Conf-9111176--1

PNL-SA--19511

DE92 006507

JAN 21 1992

REMEDIAL ACTION ASSESSMENT SYSTEM: DECISION SUPPORT FOR ENVIRONMENTAL CLEANUP

K. A. Pennock
S. Bohn
A. L. Franklin

November 1991

Presented at the
International Symposium on
Artificial Intelligence
November 13-15, 1991
Cancun, Mexico

Work supported by
the U.S. Department of Energy
under Contract DE-AC06-76RLO 1830

Pacific Northwest Laboratory
Richland, Washington 99352

Remedial Action Assessment System: Decision Support for Environmental Cleanup
by

Kelly A. Pennock
Shawn J. Bohn
A. Lynn Franklin

Pacific Northwest Laboratory[1]
Richland, Washington 99352

1.0 INTRODUCTION
The introduction to follow provides a brief characterization of the problem domain, as well as a brief description of the Remedial Action Assessment System (RAAS) application.

1.1 Overview
A large number of hazardous waste sites across the United States await treatment. Waste sites can be physically complex entities composed of multiple, possibly interacting contaminants distributed throughout one or more media. The sites may be active as well, with contaminants escaping through one or more potential escape paths. Treatment of these sites requires a long and costly commitment involving the coordination of activities among several waste treatment professionals. In order to reduce the cost and time required for the specification of treatment at these waste sites, The Remedial Action Assessment System (RAAS) was proposed. RAAS is an automated information management system which utilizes a combination of expert reasoning and numerical models to produce the combinations of treatment technologies, known as treatment trains, which satisfy the treatment objectives of a particular site. In addition, RAAS supports the analysis of these trains with regard to effectiveness and cost so that the viable treatment trains can be measured against each other.

The Remedial Action Assessment System is a hybrid system designed and constructed using object-oriented tools and techniques. RAAS is advertised as a hybrid system because it combines, in integral fashion, numerical computing (primarily quantitative models) with expert system reasoning. An object-oriented approach was selected due to many of its inherent advantages, among these the naturalness of modelling physical objects and processes.

2.0 RAAS SYSTEM DESCRIPTION
The following section describes the basic computational model of site remediation. The section then presents an outline of the RAAS approach to the problem and components used to implement the approach.

2.1 The Site Remediation Model
RAAS utilizes numerical models to simulate the actual process of waste treatment. In the physical world, a contaminated site contains a distribution of one or more contaminants within one or more media. Both medium and contaminant are described by a number of physical parameters which will determine how effective or ineffective a given treatment technology will be at a given site. The expert rules of RAAS are triggered primarily by the values of these parameters. The numerical models of RAAS are coarse-grained ,"back of the envelope" computations which

---

[1] Pacific Northwest Laboratory is operated for the U.S. Department of Energy by Battelle Memorial Institute under Contract DE-AC06-76RLO 1830

provide a quantitative estimate of a how the application of a technology will alter the values of these parameters.

In computational terms, there are two basic components of the remediation process -- site states and technology operators. Heuristics are used to determine whether the technology operator should be applied at all, while numerical simulations are employed by the applicable technologies to transform old states into new states. The solution path is a series of transformations which successfully modify an initial site until it becomes equivalent to what the user has defined as a goal site. The physical and computational process which RAAS models is described diagrammatically in figure 1.

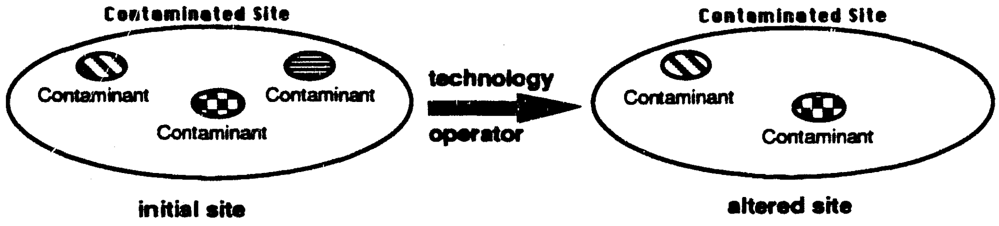

figure 1: site states and technology operators

2.2 Main RAAS Methodology
As stated, the primary duty of the RAAS computational core is to produce viable combinations of treatment technologies known as treatment trains. RAAS must model two distinctly different processes to do this. First, the decision of a waste treatment expert concerning a technology's applicability must be captured by rule-based inferencing. Next, for applicable technologies, a numerical model of the technologies effectiveness must be utilized. The rule-based inferencing selects the technology, and the numerical models applies the technology, alters the selected site, and presents the altered site to another "expert" module with the same applicability question. Technology by technology, train by train, RAAS proceeds through all possible combinations of treatment technologies.

To accomplish the iterative application of two fold modelling process, the RAAS decision system utilizes two closely interacting levels of decision making. All problem solving activities of the RAAS computational core fall into one of the two levels. The first decision level implements the decisions required of an expert in a single technology. At this level, the question is how does a single selected technology affect a contaminated site. RAAS contains the quantitative and qualitative knowledge of a technology expert in each technology object and reaches a decision using a hybrid strategy. This cycle of expert system decision followed by numerical simulation is at the heart of the first level of decision making.

The second level of decision making orchestrates the individual decisions produced in the first level. The intention at this level is to combine individual decisions to satisfy the user stated treatment objectives. This level requires an awareness of how the technology object pieces fit together to satisfy the remediation goal. The process is analogous to the activities of a technical manager who harnesses a group of experts to provide solutions to key segments of a problem. The manager then gathers the opinions of the experts, analyzes the information presented, and combines the set of partial solutions into a complete solution.

The key to the two-tiered decision support system of RAAS is integration. Several forms of integration exist. There is the integration of quantitative and qualitative models to simulate the process of waste remediation as performed by treatment technologies. Numerical models are integrated with qualitative rules derived from domain experts to determine if and how given technologies affect a site. Another form of integration is the integration of distributed functions and data. The computational core of RAAS is an object-oriented system designed for expandability and robustness. In this system, information and expertise is distributed among many objects that have the duty to maintain and share this information when appropriate. A technology object may require a parameter value from a contaminant object, a calculation from a reaction object, or a rule from a regulatory object to reach a decision concerning its own applicability. All this information is divided among the objects of the system. Yet another form of integration involves the unification of individual decisions mentioned previously. Finally, to accomplish stated objectives, RAAS must integrate the artificial intelligence technologies of object-oriented programming and expert systems. The system was designed and constructed as an object-oriented application, but extensive inferencing capabilities are combined within objects to provide the rule-based reasoning capability

3.0 TECHNOLOGY DECISIONS

The individual decision required of treatment technologies is the first stage of the computational cores operation. This section discusses briefly describes the anatomy of the technology decision concentrating upon the components of the expert decision/numerical simulation cycle - namely the qualitative and quantitative components of each technology object.

3.1 Qualitative Decision Structure

Qualitative reasoning has the duty of passing judgement on the applicability of a technology. A number of rules are built within the technologies to help them determine whether or not conditions at the site are sufficient for the utilization of a selected technology. But technology objects cannot make the decision about their own applicability in isolation. The qualitative classes of the RAAS system are constructed to assist in determining applicability. These classes are based on the heuristic knowledge of many experts, and the application of the many rules and regulations which govern waste remediation. The decision of yes or no to the applicability question is the single outcome of the cooperative rule-based computation distributed over the qualitative objects of the decision.

3.1.1 Qualitative Classes

The qualitative classes are listed in the figure 2. Together, the instances of these classes cooperate to reach the important conclusion about applicability.

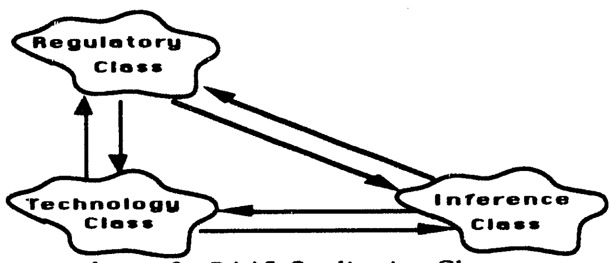

figure 2: RAAS Qualitative Classes

3.1.1.1 Technology Class

The nature of the qualitative reasoning within the technologies is straight forward. Basically, two types of rules exists: enabling and disabling rules. The first type of rule specifies what must be present at the site in order for the technology to be utilized. The list of enabling conditions may for example include such requirements as access to large power sources or flat terrain. The second type of rule involves disabling conditions. Any number of disabling conditions may exist at a site which prevent the application of individual technologies. Individual site characteristics or combinations of site characteristics may establish such unfavorable conditions. If the inferencing of the technology deems this to be the case, the technology disqualifies itself or seeks help from other technologies to alter the constraining characteristics. This strategy of applying for help from other technologies will be discussed in the manager decisions section.

The technology operates qualitatively by inferencing with both types of rules when called upon for a decision. After completing the inferencing process, which will involve the other qualitative classes to be described below, the technology indicates whether it is applicable and therefore should be added to a sequence of viable treatments to create an alternative.

Primarily, the qualitative rules will exclude technologies because one or more parameters is out of an operational range. For example, the utilization of the technology ex-situ biotreatment is in part dependent on the moisture content of the soil. If the moisture content is above or below the active range of this parameter, then the technology is disqualified. The rules that the technology utilizes are similar to the rules a technology expert would use to make the decision, since experts were contracted to provide the qualitative reasoning.

3.1.1.2 Regulatory Class

The second of the three decision classes is the regulatory class. When the RAAS user enters the appropriate state, a state regulatory object is initialized. This object has all the federal regulatory information which will be added to each instance of the regulatory class. The regulatory object will be asked a straight forward question, namely: "is this particular technology permitted by federal and state regulations for the current conditions?". For example, if the site being remediated is in South Carolina, an instance of the regulatory class called South Carolina will be initiated with data from a database containing regulatory information from this state. The South Carolinian regulatory object is queried concerning the permissibility of the technology. If the answer is yes, the object may be applied to the site. If the answer is no, then the next technology in line will be selected while the current technology is dropped from the applicable list.

The regulatory class instance will be consulted before the search process begins. The regulatory class will further hone the list of applicable technologies, removing those technologies which are physically applicable, but which are disallowed by federal or state regulations governing waste treatment. It is therefore the first class after the planner to participate in decision.

3.1.1.3 Inference Class

The inference class is the specialized inference engine embedded within the RAAS application. Currently, we have imbedded the CLIPS inference engine for this purpose. This class simply receives the request for inferencing, and the rules with which to inference, and returns the appropriate response as specified by those rules.

3.2 Quantitative Models

As stated, RAAS is designed to assist users in producing a list of treatment alternatives which will remediate a particular waste site. It has a second and related goal of providing quantitative information about the site such as estimates of concentration and containment values , dynamic parameter values, and additional waste streams that may be engendered as a by product of a technology's utilization.

This section briefly describes the problem solving architecture for the quantitative models of RAAS. In an object-oriented system, computation and data are distributed among several object classes according to the logical division of labor suggested by the task itself. In RAAS, the technology objects have the primary responsibility of determining their own numerical effectiveness, but do not do so alone. Several object classes have been constructed to share the computational burden of quantitative modelling. The quantitative classes in the figure 3 are used in the derivation of numerical measures of effectiveness.

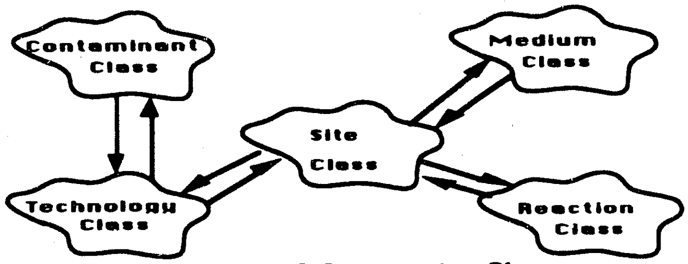

figure 3: RAAS Quantitative Classes

3.2.1 Technology Class: Numeric
Technology objects are the chief participant in the quantitative simulations, just as they were for the qualitative decisions discussed in the previous subsections. In general, the quantitative evaluation a technology performs will alter one or more data values at a site. Values altered will be either primary, secondary or a combination of the two. Primary values are values which are identified specifically in the user's site goals. For instance, a technology developed to remove contaminants from groundwater would reduce the concentration of the contaminant in the groundwater, a primary value. Additionally, the hypothetical technology might also increase or decrease the Ph or temperature in the groundwater, both secondary values. In this way, technologies can cause both "intentional" and "unintentional" quantitative changes at a site.

The effect a technology has of course depends on the specific technology chosen and the specific site to which it is applied; but there are several primary effects a RAAS technology object might have upon a site in our model of remediation. RAAS has seven different types of technology operators which numerically affect the state of the site, and each of these is represented by a subclass in the RAAS class hierarchy. These seven subclasses are shown in figure 4.

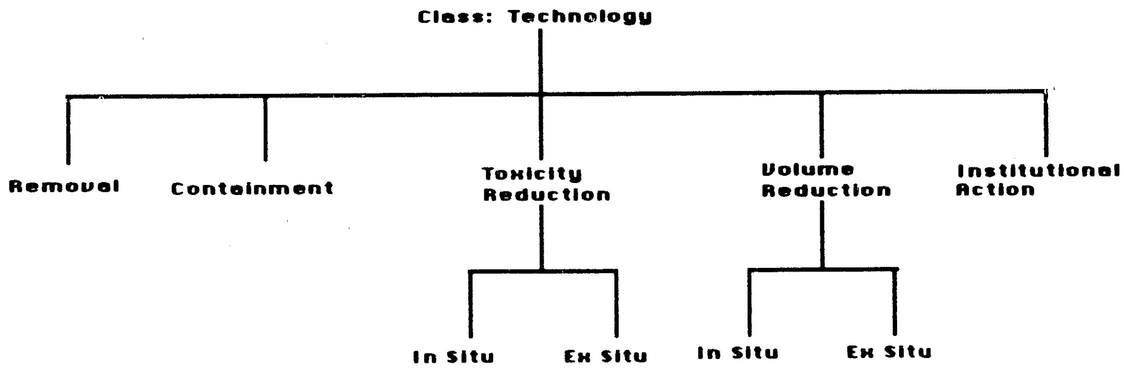

figure 4: treatment types

One example of a technology operator is removal. Removal technologies reduce the level of contaminants at a site, thereby reducing the danger of contamination. A second type of a technology effect containment. Containment will prevent the particular contaminant from escaping to an outside area where it might endanger public health, or simply expand to surrounding locations uncontrolled. Other technology operators affect primary site parameters in different ways.

3.2.2 Site Class
The site was described before as a representation of the state of the remediation process. The site class creates instances which are used as "scratch pads" during the search for viable treatment alternatives. As each technology is applied to a specific site object, the values of the data items of that site change depending on the effects of the technology, and on the unique combination of

technologies which have been applied before. For instance, one of the parameters of a cell object selected for a soil medium is hydraulic conductivity. Intuitively, this is a measure of how easily water may move through soil. The initial cell specified by the user contains the beginning value for hydraulic conductivity. For example, In-situ vitrification, a technology which "glassifies" the soil by sending a very strong current between two electrodes, may have a dramatic effect on hydraulic conductivity, in effect zeroing out the parameter. Any technology applied after the in-situ vitrification process will have to operate on a site with a very low hydraulic conductivity. It is the role of a site object to keep a current version of parameter values, as well a contaminant concentration and containment levels, and location of medium (in-situ or ex-situ). Thinking of the search for viable treatment sequences as a depth first traversal of an n-ary tree (n variable and determined by the number of applicable technologies at a specific level of the tree), the multiple site objects are the nodes of the tree (used as scratch pads for the technologies to write to), and the technologies are the links between the nodes so that each site is reached only by application of the proper technology.

3.2.3 Contaminant Class

Another important quantitative class is the contaminants class. The contaminants class contains information about the contaminants which a technology might need to know to determine how effective it is at treating the particular contaminant. The hierarchy of this class is well defined due to the useful taxonomy of chemical compounds.

3.2.4 Reaction Class

A related class is the reaction class. This class contains a variety of equations which are important to the numerical calculations used in quantitative models. The equations relate to the numerical estimates of important parameter values and other scientific calculations of importance to either the contaminants, the medium, or the technology which may require values from the contaminants and the medium. This class contains the type of calculations which arise due to the interactions between the other physical classes and subclasses, such as the interactions between medium and contaminants, and contaminants subclasses.

3.2.5 Medium Class

The final quantitative class is the medium class. The medium a technology operates within serves to define the applicability and effectiveness of a technology. The three general classes of media the system holds are the natural "elements" of soil, water, air. These three classes are further decomposed into subtypes. Soil, generally considered the most difficult of the media to remedy, can be considered for illustrative purposes. A number of parameters are used to define the soil medium. The values of the parameters will in turn determine the soil type. For instance, clay would be defined by a very low value for permeability, while a high permeability would determine a more sandy soil. The technology equations and rules interact with the parameters of a given medium dynamically: while the medium parameters determines a technology's effectiveness, the technology is determining the values of the medium's parameters.

4.0 MANAGEMENT DECISIONS

This section discusses the coordination of individual technology decisions into a global solution. A global solution must address the global goal of site remediation, as specified by the user, and therefore requires a decision strategy which uses the individual technologies as pieces in the solution. Three major complications - the decomposition of user defined goals into a series of subgoals, the subsearches for support technologies, and the construction of associated problems through alternate contaminant pathways - arise in the depth first search for a complete list of technology alternatives. Each of these complications will be discussed in terms of the RAAS solution strategy.

4.1 The Remediation Problem as Search

Having discussed the overall goal of the RAAS software, and viewed the classes that RAAS is composed of, the intention is now to provide a further glimpse of how all the RAAS objects work together to produce a correct and complete response. As stated before, the reason for the RAAS computational core's existence is to identify a complete list (within the limits set by operational constraints) of treatment trains. Previously, the classes involved with this computational process were described, and their roles briefly mentioned. This was a description of the static structure of RAAS. The search process to be described is the dynamic structure.

It is the duty of the RAAS manager object to specify the control of treatment train development. A treatment train specifies a complete solution - with a definition of complete depending upon the user's objectives. If the user has decided that at this location, the only goal is to restrict access to the area, then a single technology such as fencing may be sufficient. On the other hand, the goal of the user can be much more complicated, such as the collection, treatment, and disposal of the multiple contaminants, each to a different level, depending on their long term risk to the neighboring community. Whatever the defined goal, the search through technology objects within the RAAS application will attempt to construct treatment trains to satisfy it. Figure 5 illustrates the search, with links as technologies and site states as nodes. Darkened nodes represents altered sites due to the successful application of a technology, while light nodes represent unsuccessful technologies.

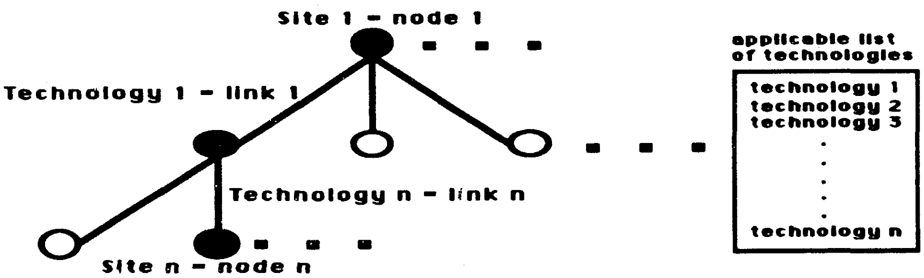

figure 5: Search for Solutions

The search is enumerative within the constraints set by the system concerning such parameters as train length. The numerically driven depth first uncovers the nonmonotonic paths of reasoning from the initial site or state to the goal state. The reasoning is nonmonotonic because the application of technologies is not based solely on whether the remediation technology addresses the goal of the site (such as contaminant removal), but is based instead on whether the technology has any effect at all on cell parameters. Therefore, a technology can actually worsen the conditions at a site, moving away from the goal, and still be included as an effective technology because of its potential side effects.

As stated, the manager object has the duty to manage individual technology decisions to the end of constructing the viable treatment alternatives. To construct a single treatment train, the manager must follow the five steps identified below.

1. Specify site characteristics and user goals.
2. Derive applicable technology list.
3. Apply selected technology to site.
4. Determine effectiveness of technology.
5. Check for completeness and return to step three if incomplete.

Steps number one and two are preparatory steps. The first step is the specification of the site characteristics and the identification of user goals. The user describes the site in terms of the medium, contaminants, and treatment intentions, such as cleanup or containment. Step number two retrieves from a database containing approximately 10 media types, 400 unique contaminants, and approximately 95 treatment technologies a subset of technologies applicable to the stated characteristics and goals of the problem.

Steps three, four and five are performed within the computational core of RAAS. Step number three involves the selection and application of one of the applicable technologies to the user specified site. The manager object orders and selects technologies from the applicable list. It also manages the list of alternatives both successful and unsuccessful, and holds on to the trains currently under consideration. Step number four utilizes numerical models and heuristics to determine the applicability and the effectiveness of the applied technology along with recording the changes this technology made upon the site. Finally, step number five tests the process for completeness (i.e. determines whether or not user goals have been met) and returns to step number three to apply another technology if necessary. These five steps are applied again and again until all viable treatment trains have been identified.

4.3 Subgoals

RAAS follows a divide and conquer strategy to find the complete list of treatment trains. The management decisions about how to connect technologies together to solve the overall problem of site remediation requires the problem to be decomposed into a sequence of smaller problems. A single problem defined by the user is actually represented internally as a collection of subproblems. Each user must select a remedial strategy which guides the solution process in two distinct ways. The first is that the selected strategy helps determine a query to the database which returns a list of technologies which are generally appropriate to the problem. The user defined strategy therefore determines the building blocks which will be used by the system in the solution alternatives. The second way in which the user selected strategy affects the solution process is that it establishes the overall criterion for success and delineates the series of subgoals which must be satisfied in sequence. Each subgoal is actually an instruction to the applicable technologies. For example, the user specified strategy may be a Collect, Treat, and Dispose option. Three segments of the problem-Collect,Treat,Dispose-must each be satisfied in sequence. Three feed forward search trees stacked on top of another would represent the multiple subgoal search.

4.4 Support Technology Search

The above search is complicated by the ability of technologies to search for support. Any of the technologies in the trees above have the ability to search for support from other technologies when they find themselves ineffective for one reason or another. Technologies will require help when one of the enabling conditions is not met, or one of the disabling conditions is set. In this case, the technology will query a database for a list of technologies which are able to affect the particular parameter which disabled the technology of interest. For example, the application of an arbitrary technology may set a flag identifying soil temperature in the medium as out of range. The flag will cause a query to be sent to a database of technologies with parameter attributes. Returned from the query will be a list of technologies which can support the primary technology by altering the constraining parameter, temperature in the example just presented.

The search for support technologies then creates its own search tree of activities which must be traversed before further progress on the subgoal can be made. This is illustrated in the figure below. Self-knowledge and communication are the essential elements of the technologies. Each technology has to be aware of why it failed to be effective. It must know what type of support it needs (i.e. which parameters are out of range), so it can send messages to other technologies. It must then communicate with the potential useful support technologies to shift the pH, or moisture content back into a usable range. The manager must of course control these support searches, using certain performance requirements and length of train constraints to limit the number of technologies which will be added to each support technology. This control will prevent support technologies from searching for support technologies from searching for support technologies, and so ad infinitum.

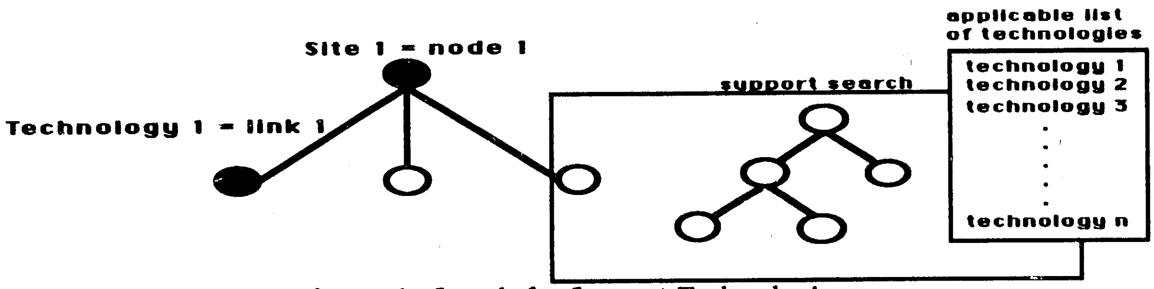

figure 6: Search for Support Technologies

4.5 Residual Streams Search

The third major complication affecting the search for the complete list of remedial sequences is the spontaneous generation of new problems through the production of residual streams. In the normal course of operation, selected technologies produce what are called residual streams. A residual stream is simply a transfer of one or more contaminants to a new media, such as the venting of a water bound contaminant into the air. The residual steam is actually a new problem in the eyes of the RAAS computational core. A fully successful treatment sequence must address not only the current cell, but all residual streams created by the technologies applied in the sequence.

If RAAS successfully completes a treatment sequence, it proceeds to a queue of these residual streams created by the sequence and handles each of these. The system has already determined site characteristics such as medium type and contaminant list, but must still request of the user a new goal and solution strategy. A new residual stream therefore implies a new applicable list, a new series of subgoals.

5.0 CONCLUSION

This section provides a summary of the previous application description and a brief explanation of the anticipated impact of the application, as well as the future direction for development.

5.1 Summation

RAAS was funded to assist in the costly Remedial Investigations and Feasibility Studies (RI/FS) process required for the remediation of many hazardous waste sites in the United States. The Remedial Action Assessment System is a true object-oriented application which relies on the close cooperation between coarse numerical or quantitative models of the physical process of site remediation and rule-based or qualitative models of expert decision making. It relies on the strengths of object-oriented analysis(OOA) and object-oriented design(OOD) in these modelling processes.

The requirement of building treatment trains introduces many complexities, some of which were discussed in the above pages. The fact that the system attempts to provide models of nearly 100 proven technologies implies that the models are in no way assumed to be precise. Instead, the objects cooperate in the utilization of heuristics and actual numerical models to supply responses which are useful.

5.2 Impact

The RAAS application is anticipated to have a major positive impact for several reasons. First, the system will shorten the time consuming and expensive RIFS process by initially providing a list of treatment alternatives and important parameters. This will direct the professionals at the waste site in their information gathering. The system should also increase the uniformity of the responses among the waste treatment community. Innovative but unusual alternatives will be captured by the system and will therefore come to the attention of professionals whose attention they might otherwise escape. The product will also serve as storehouse of knowledge, and will capture the advances and innovations made by waste treatment professionals. It may therefore facilitate the dissemination of relevant information across the country. Finally, the system should help fill a current void in the waste treatment community due to a shortage in the number of experts with broad general knowledge of a large number of treatment technologies. RAAS is designed to produce the type of "back of the envelope" decision that a good generalist would produce for a large number of waste treatment technologies. RAAS as a good generalist will be able to contribute to the more efficient use of waste treatment experts.

5.3 Future Direction

Future versions of RAAS are planned for the next three fiscal years. The improvements anticipated will be two fold: the improvements scheduled in the long term development plan and the improvements directed by comments, suggestions, and review provided by user sites across the country. The primary scheduled improvements will be to the quantitative and qualitative technology modules. Incremental improvements in these technologies are planned in the over the course of the project, stimulated by further expert involvement in construction and review.

Also included within future versions will be modules to provide cost and time analysis of remedial trains constructed by RAAS as solutions.

6.0 BIBLIOGRAPHY

Grady Booch. *Object-Oriented Design with Applications*. Redwood City, CA: The Benjamin/Cummings Publishing Company, Inc., 1991.

Ken Pedersen. Expert Systems Programming. John Wiley & Sons, Inc., 1989.

James Rumbaugh, Michael Blaha, William Premerlani, Frederick Eddy, William Lorensen. *Object-Oriented Modelling and Design*. Englewood Cliffs, NJ: Prentice Hall,1991.

Ann L. Winblad, Samuel D. Edwards, David R. King. *Object-Oriented Software*. Reading, MA: Addison-Wesley Publishing Company, Inc., 1990.

U.S. Environmental Protection Agency, Office of Emergency and Remedial Response, "Guidance for Conducting Remedial Investigations and Feasibility Studies (RI/FS) Under CERCLA," EPA/540 G-89 004, October 1988.

END

DATE
FILMED
3/25/92