wide application. The use of these tools, even though still in development, provided insight into the system investigation as well as the tools' most effective use. For the greatest efficacy, these tools should be used in concert and as development unfolds they should continue to be used together, or melded into one tool which would provide all of the associated functionality.

10.2.1 Process Diagram

The process diagram is a visually oriented schematic diagram which provides the analyst and customer with a picture of the problem or system under investigation. The diagram allows for an overall system level view, yet it can be decomposed into as much detail as needed to adequately describe the system or problem. The diagram is also flexible enough to allow questions (with or without answers) to be expressed in the model.

There were some challenges in utilizing this tool, however. It is currently a manual tool which engenders a slow and tedious development of a system diagram. There is no interaction with a diagram. If changes need to be made, the diagram must be redrawn. Finally, a concern that arose during the development of the TWR System Diagram is that for the best utilization of this tool, input from more than one person during a diagram development is best.

10.2.2 Cost Modeling Tool

This tool is incorporated into a Microsoft Excel™ workbook that provides a very detailed, numerically based analysis capability. The tool can act alone or it can use input from an adjunct graphical based simulation. The tool allows for input parameters decomposed into the system parameters, the parameters describing the problem or environment in which the system must operate, and operations personnel related information.

Some advantages of this tool include its ability to be easily adapted for many robotic applications. It currently includes some modeled robotic operations that can apply to a wide variety of RTDP activities. This leveraging of portions of models could allow building of future models more quickly.

On the other hand, there are some concerns in using this tool in the future. If use of this tool continues, it will need to be expanded to produce graphical information, rather than in the current manual method. The tool also outputs only a single point estimate rather than showing and trending information based on a series of input data. Trends provide valuable information about the behavior of a system over a range of stimuli. Also, the current tool is focused on a system in an environment which does not give an analyst a system level view.

10.2.3 Amortization Modeling Tool

The Amortization Modeling Tool provides a method to account for the distribution of costs over several applications of a system. This tool has only been explored slightly, but it does look promising. It provides the system level orientation required to study factors affecting all applications of a system such as fabrication, research, set up, and other one time costs. However, the tool does have some limitations. It has only been used once, and it is clear from this use that accurate component cost data (as well as accurate performance data incorporated from the OCM) are needed to provide meaningful output for the analyst. Additionally, using this particular tool, a percentage of equipment and supplies is projected for reuse. Currently, the percentage of the system components that can be re-used is unknown.

10.3 TWR Analysis

Using the tools, three portions of an analysis were completed for the TWR program. These three sub-analyses resulted in a TWR System Diagram, an Operational Cost Model, and a TWR Amortization Model. These models provide some interesting and surprising results.

10.3.1 TWR System Diagram

The System Diagram raised several questions and brought to light several potential retrieval strategies. Retrieval strategies that could be considered for retrieving waste include:

1. Removing all hardware first, then retrieve waste.
2. Removing the hardware and waste in layers.
3. Retrieving all the waste maneuvering around the hardware, then removing the hardware.
4. Maneuvering around the hardware to retrieve all the waste and leave the hardware in place.

The system diagram provides pictorial representation of the tank waste retrieval problem and a proposed system to alleviate the problem.

10.3.2 Operations Cost Model (OCM)

The OCM is a Microsoft Excel™ workbook model of the operations to retrieve waste from the underground storage tanks. The operations range from system insertion to system removal. The initial result of the OCM was most surprising. Hardware retrieval costs accounted for over 60 percent of all retrieval costs under the nominally required operating conditions. After examining this outcome, the OCM was used to conduct sensitivity analyses of seven parameters of which four had some impact on the cost operate the system. The factors studied were: The size of disposable hardware, the time to cut hardware, the time to dispose of hardware, the depth of waste retrieval, the size of the waste retrieval end effector, the waste retrieval end effector speed, and the time to create an electronic map of the waste surface.

The sensitivity analysis revealed that a major reduction in cost could be accomplished by increasing the size of the disposable hardware. This reduction of hardware retrieval costs lowered overall expenditures by nearly 29 percent. In studying waste retrieval cost factors, the depth of waste retrieval yielded the most impact on waste retrieval costs. However, when waste retrieval costs dropped by 50 percent the overall cost only dropped by one percent. When these two factors were combined, the overall impact on the system was a reduction in cost of 40 percent. Given THE results, it could be concluded that based on current information that hardware retrieval should be a primary focus of future efforts. There could also be a cost savings realized if ITH is handled as little a possible. On the other hand, this practice could necessitate better waste retrieval mapping and motion planning techniques which, in turn, may result in higher waste retrieval costs.

10.3.3 TWR Amortization Model

The TWR Amortization Model is a system level model which estimates the cost of a system used in several applications. It is an initial development product that used Kaiser Engineering staff estimates from 1990 for a majority of the capital costs associated with deploying a long reach manipulator. Even so, the model was able to show a significant decrease in cost of approximately \$25M by using a single system over multiple applications. Subsequent uses showed a 40 percent savings after the first reuse of the system assuming 25 percent. The model also showed a total system cost of \$180M on the second use, a 38 percent decrease compared to purchasing two identical systems to complete the same tasks.

11.0 RECOMMENDATIONS

Throughout this project, efforts have been made to develop tools and processes that can be used by an analyst or his/her customer. However, there is still progress to be made in all areas. This section reviews the needs of the customer from the standpoint of unresolved issues, then discusses further development of tools, further performance testing and development of a process to conduct system analyses.

11.1 Customer Needs - Where to Improve

In Section 2.1, "Customer Needs - An Interpretation" and Section 10.0, "How to Meet Customer Needs," this paper discussed the customer's needs as they are understood and how the tools thus far match those needs. Here, the discussion centers on how the tools should be improved to better meet these needs. The major improvement needs to be seen in the ease of use. The modeling tools for the RTDP should allow for a more intuitive input of system characteristics, operations, building, and set-up. Further, the tools should provide some means of reducing detailed information to intelligent, easy-to-use, readable reports. These reports should call attention to information that a decision maker is most likely to need.

The tools should include features which provide more flexibility for the analyst, and they should develop a library of operations, or functions, that can be used in other applications of the tool. Eventually, such a library should contain modules which can be used in developing models. They could be connected by well defined interfaces to produce a stand-alone model in a shorter time than is now required to build a complete model from scratch. This library could also be used to add functionality to an existing model. This conclusion implies that models will have interfaces available for new modules even when complete.

Finally, the idea of the correct answer needs some discussion. Even when tools have reached their peak, system analysis will still require research. It is this research, analysis, and knowledge of the system that can provide a decision maker with the confidence to choose an option. System analysis and any associated tools will provide the decision maker a list of options and information regarding those options.

11.2 Further Development Required for Tools, Techniques

Now, the discussion will focus on the continued development of tools and the learning required to use those tools. The future needs of the customer will be addressed as well as suggesting some courses of action. The potential use of

commercially available tools will also be discussed either in consort with use of RTDP developed tools, or as a foundation on which RTDP knowledge can build.

11.2.1 Identification, Development, and Improvement of Tools

The first recommendation from this paper is to identify additional tools either within RTDP, or in commercially available sources that can provide assistance in system analysis and cost justification. The system analysis tools under an in-depth review are those which have a wide variety of possible applications in which they can be used. These tools, DECIDE (Section 2.6), IGRIP/QUEST (Section 3.2/3), and *ithink*® (Section 3.1) were discussed previously. These cost justification tools have just begun to be surveyed both in the commercial and RTDP arenas. As such, it is recommended that these survey activities continue.

There are two basic areas in which the tools developed for use in the RTDP thus far need improvement: user interfaces and calculations content. In the areas of user interface, as discussed in the user needs, more functional output is required. An analyst needs more than a set of numbers to develop insight into the way the system works and is being modeled. An analyst desires graphical output which gives information on parameters of interest and statistical analysis. Further, the tools need to be usable by persons who are new to analysis or who infrequently use analysis tools. The non-experienced user needs to be catered to. Work has begun on providing input from graphical simulations to the cost modeling tools. This work will somewhat ease the burden on an analyst when he/she would like to experiment with various system options.

Also the current tools are lacking an important calculational capability, especially for the case of the RTDP. That capability is factoring in the effects of radiation into an analysis. Radiation is known to affect costs by virtue of exposure of humans and machines, reducing effectiveness in doing the required tasks. Additionally, there is a potential impact on the environment when dealing with radiation hazards. Also, if radiation hazards and their impact on analyses calculations are known, then presumably, one can also calculate impacts based on other hazardous substances.

Further, whether working with the user interfaces, calculations, or directed data transfer, the tools must be improved so that the analyses can be conducted faster. This recommendation is long range and multifaceted, and as such has several parts. RTDP analysts need to develop an expertise at developing models of problems and proposed systems to solve these problems. The skills and thinking of analysts need to be applied to RTDP challenges. Tools for analysis will come from meeting these challenges as needed. It is more than likely that the initial step of applying a commercial tool using RTDP creativity and thinking will lead to better solutions to problems and enhanced tools.

11.2.2 Performance Testing

The second recommendation is to continue performance testing for telerobotic and teleoperational systems. Analyses of robotic systems hinge on how systems perform in actual use conditions. In order to estimate potential effects of robotics systems, teleoperational performance testing was conducted this year. (See section 4.0, "Performance Testing Used as a Tool to Increase Understanding") However, further work needs to be completed to link performance testing and telerobotics to the tools. Linking the tools with performance testing will keep them in the realm of actual usage versus a simulated world. Also the tools will provide information on when the performance testing can yield the most or best information with the least cost. This activity will call upon all of RTDP to build a database of task completion times that can be utilized in the prediction of system performance. Currently, the RTDP performance testing program (as described in Section 6.0) has completed testing of some components in teleoperational pipe cutting. These data have been incorporated into cost models and made a difference of approximately four percent of total cost from the original estimates. This leaves a wide array of performance data needs unfulfilled.

For example, while some of the hardware cutting application of teleoperation has been executed, completion times from tasks such as disposal, retrieval from surfaces, etc. are at best, estimates. Further, performance testing of automated or telerobotic tasks is not started. The demand for data concerning telerobotic tasks in modeling and analysis is great and the supply, virtually non-existent.

Data are needed in all aspects including telerobotic decontamination and dismantlement tasks and waste retrieval efforts. There is no experimental data available yet for the Sandia based telerobotic technologies which assists operators in planning and executing operational strategies in a graphics based control environment. To ensure that data are collected to help future analyses, it is recommended that performance testing be continued until sufficient data points exist to provide a base of data for these future analyses.

11.3 Developing General Procedures to Conduct System and Cost/Benefit Analyses

A third category of recommendations involves the development of a system analysis and cost benefit analysis procedure. The procedure for both types of analyses should be illustrated in a step by step approach. These procedures or "recipes" for conducting analyses would help people new to a justification process for technologies and products conduct their analyses. A procedure would also help with new projects. Project leaders and staff would have a better idea of the information needed to

conduct a complete and careful analysis. As such, the procedure could also point out some areas that could be potentially troublesome. Further, it would assist in the execution of uniform analyses so results from differing analyses on the same subject could be compared.

Along these lines [GUTHR1994], has developed an initial procedure during the development of DECIDE. The procedure is a set of 10 suggested steps to build a decision making plan using the DECIDE product. It is a beginning to creating a helpful procedure, however, it needs more detail before it could be used to standardize analyses. Therefore, it is recommended that the analysis method developed in [GUTHR1994] be used as a starting point to develop an analysis procedure.

Once the system analysis or cost benefit analysis procedure is developed, or near completion, a project should be chosen as a demonstration effort for the procedure. The efforts of team members involved in the execution of the procedure should be chronicled to determine what works and what does not. This will help validate (perhaps repair) the initial procedure so others can use an improved procedure with confidence.

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Appendix A

Terms and Acronyms

<i>TERM or ACRONYM</i>	<i>DEFINITION/FULL IDENTIFICATION</i>
Alpha Test	The test of a product (usually software) by customers, immediately after development activities have been completed. The customers using the product under actual work conditions communicate errors found in the product directly to the developers.
Analysis	The examination of a complex system, its elements, the relationships between elements, and relationships between relationships.
bridge (structure)	A structure spanning across the top of the tank to prevent structural loading directly on the tank itself. <i>Ref. [WALLA1993]</i>
BTU	British Thermal Unit
CCTV	Closed Circuit Television System
center riser (extended)	Center risers constitute rigidly attached ITH. Although most center risers do not extend significantly into the SST, in at least one tank farm, risers from the center extend down into the waste. All center, 42-inch, risers protrude into the tank to the top of the steel liner. <i>Ref. [TUCKE1994]</i>
component failure	Component failure occurs when the system of which the component is a part is unable to function properly. <i>Ref. [FOX1995]</i>

contained sluicing - air conveyance option	One of 11 options analyzed in 1991, the contained sluicing - air conveyance concept is a variation on the Reference Concept, using 42-inch diameter SST access holes, with the key features that all water added to the SST is contained by the equipment inside the tank, that the end effector is a clam shell bucket, and that the water injection system is inside a collapsible hopper attached to the air conveyance system. <i>Ref.</i> [JENKI1991]
contained sluicing - pump out option	One of 11 options analyzed in 1991, the contained sluicing - pump out concept is also another variation on the Reference Concept with key features that are the same as the contained sluicing - pump out concept but with the difference that the waste is prepared for transport before it leaves the tank. <i>Ref.</i> [JENKI1991]
DM	LRM deployment mast
DOE	US Department of Energy
DST	double-shell tank
end effector	Generic descriptor for various devices attaching to the end of the LRM that implement waste retrieval operations within an SST <i>Ref.</i> [WALLA1993]/[HORSC94]
EEEM, end effector exchange module	End Effector Exchange Module. A bridge module consisting of a 16'x16'x10' high sealed glovebox that provides a shielded confinement space for replacing manipulator end effectors. <i>Ref.</i> [WALLA1993]
enlarged hole concept option	One of 11 options analyzed in 1991, the enlarged hole concept provides additional SST access space for inserting the LRMS arm and other potentially desirable equipment, as well as allowing for a very rigid arm. <i>Ref.</i> [JENKI1991]
expert system fault tolerance simulator	A software package (Robo-MEDIC) developed by Rice University that addresses robotic fault tolerance, incorporating the CLIPS public domain expert system package. <i>Ref.</i> [HARRI1993]

fault tree	Robot system fault trees are a system wide method for linking faults and their effects, in which the root of the tree is a critical feature scenario for the entire system and the possible causes of the failure of interest and, in turn, their causes form the branches and leaves of the tree. <i>Ref.</i> [HARRI1993]
gal	Gallon(s)
IGRIP	Interactive Graphics Robot Instruction Program
in tank solidification	Rigidly attached ITH, experimental and found in only two tanks, consisting of a complex struction integral with an air lift circulator, identified as a significant problem for removal. <i>Ref.</i> [TUCKE1994]
ITH, In-Tank Hardware	Hardware items that are to be found within SST. <i>Ref.</i> [TUCKE1994]
Kepner-Tregoe analysis	A decision analysis model published by Kepner-Tregoe, Inc. in 1982 that has six steps: clarifying decision purpose; listing selection criteria ("musts" and "wants"); assigning criteria weights; generating alternatives; assessing alternatives; and (multiplying weight factor by rank factor for each want and total for each alternative) ranking each alternative. <i>Ref.</i> [JENKI1991]
levels of control	A continuum ranging from pure manual control (pure teleoperation) to pure robotic control (pure telerobotic). Draper depicts the spectrum as manual control, manual control with intelligent assistance, shared control, traded control, and supervisory control. <i>Ref.</i> [HORSC1994/DRAPE1994]
long reach manipulator	Device inserted into a tank allowing deployment of end effectors within the SST <i>Ref.</i> [WALLA1993]
LRMS	Long Reach Manipulator System, a proposed remote manipulation system to be utilized in retrieving waste from underground storage tank.

manual control	Within the <i>levels of control</i> concept, a control mode in which the human operator/user must control the entire range of system functions, with the task of the machine being restricted to display of work site information and reaction to user inputs. <i>Ref.</i> [DRAPE1994]
manual control with intelligent assistance	Within the <i>levels of control</i> concept, a control mode in which greater machine intelligence becomes available, so that the user is able to teach the machine rudimentary information about the work site, such as defining regions that must not be entered. <i>Ref.</i> [DRAPE1994]
mapping	Using structured lighting to electronically survey a three dimensional space and create an electronic representation of that space.
model	A representation or simulation of a problem or a system trying to solve a problem.
OCM	Operations cost model
Parazin Principle option	One of 11 options analyzed in 1991, the Parazin Principle uses a slot to gain access through the dome of the tank, so that the horizontal LRMS arm remains horizontal during all operations. <i>Ref.</i> [JENKI1991]
Reference Concept option	One of 11 options analyzed in 1991, the Reference Concept has the key feature of the LRMS arm being able to operate by insertion through a 42-inch diameter hole in the SST dome center (a feature of about one-half the existing SST), thus minimizing preparation operations. <i>Ref.</i> [JENKI1991]
Reference Concept-Multihole option	One of 11 options analyzed in 1991, the Reference Concept-Multihole is identical to the Reference Concept with the exception that the LRMS arm is inserted into 42-inch diameter holes that are not at the SST dome center (42 SST have three to four such holes). <i>Ref.</i> [JENKI1991]
riser	A pipe that is welded to the tank roof and rises to ground level through which in-tank hardware can be inserted. Almost no risers extend appreciably into any tanks, and the few that do may, or may not, have to be cut.

shared control	Within the <i>levels of control</i> concept, a control mode in which control is shared between the human operator and a computer. <i>Ref.</i> [DRAPE1994]
side entry option	One of 11 options analyzed in 1991, the side entry concept is similar to the Tokamak, differing in the LRMS arm configuration. <i>Ref.</i> [JENKI1991]
single-shell tank	A large (circa 500+ thousand gallon) tank that contains mixed high-level radionuclides/waste products with greater than 100 nCi/g TRU content in such forms as sludge, saltcake and supernat liquids. SST are often subject to radioactive decay generate heat that can produce temperatures projected to exceed 450 °F, requiring continuous water addition to the tank to support evaporative cooling. <i>Ref.</i> [WALLA1993]-
sluicing jet	Rigidly attached ITH, used to free up sludge and other solids so that they could be pumped out of waste tanks, generally consisting of a high pressure rotatable water nozzle that can be position to cover a large area of the tank. <i>Ref.</i> [TUCKE1994]
SST	Single shell tank, a portion of the underground storage tank system on the Hanford Reservation near Richland, Washington.
structured lighting	A process by which a laser line is project on a surface and then an image of that projection is captured by a calibrated camera. The image is then analyzed to determine the spatial location of the surface reflecting the laser light. <i>Ref.</i> [BURKS1992]
supervisory control	Within the <i>levels of control</i> concept, a control mode in which one or more human operators are intermittently programming and continually receiving information from a computer that controls a teleoperator. <i>Ref.</i> [DRAPE1994]
support mast	The LRM support mast, the outermost member of the telescoping system, serves as the enclosure to house the vertical DM and waste retrieval arm when retracted <i>Ref.</i> [WALLA1993]

support tower	A tower that provides a structural link between the DM and support tower, ultimately communicating with and transferring operating loads from the support mast to the bridge structure <i>Ref.</i> [WALLA1993]
support tower module	A bridge module consisting of a 16'x16'x50' high metal frame that encloses and provides direct support to the manipulator deployment system. <i>Ref.</i> [WALLA1993]
TAM	TWR amortization model
tank waste remediation system	A system established by the DOE to resolve environmental and safety issues related to tank stored radioactive waste retrieval from aging SST and confinement in new DST <i>Ref.</i> [WALLA1993]
teleoperated extraction unit	The robotic system with associated waste handling equipment and structures. <i>Ref.</i> [EDENB1992]
teleoperational system	A human manually operated system that extends a human operator's sensing, control and manipulating capabilities to a remote location, including capabilities for artificial sensing of the remote environment, manually guiding the remote manipulator, and communications between human operator and system necessary to support the remote functions. <i>Ref.</i> [HORSC1994]
teleoperator	A general-purpose, dexterous man-machine system that augments man by projecting his manipulatory and pedipulatory capabilities across distance through physical barriers into hostile environments. <i>Ref.</i> [DRAPE1994/CORLI1968]
telerobotic system	A robotic system that uses sensors and computational capabilities, allowing the system to respond to functional commands rather than simply tracking human manual motion as occurs in a teleoperational system. <i>Ref.</i> [HORSC1994]

Tokamak option	One of 11 options analyzed in 1991, the Tokamak concept provides SST access via a hole/slot in the side of the SST, so that the deep section of the LRMS arm can provide a high degree of stability in the vertical direction. <i>Ref.</i> [JENKI1991]
top off concept option	One of 11 options analyzed in 1991, the top off concept's major feature is the removal of a large (circa 48-foot diameter) portion of the top of the 75-foot diameter tanks, providing the only concept that allows direct viewing of the waste retrieval operations and affording great physical access capabilities to the SST during waste operations. <i>Ref.</i> [JENKI1991]
traded control	Within the <i>levels of control</i> concept, a control mode in which the machine and human operator are consecutively responsible for subtasks, so that sometimes the machine is in complete control and sometimes the human operator. <i>Ref.</i> [DRAPE1994]
Tuesday Marvel option	One of 11 options analyzed in 1991, the Tuesday Marvel has the feature of multiple effectors being in the tank and ready to operate at any time. <i>Ref.</i> [JENKI1991]
turret tank concept option	One of 11 options analyzed in 1991, the turret tank concept uses a relatively short arm suspended from the bottom of a turret situated low in the SST. <i>Ref.</i> [JENKI1991]
TWR	Tank Waste Retrieval
TWRS	Tank Waste Retrieval System <i>Ref.</i> [WALLA1993]
USDOE	The United States Department of Energy
UST	underground storage tank
waste retrieval deployment system	The physical system that provides a method by which the LLRM enters vertically through an SST top opening <i>Ref.</i> [WALLA1993]

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B 1 Total Costs to Remove Waste From a Tank

B 2 Cost to Insert TWRS

B 3 Costs of Hardware Retrieval

B 4 Time to Insert TWRS

B 5 Time to Remove Hardware

B 6 Time to Make a Single Cut Manually

B 7 Time to Make a Single Cut Autonomously

B 8 Number of Disposals to Complete

B 9 Time to Dispose of a Single Cut Piece Manually

B 10 Time to Dispose of a Single Cut Piece Autonomously

B 11 Costs for Waste Retrieval

B 12 Cost to Remove TWRS

B 13 Time for Waste Retrieval

B 14 EE Rate for Primary Waste Retrieval

B 15 Size of One Residual Layer

B 16 Number of Primary Layers to Retrieve by Manipulator

B 17 EE Rate for Residual Waste Retrieval

B 18 Number of Residual Layers to Retrieve by Manipulator

B 19 Time to Remove TWRS

B 20 Costs of Operations and Maintenance

C 1 Insert TWRS into Tank

C 2 Insert CCTV System into Tank

C 3 Insert LRM/DM into Tank

C 4 Remove Waste From Tank

C 5 Remove all Hardware at Once in the Beginning

C 6 Teleoperational Cutting Strategy

C 7 Hardware Retrieval Loop

C 8 Primary Waste Retrieval Loop

C 9 Retrieve Waste From Tank Autonomously until Stop Point

C 10 Telerobotic Cutting Strategy

C 11 Retrieve Waste From Tank Autonomously until Stop Point

C 12 Remove Waste and Hardware in Layers

C 13 Remove One Layer of Waste Telerobotically

C 14 Remove Hardware and Risers Teleoperationally to the Current Level of Waste

C 15 Carry out Plan

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