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COST-BENEFIT STUDY OF THE APPLICATION OF BOREHOLE GEOPHYSICS TO HANFORD CERCLA PROGRAMS

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EXECUTIVE SUMMARY

Borehole geophysical logging techniques (BHGs) are additional and/or potential alternative components of test programs for Remedial Investigation/Feasibility Studies (RI/FS) associated with the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA) programs at Hanford. BHGs could potentially be utilized in the site characterization process for assessing the geologic and hydrologic characteristics of the various operable units. They can also potentially provide in situ radionuclide contamination assays to be used for developing site contaminant migration models required for feasibility studies and for post-closure monitoring. Hence, it is possible that BHGs can be substituted for other program elements (e.g., sampling and lab testing) to provide equivalent data at less cost and in less time. However, because the BHGs are currently not available, the additional cost and time required for their development, as well as the possibility that such development will not be successful, must be considered. Also, the issue of whether regulators will accept the results of BHGs (especially in place of more standard techniques) and the potential benefit of using developed BHGs at other Department of Energy (DOE) sites must be considered.

To further define the economic feasibility and potential benefits of the application of BHGs to the Hanford CERCLA programs, a cost-benefit study has been conducted. This study summarizes the costs and benefits of developing and applying various combinations of specific BHG systems, including:

- Spectral Gamma Logging System (Radionuclide Logging System)
- Gamma-Gamma Density Logging Tool
- Neutron-Neutron Logging Tool
- Neutron Activation Logging System.

However, the evaluation of such BHG systems must be done in the context of the entire characterization/monitoring program. Hence, the relevant attributes of various characterization/monitoring programs which incorporate BHGs are assessed and compared with those of the current Base Case (which does not incorporate BHGs). This evaluation has been based, to a large extent, on information and assessments provided by Westinghouse Hanford Company (WHC) staff, as well as on discussions with external experts and regulatory agency staff and on judgement.

A Base Case program for characterization of a "typical" operable unit has been compiled from those already conducted or currently in progress at six of the 78 operable units in the 100, 200, 300 and 1100 Areas; it should be noted that these six operable units tend to entail more effort than others, so that the Base Case program may be somewhat larger than the average of the 78 operable units. It is assumed that this Base Case program will adequately satisfy the data requirements and be acceptable to the regulatory agencies.

A set of alternative programs, each incorporating a different combination of BHGs substituting for some elements of the Base Case, has been identified and assumed to be technically equivalent to the Base Case (in terms of adequately satisfying the data requirements), based on the capabilities of each candidate BHG. These alternative programs were similar to the Base Case but included application of the following BHG systems, each of which replace specific sampling and subsequent lab testing in new boreholes during characterization:

Program 1) The spectral gamma tool will replace 50% of the soil and groundwater radionuclide sampling/lab testing.

Program 2) The spectral gamma tool and gamma-gamma tool will replace 50% of soil and groundwater radionuclide sampling/lab testing, and 40% of soil physical property sampling/lab testing, respectively.

Program 3) The spectral gamma tool and gamma-gamma density tool plus neutron porosity tool will replace 50% of soil and groundwater radionuclide sampling/lab testing, and 50% of soil physical property sampling/lab testing, respectively.

Program 4) The spectral gamma tool, gamma-gamma density tool plus neutron porosity tool, and neutron activation tool will replace 50% of soil and groundwater radionuclide sampling/lab testing, 50% of soil physical property sampling/lab testing, and 50% of soil and groundwater chemical sampling/lab testing, respectively.

Program 5) The spectral gamma tool and neutron activation tool will replace 50% of soil and groundwater radionuclide sampling/lab testing, and 50% of soil and groundwater chemical sampling/lab testing and 40% of soil physical property sampling/lab testing, respectively.

These alternative programs are considered to be somewhat conservative with respect to evaluating the benefits of developing and applying BHGs, since they represent a relatively low substitution rate of BHGs for sampling/lab testing in new boreholes during characterization, no substitution of new boreholes during characterization, and no substitution of any monitoring activities.

The relevant attributes of each of these programs were then assessed, including:

- The absolute expected cost and schedule, and expected cost and schedule savings relative to the Base Case, for characterization of five "typical" operable units (which is somewhat conservative with respect to evaluating the benefits of developing and applying BHGs), which in turn were based on
  - The absolute <u>potential</u> cost and schedule, and potential cost and schedule savings relative to the Base Case (assuming that BHG development is successful), based on estimated unit quantities, costs, and durations, and specified system capacity and schedule logic
  - The assessed probability of successful BHG development
  - The estimated cost and schedule if BHG development is unsuccessful (contingencies).
- The assessed likely degree of regulatory acceptance and the assessed usefulness of successfully developed BHGs at other DOE sites.

Based on these assessments, in conjunction with reasonable value judgements regarding tradeoffs among them, a collective rating was developed, on which basis the programs could be compared and ranked. The results of this preliminary evaluation were as follows:

- Program 1 has the highest rating (+12%), based on its large expected cost savings ($1.8 million) and increased technical capability (+20%), partially offset by minimal expected schedule penalty (0.2 years) and minimal impact on regulatory acceptance (-20%). It is the only program rated higher than the Base Case, although not substantially.

- Program 5 is rated below the Base Case (-21%), but not substantially, due to its moderate expected schedule penalties (0.7 years) and minimal impact on regulatory acceptance (-20%), partially offset by relatively low expected cost savings ($0.5 million) and increased technical capability (+40%).

- Programs 2, 3 and 4 are rated substantially below the Base Case (-64, -69, and -60%, respectively), due to large expected schedule penalties (1.4, 1.2, and 1.2 years, respectively), insignificant or negative expected cost savings ($0.2, -$1.3 and -$1.5 millon, respectively), and increased impact on regulatory acceptance (-40%, -40%, and -20%, respectively), partially offset by increased technologic capability (40%, 60%, and 80% respectively).

On this basis, Program 1 would be preferred and only the spectral gamma tool should continue to be developed and applied.

However, there is significant uncertainty in many of these assumptions, assessments and value judgements. Hence, sensitivity studies have been conducted to evaluate the "robustness" of the rankings. These sensitivity studies evaluated the effects of changes in various factors, assuming everything else constant, and found the following:

- The ratings for all of the alternative programs increase as the number of "typical" operable units to be characterized increases, everything else being equal, although the relationship among the alternative program ratings is not significantly affected. Programs 1, 5 and 2 have a higher rating than the Base Case program if more than about four, nine and 27, respectively, "typical" operable units are to be characterized. Programs 3 and 4 have a higher rating than the Base Case only if substantially more than fifty "typical" operable units are to be characterized.

- The ratings for all of the alternative programs increase as the substitution percentage by BHG for Base Case sampling/lab testing in the characterization program increases, everything else being equal, although the relationship among the alternative program ratings is not significantly affected. Program 1 has a higher rating than the Base Case as long as the BHG substitution rate is greater than some relatively small percentage. Program 5 has a higher rating than the Base Case program if the BHG substitution rate is greater than about 80%. Programs 2, 3, and 4 do not have a higher rating than the Base Case Program for any BHG substitution percentage.

- The ratings for all of the alternative programs increase as the substitution percentage by BHG for new boreholes in the characterization program increases, everything else being equal, although the relationship among the alternative program ratings is not significantly affected. Program 1 has a higher rating than the Base Case for any BHG substitution percentage. Programs 5 and 2 have a higher rating than the Base Case program if the percentage is greater than about 15% and 30%, respectively. Programs 3 and 4 have a higher rating than the Base Case program if the percentage is very much greater than 30%.

- The ratings for some of the alternative programs increase whereas for other alternative programs decrease as the probability of successful BHG development increases, everything else being equal, although the relationship among the alternative program ratings is not significantly affected. Programs 1 and 5 have a higher rating than the Base Case if the probability of successful BHG development is greater than 40% and 90%, respectively. Programs 2, 3, and 4 do not have a higher rating than the Base Case program for any probability of successful BHG development.

- The ratings of the alternative programs change as the value judgements (tradeoffs) change, everything else being equal, although the relationship among the alternative program ratings is not significantly affected. Program 1 has a higher rating than the Base Case for all cases unless schedule or regulatory acceptance has more importance than the other three factors combined. Program 5 has a higher rating than the Base Case only if cost or technologic capability has more importance than the other three factors combined. Programs 2, 3, and 4 have a higher rating than the Base Case only if technologic capability is much more important than the other three factors combined.

- The ratings for all of the alternative programs increase as substitution by BHG for new boreholes, sampling and laboratory testing in monitoring programs increases, everything else being equal, although the relationship among the alternative program ratings is not significantly affected. Program 1 has a higher rating than the Base Case program for any substitution rate. Program 5 has a higher rating than the Base Case if the number of substituted monitoring vadose boreholes is greater than about seven or if the number of substituted groundwater monitoring wells is greater than about 1,000, or for equivalent combinations of both. Programs 2, 3, and 4 have a higher rating than the Base Case if the number of substituted monitoring vadose boreholes is greater than about 25 or if the number of substituted groundwater monitoring wells is greater than about 3,500, or for equivalent combinations of both.

- In addition, the ratings of the alternative programs change as some of the other factors change, everything else being equal, although the relationship among the alternative program ratings is not significantly affected. The ratings of all the alternative programs tend to increase as: the technologic capability or regulatory acceptance of that program increases; the unit costs and unit durations (critical path elements only) of drilling, sampling, and testing increase, or the unit costs and unit durations (critical path elements only)

associated with BHG development and application decrease; and the system capacity regarding drilling, sampling, testing decreases, or the system capacity regarding BHG development and application increases. However, these sensitivities, and the values required to make each program preferred over the Base Case program, have not been quantified.

It should be noted that for virtually any set of conditions considered, Program 1 has a significantly higher rating than Program 5, which in turn has a significantly higher rating than Programs 2, 3, and 4.

Based on the results discussed above, the following conclusions and recommendations can be made:

- It is very likely that Program 1, incorporating the spectral gamma tool, has a higher rating than the Base Case or any other alternative program for virtually any reasonable set of evaluation parameters. However, Program 5, incorporating the neutron activation tool in conjunction with the spectral gamma tool, may have a higher rating than Program 1 if the monitoring program, which is presently poorly defined, is sufficiently large.

- The spectral gamma tool should continue to be developed and, if successfully developed, applied in Hanford CERCLA characterization/monitoring programs. The neutron-neutron porosity and gamma-gamma density tools are not cost-effective and should not be developed to the levels identified in this report.

- The Base Case monitoring program should be better defined, and Programs 1 and 5 evaluated with respect to both characterization and monitoring. In the absence of this evaluation, it is anticipated that, if the monitoring program is sufficiently large, the neutron activation tool will be cost-effective and should be developed and, if successfully developed, applied in conjunction with the spectral gamma tool in Hanford CERCLA characterization/monitoring programs.

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APPENDIX B BOREHOLE GEOPHYSICAL TOOLS DOCUMENTATION B-1

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1.0 INTRODUCTION

Golder Associates Inc. has conducted this study, entitled "Cost-Benefit Study of the Application of Borehole Geophysics to Hanford CERCLA Programs", for Science Application International Corporation (SAIC) under Task Order S-92-18, Westinghouse Hanford Company (WHC) Contract No. MLW-SVV-073750.

1.1 STUDY PURPOSE

Borehole geophysical logging techniques (BHGs) are potential alternative components of test programs for Remedial Investigations/Feasibility Studies (RI/FS) associated with the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA) programs at Hanford, as well as at other Department of Energy (DOE) sites. BHGs could potentially be utilized in the site characterization process for assessing the geologic and hydrologic characteristics of the sites. They can also potentially provide in situ radionuclide contamination assays to be used for developing site contaminant migration models required for feasibility studies (such as for the "leave in place" option) and for post-closure monitoring.

To further define the economic feasibility and potential benefits of the application of BHGs to the Hanford CERCLA programs, a cost-benefit study has been conducted. This study summarizes the costs and benefits of developing and applying various combinations of specific BHG systems. This study has taken into account the following:

- The capability of each BHG system to adequately satisfy specific data requirements, and thus to potentially substitute for other program elements (e.g., sampling and lab testing).
- The costs and schedule savings associated with BHG development and application, depending on whether BHG development is successful or not.
- The probability of each BHG system being successfully developed.
- The likely degree of regulatory acceptance of each BHG system.
- The likely usefulness of each BHG system (if successfully developed) to other DOE sites.

1.2 STUDY SCOPE

This study has been concerned with the potential development and subsequent application of specific BHGs to Hanford's CERCLA programs. It has been limited to consideration of specific combinations of the following BHGs:

- Spectral Gamma Tool (Radionuclide Logging System)
- Gamma-Gamma Density Logging Tool
- Neutron-Neutron Logging Tool
- Neutron Activation Logging System.

Due to schedule and budget limitations, this study has been conducted at a broad level of detail. Although additional detail would be possible, it was believed that the current level would be sufficient to make recommendations regarding further development of the candidate BHGs. Only readily available information was used; it was not within scope to develop definitive alternative work plans or cost and schedule estimates. The costs given in this study are all in current (1992) dollars with no adjustments for future inflation, i.e., assuming inflation exactly balances the discount factor.

The study has necessarily been based to a large extent on discussions with WHC staff, discussions with others involved in government or private geophysical programs, and literature review, which provided much of the requisite information regarding the following:

- Hanford characterization data requirements
- Currently proposed test programs (unit quantities, costs, and durations)
- Candidate BHGs (capabilities, development success, costs, durations, regulatory acceptance, and technology transfer).

In many cases, actual hard data are unavailable. Hence, many of the assessments contained within this study are necessarily subjective, and based on reasonable judgement. In such cases, the range in possible assessments and the sensitivity of the results to such assessments have been considered. However, it was not within scope to assess the uncertainties in assessments and conduct probabilistic assessments. If the results are not definitive, appropriate refinements in these assessments have been recommended, but their implementation is not within the scope of this study.

The scope of this study was limited to evaluating the cost-benefit of developing and applying specific candidate BHG systems. The costs and potential BHG program applications given in this study should not be misinterpreted as representing program budgets or proposed characterization plans, or be used for purposes other than those for which they were intended.

1.3 REPORT FORMAT

This report is presented in the following format:

- The approach adopted for conducting the cost-benefit study is presented in Section 2.

- The data requirements and the current characterization/monitoring program for satisfying those requirements are summarized in Section 3, and presented in detail in Appendix A.

- The candidate BHGs are described summarily in Section 4, and presented in detail in Appendix B.

- The evaluation of the development and application of the candidate BHGs is described summarily in Section 5, and presented in detail in Appendix C.

- Conclusions of the study and recommendations regarding the development and application of the candidate BHGs are presented in Section 6.
- References are provided in Section 7.

2.0 STUDY APPROACH

A formal, explicit approach has been adopted for evaluating the development and subsequent application of the various candidate BHGs. This approach is based on the realization that the BHGs are simply one potential integrated component of the overall site characterization/monitoring program. Their cost-effectiveness in satisfying the site characterization/monitoring needs will be a function of the other components of the program. For example, BHG may not be very cost effective in determining the in situ concentration of an isotope if water quality samples must be obtained anyway for other reasons. Hence, BHGs must be evaluated in the context of the entire program as opposed to being evaluated in isolation.

As illustrated schematically in Figure 2-1, the study approach consisted of the following steps:

1. Hanford Site Characterization Program Objectives

   a. Identify Program Objectives - The Test Program (with or without BHG) must satisfy minimum data requirements for characterization at the Site (see below), to the satisfaction of the Regulatory Agencies. Objectives for the Test Program (i.e., desired attributes beyond those required) include:

      - maximize reliability of satisfying minimum site data requirements (including schedule)
      - maximize Regulatory Agency acceptability
      - minimize cost
      - maximize additional data beyond minimum required
      - maximize cost-effectiveness of Test Programs for other DOE sites

   b. Identify Data Requirements - The data requirements consist of specific:

      - types of data
      - accuracy of data
      - location of data (spatial density and coverage)
      - duration or schedule of data (time and frequency).

   c. Establish Value Scale for Each Objective - Relative preferences must be identified among the possible "attributes" of any program with respect to each objective, with everything else being equal. This determines the "value scales" (or "utility functions") by which each program's attributes can be converted to the degree of satisfying each objective. For example, with everything else equal, a program which costs less than another would be preferred, with the value scale ranging from 0 at a maximum cost to 10 at zero cost, varying linearly in between.

   d. Establish Tradeoffs Among Objectives - Relative preferences must be identified among the possible values of any program with respect to the set of objectives. This determines the "relative weights" of the various objectives. For example, satisfying the cost objective (as defined by its utility function) might be twice as

important as satisfying the objective related to additional data, so that the ratio of their relative weights is two.

2. Candidate BHGs

   a. Identify Candidate BHGs - The candidate BHGs have been specified by WHC.

   b. Assess Relevant Attributes of Candidate BHGs (including uncertainties) - These attributes include the following:

      - Satisfaction of Individual Data Requirements (uncertain, depending on development level)
        - Data types addressed
        - Accuracy of results

      - Costs
        - Fixed cost (including feasibility studies, tool development, calibration and field studies, as required)(various levels).

      - Schedule
        - Development (various levels)
        - Implementation (per application)

      - Other
        - Program compatibility (limitations in application)
        - Likelihood of successful development
        - Regulatory Agency acceptability
        - Support requirements (e.g., borehole drilling, lab testing)

3. Base Case Test Program (without BHG)

   a. Identify Base Case Test Program - The Base Case Test Program consists of a specific number of various program "elements." The various elements of the characterization test program includes the following:

      - Field activities
        - Achieving access to boreholes (BHs)
          - drilling and completing new BHs (various types)
          - mob/demob test rigs on existing BHs (various types)
        - Obtaining BH samples
          - geologic (various types) in new BHs
          - water quality (various types) in new or existing BHs
        - Conducting other BH tests (various types) in new or existing BHs

      - Lab or other off-site activities
        - Lab testing on BH samples
          - geologic (various types)
          - water quality (various types)
        - Analyzing other BH tests (various types)
        - Combining/interpreting all data.

b. Assess Relevant Attributes of Base Case Test Program (including uncertainties) - Each of the program elements has an associated cost and duration. Moreover, the elements must be conducted in specific sequences and in many cases can be conducted simultaneously. For example, the various field activities must be conducted in sequence within a borehole, but can be conducted simultaneously in different boreholes if enough equipment is available. Based on the quantity and unit cost and duration of each element, the sequence of elements, and the number of elements that can be done simultaneously (based on the system capacity), the overall costs and duration of the program can be determined.

In addition to cost and schedule, it is assumed that the Base Case Program will adequately satisfy the data requirements, will be acceptable to the regulatory agencies, and will not be useful at other DOE sites.

4. Alternative Test Programs (with BHG)

a. Identify Alternative Test Programs - Alternative Test Programs which incorporate various combinations of BHGs and are conservatively expected to provide equivalent data to the Base Case have been identified. This has been done subjectively, based on assessments of how well the base case satisfies the data requirements and how well each of the BHG tools satisfies the data requirements, both independently and jointly, as well as on program compatibility and support requirements. These alternative programs also include contingencies if BHGs are not successfully developed.

b. Assess Relevant Attributes of Alternative Test Programs (including uncertainties) - Based on the assessments of costs and durations of each program element (including development and application of BHGs), the quantity of each element, the sequence of elements, and the number that can be done simultaneously (based on the system capacity), the overall costs and duration of the program can be determined, similar to the Base Case, assuming that BHG development is successful and acceptable to the regulatory agencies. It is assumed that each alternative program is equivalent in terms of satisfying the data requirements, because that was the basis for their formulation. However, it is also possible that alternative programs may provide additional data or capabilities beyond the Base Case program.

The cost and duration of the program assuming that BHG development is unsuccessful is also determined as simply the Base Case plus BHG development. The "expected" cost and duration of the program is then simply the product of the program cost and duration assuming successful BHG development and the probability of successful BHG development, plus the product of program cost and duration assuming unsuccessful BHG development and the probability of unsuccessful BHG development. In this way, the potential savings and penalties associated with BHG development are considered in context with their relative likelihood, so that more reliable BHG development and/or potentially more cost-effective BHGs will be favored.

Regulatory acceptability and potential technology transfer are assessed separately.

5. Evaluation of Programs

   a. Evaluate Degree to which Program Objectives are Satisfied by each Test Program (including uncertainties) - The Alternative Test Programs have been evaluated in terms of the difference (relative to the Base Case) in their overall cost and schedule (for characterization only), considering contingencies if BHG development is unsuccessful and their likelihood, and in terms of their regulatory acceptability and potential technology transfer. The previously established utility functions were used to determine program ratings with respect to each of these objectives, based on the assessed attributes.

   b. Compare and Rank Test Programs in terms of Degree to which Set of Program Objectives are Satisfied (considering tradeoffs among objectives, as well as uncertainties) - Tradeoffs were made among the various objectives using the relative weights, and overall ratings were developed for each Alternative Test Program. The Alternative Test Programs were then ranked based on these overall scores.

   c. Conduct Sensitivity Study of Test Program Ranking to Various Assessments - Sensitivity of the cost-benefits (and thus in ranking) of Test Programs which include BHGs have been determined with respect to changes in:

      - Primary Factors
        - Base Case Program
        - Alternative Test Programs (technically equivalent combination of elements)
        - BHG development/application levels
        - Probability of successful BHG development
        - Value judgements (utility functions and relative weights)

      - Secondary Factors
        - Data requirements
        - Other program element attributes (e.g., costs and durations)
        - Other programmatic factors (e.g., Base Case elements)

6. Conclusions/Recommendations

   a. Determine Sufficiency of "Robustness" of Evaluation of Alternative Programs - The sensitivity in the ranking of Alternative Programs has been determined based on the results of the sensitivity studies regarding the overall score of each to changes in various parameters, in conjunction with assessments of reasonable ranges in the possible values of those parameters. This has been expressed in terms of the parameter values at which the rankings change, and the possibility of those parameter values being correct.

   b. If Sufficiently Robust, Make Recommendations Regarding BHG Development and Subsequent Application - If the evaluations are sufficiently robust, then it will be possible to clearly differentiate among the Alternative Programs. Based on robust evaluations, definitive recommendations can be made as to whether specific BHGs should be developed and incorporated in the Test Programs.

c. <u>If Not Sufficiently Robust, Make Recommendations Regarding Study Refinements</u> - If the evaluations are not sufficiently robust, then it will not be possible to clearly differentiate among the Alternative Programs and to clearly determine whether specific BHGs should be developed and incorporated in the Test Program. In this case, those evaluation factors (including possibly objectives, values, alternatives, and assessments) which affect the ranking most and which are most uncertain will be identified. Recommendations will then be made regarding which of these factors should be focussed on for further study, in order to subsequently provide a sufficiently robust evaluation.

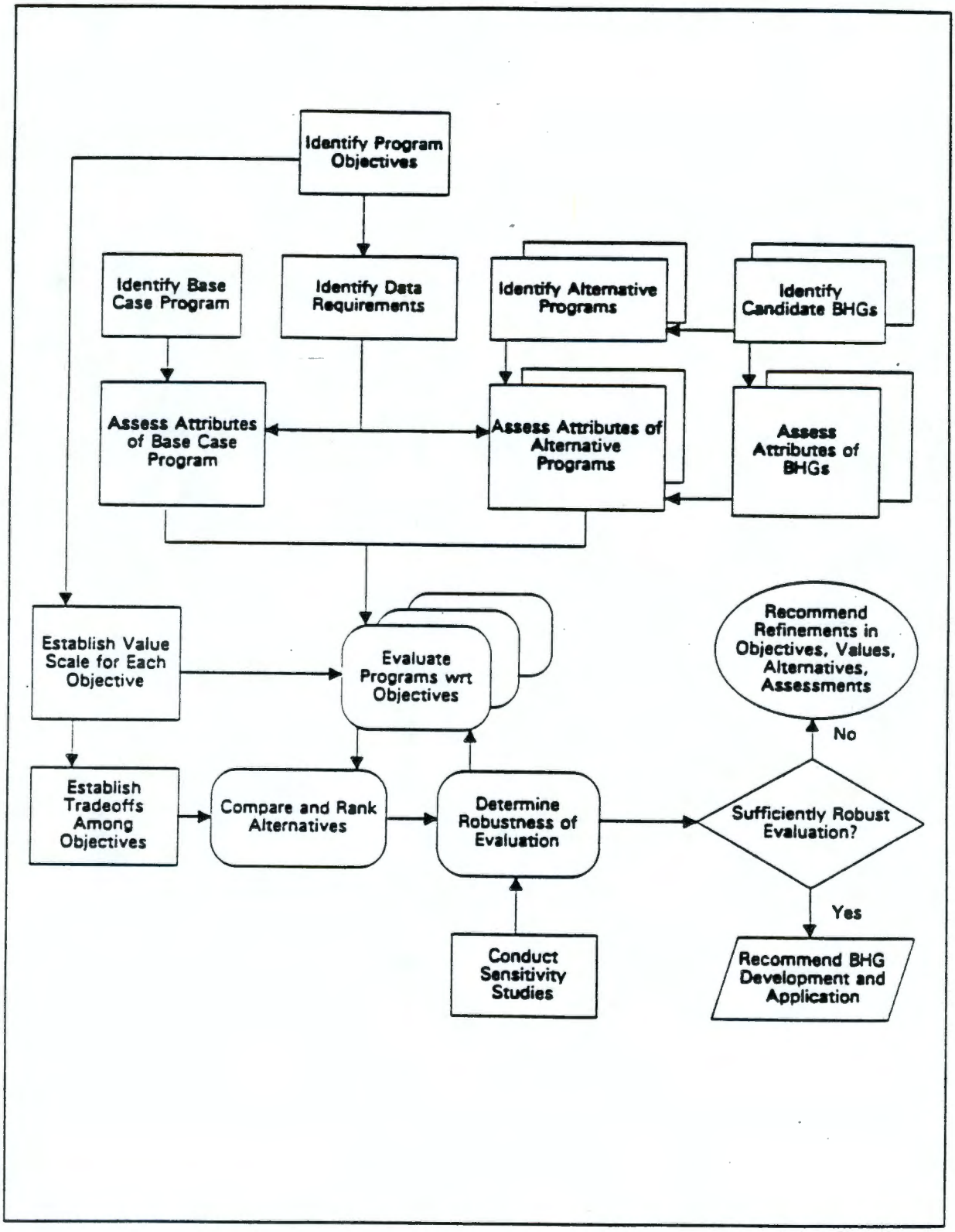

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Figure 2-1. Study Approach.

3.0 SITE CHARACTERIZATION/MONITORING DATA REQUIREMENTS AND PROGRAMS

The site characterization/monitoring data requirements at Hanford, which BHGs might address, and the test programs currently proposed for addressing those requirements have been identified in a broad way to provide a basis for evaluating the candidate BHGs, per the approach presented in Section 2. These data requirements and programs have been identified primarily through a review of RI/FS work plans and an RI report, and discussions with Westinghouse Hanford staff. They are documented in Appendix A and are summarized below.

3.1 DATA REQUIREMENTS

The various types of data required for site characterization and monitoring of the vadose zone and groundwater in the CERCLA program at Hanford are summarized in Table 3-1. Then data types were compiled from a survey of various Hanford RI/FS work plans and reports, including RI/FS work plans for the 100-KR-1, 100-KR-4, 200-BP-1, 300-FF-1 and 300-FF-5 operable units and the 1100-EM-1 Phase 1 RI report (DOE 1991a, 1991b, 1990a, 1990b, 1990c, 1990d). The survey was limited to identifying data requirements that involved the use of vadose zone or deeper boreholes (existing or new). This survey provides a representative cross section of the types of data being obtained from boreholes for characterization and monitoring of operable units across the site.

The data quality, spatial and temporal codes are listed to give a relative understanding of "how important" various data types are with respect to each other, the importance of the spatial distribution of data (especially regarding data density and coverage), and the frequency of data collection or analysis. The assignment of codes was based on the survey of the work plans and report described above, and is subjective in nature.

Any characterization/monitoring program must adequately satisfy the above data requirements.

3.2 CURRENT CHARACTERIZATION/MONITORING PROGRAM

The description of the current vadose zone and groundwater characterization/monitoring activities within the CERCLA program at Hanford was compiled from a survey of the various Hanford RI/FS work plans and report described in Section 3.1. The relationship of these activities to the data requirements is summarized in Table 3-2. The current program incorporates review of existing data and drilling, sampling, and laboratory analysis of soil and groundwater samples from new boreholes and monitoring wells installed for each operable unit. In the current program, borehole geophysical logging with the spectral-gamma tool is limited to specific requests for logging individual boreholes prior to well construction. The tank farm surveillance team also employs a passive gamma-ray logging tool in their monitoring program.

The current characterization/monitoring program of each operating unit typically involves the drilling of tens of new soil boreholes, the drilling and construction of tens of new monitoring wells, and the collection and laboratory analysis of hundreds of soil and groundwater samples. Additional background data regarding the current characterization/monitoring programs are given in Appendix A.

A current Base Case program for characterization of a "typical" operable unit has been compiled from those already conducted or currently in progress at six of the 78 operable units in the 100, 200, 300 and 1100 Areas, as previously identified in Section 3.1. These six operable units tend to entail more effort than others, so that this Base Case program may be somewhat larger than the average of the 78 operable units. This program is very approximate, and is intended to serve only as the Base Case for evaluating the potential development and application of candidate BHGs, per the approach presented in Section 2. It is assumed that this current program adequately satisfies the data requirements presented in Section 3.1. It snould be noted, however, that there is currently little information available regarding monitoring programs. Hence, although the likely monitoring activities can be identified, their quantities cannot be estimated at this time.

A current characterization/monitoring program has been summarized in Table 3-3 which is applicable to about five "typical" operable units. It is believed that a program for five "typical" operable units is conservative for evaluating the benefits of BHG development and application, because it results in a somewhat smaller program than expected and will thus understate the benefits. Although each such "typical" operable unit may entail more effort than the average of the 78 operable units, only five (rather than 78) units are considered. Smaller programs offer less benefits, because they have to absorb BHG development costs and schedules.

Table 3-1. Data Requirements. (sheet 1 of 2)

Data Type	Data Quality	Spatial	Temporal
Vadose Zone			
Geology lithology physical character uniformity	1	5	1
Physical Properties permeability porosity density moisture grain Size	1-3	2-3	1
Contamination Type radionuclides, emitting radionuclides, non-emitting organics inorganics/metals	1-5	5	1
Flux (leach) Tests radionuclides, emitting radionuclides, non-emitting organics inorganics/metals	3-5	2	1
Contamination Extent vertical horizontal	1-2	5	1
Groundwater/Hydrogeology			
Geology lithology physical character uniformity	1	5	1
Physical Properties (sediments) density grain Size	2-3	2-3	1
Hydraulic Properties hydraulic conductivity velocity	2	3	1
Contamination Type radionuclides, emitting radionuclides, non-emitting organics inorganics/metals	1-5	5	2-3
Contamination Extent vertical horizontal	1-2	5	2-3

Table 3-1. Data Requirements. (sheet 2 of 2)

Data Type	Data Quality	Spatial	Temporal
Groundwater/Hydrogeology (cont.) Solute Retardation/Sorption Tests radionuclides, emitting radionuclides, non-emitting organics inorganics/metals	3-5	2	1
Operational/Post-Closure Monitoring Vadose Zone Contamination Type radionuclides, emitting radionuclides, non-emitting organics inorganics/metals	1-5	3-4	3
Groundwater Contamination Type radionuclides, emitting radionuclides, non-emitting organics inorganics/metals	1-5	3-4	3

Data Quality Codes:
1 - field screening/qualitative
2 - field analysis/qualitative/semi-quantitative
3 - laboratory analysis (non-CLP)
4 - CLP-RAS/stringent QA/QC
5 - CLP-SAS/special methods

Spatial Codes (considering data density and coverage):
1 - not very important
to
5 - very important

Temporal Codes:
1 - one time analysis
2 - several times analysis
3 - many times analysis

Table 3-2. Relationship of Characterization/Monitoring Activities to Data Requirements. (sheet 1 of 2)

Data Type	Tools/Methods
Vadose Zone	
Geology lithology physical character uniformity	existing data plus drilling and geologic logging of cuttings and soil samples
Physical Properties permeability porosity density moisture grain Size	existing data plus laboratory testing of soil samples
Contamination Type radionuclides, emitting radionuclides, non-emitting organics inorganics/metals	laboratory testing of soil samples
Flux (leach) Tests radionuclides, emitting radionuclides, non-emitting organics inorganics/metals	laboratory testing of soil samples
Contamination Extent vertical horizontal	data evaluation based on sample analysis interval and borehole spacing

Table 3-2. Relationship of Characterization/Monitoring Activities to Data Requirements. (sheet 2 of 2)

Data Type	Tools/Methods
Groundwater/Hydrogeology	
Geology lithology physical character uniformity	existing data plus drilling and geologic logging of cuttings and soil samples
Physical Properties (sediments) density grain Size	existing data plus laboratory testing of soil samples
Hydraulic Properties hydraulic conductivity velocity	existing data and field aquifer testing (slug tests, pump tests)
Contamination Type radionuclides, emitting radionuclides, non-emitting organics inorganics/metals	laboratory testing of groundwater samples
Contamination Extent vertical horizontal	data evaluation based on sample analysis interval and well spacing
Solute Retardation/Sorption Tests radionuclides, emitting radionuclides, non-emitting organics inorganics/metals	laboratory testing of groundwater samples
Operational/Post-Closure Monitoring	[inferred]
Vadose Zone	
Contamination Type radionuclides, emitting radionuclides, non-emitting organics inorganics/metals	collection of soil samples and laboratory testing of samples (gamma-ray logging at Tank Farms)
Groundwater	
Contamination Type radionuclides, emitting radionuclides, non-emitting organics inorganics/metals	collection of groundwater samples and laboratory testing of samples

Table 3-3. Approximate Current Characterization/Monitoring Program.

CHARACTERIZATION
Drill/Complete New Boreholes
75 non-radioactive vadose 50 non-radioactive well 50 radioactive vadose 50 radioactive well
Obtain Geologic Samples in New Boreholes and Conduct/Analyze Lab Tests
625 soil chemistry 660 soil radiation components 920 soil physical properties
Obtain Water Quality Samples and Conduct/Analyze Lab Tests
325 water chemistry in new boreholes 320 water chemistry in old boreholes 215 water radiation components in new boreholes 215 water radiation components in old boreholes
Conduct and Analyze Borehole Tests
100 slug tests in new boreholes 50 slug tests in old boreholes
MONITORING
Drill/Complete New Boreholes
[TBD] non-radioactive vadose [TBD] radioactive vadose
Obtain Geologic Samples in New Boreholes and Conduct/Analyze Lab Tests
[TBD] soil chemistry [TBD] soil radiation components
Obtain Water Quality Samples in Old Boreholes and Conduct/Analyze Lab Tests
[TBD] water chemistry [TBD] water radiation components
Note: This program is based on the level of effort required for five operating units similar to 100-KR-1, 100-KR-4, 200-BP-1, 300-FF-1, 300-FF-5, and 1100-EM-1. However, little information is currently available regarding the magnitude of the monitoring program. Hence, although the likely types of monitoring activities are known, their quantities are not.

4.0 CANDIDATE BHG TOOLS

Borehole geophysical (BHG) methods are an important part of many site characterization studies and can provide information at varying levels of detail. In oil exploration, BHGs are an integral part of exploration programs as well as reservoir development programs. The BHG methods are being used with increasing regularity to obtain reliable and quantitative hydrogeologic information from boreholes. Borehole geophysics programs have been successfully implemented at environmental sites including the Nevada Test Site and Idaho National Engineering Laboratory. At the Nevada Test Site, for example, BHG measurements have completely replaced sampling activities (with the exception of drill cuttings) in exploratory boreholes.

There are a number of general advantages and limitations to applying BHGs for hydrogeologic applications. The ability to obtain objective, repeatable and continuous information regarding the conditions in and around a borehole is generally considered the greatest advantage of using BHGs (Keys 1989). This enables accurate correlation between boreholes, monitoring of changes in the borehole environment over time, and statistical evaluation of one or multiple geophysical responses. Qualitative and semi-quantitative interpretation of BHG logs can provide valuable site characterization information, especially when evaluated in conjunction with other information, such as pumping tests, borehole logs, or water quality data. Detailed quantitative interpretation of BHG logs involves complex theory, and requires adequate calibration standards for specific lithologies.

Among BHGs, nuclear logging techniques are applicable in the widest range of borehole conditions, and are potentially the most useful BHGs at the Hanford Site. The scope of this study was limited to four specific nuclear logging tools; other nuclear tools or other borehole techniques which might be applicable at the Hanford Site were not within scope and have not been considered in this study. Methods, such as caliper logging, are not considered since the logging under consideration will be carried out in cased holes. The relevant attributes of the four candidate BHGs are summarized in Table 4-1 in terms of various factors considered in the evaluation of these tools. These attributes, which provide a basis for evaluating those BHGs per the approach presented in Section 2, have been subjectively assessed, based on discussions with Westinghouse Hanford staff and other references as cited. A brief description and summary of each tool is provided in the following sections, with specific details on effectiveness, cost, duration, compatibility, regulatory acceptance, and probability of successful development as documented in Appendix B.

4.1 SPECTRAL GAMMA TOOL (RADIONUCLIDE LOGGING SYSTEM)

4.1.1 Potential Application

The spectral gamma method measures the gamma energy spectra resulting from the natural disintegration of gamma-emitting radionuclides. The disintegration of radionuclides is statistically precise, and the measured intensity of the spectra is directly related to the concentration of the gamma-emitting radionuclide. By using a highly sensitive Germanium detector, very high resolution of the spectral response is possible,

providing more detailed information on the type and quantity of gamma emitters present in the formation. Gamma-emitting radionuclides of interest at Hanford include Cs-137, Co-60, Eu-152, Al-25, and Am-241 (DOE, 1990a). Spectral gamma measurements can be used to calculate concentrations of gamma-emitters to accuracies on the order of pCi/g. These calculations are based on a patented theoretical relationship and are in the process of being evaluated relative to actual sample results.

The technique can also be used to identify and correlate lithologies (particularly silts and clays) between boreholes. This is the typical application of spectral tools, and would provide an objective, quantitative means of identifying and correlating lithologic units at the Hanford Site.

The tool can be applied in existing or newly drilled wells. The effects of carbon steel casing, and well diameter have been quantified. The effects of PVC casing, grout, and water-filled casing have not been determined. The accuracy of spectral gamma measurements in existing wells will depend on well completion effects. However, spectral gamma techniques will detect gamma-emitting compounds in most single-cased wells. Spectral gamma measurements will be most reliable in newly drilled wells, prior to well completion. In these applications, there are relatively few factors affecting the performance of the tool.

Future refinements in data processing may provide a means for identifying the distribution of gamma-emitting radionuclides away from the borehole. This would include elements adhered to the casing or distributed in the formation. Penetration distances would be on the order of 1 to 1.5 feet outside the borehole casing. Information on formation uniformity may also be possible through data processing refinements.

4.1.2 Attributes

The spectral gamma tool can potentially satisfy data needs pertaining to lithology, formation uniformity, and the presence and concentration of gamma-emitting radionuclides in both the vadose zone and groundwater environment. Hence, application of this tool in new or existing boreholes can potentially substitute for some of the soil and groundwater radionuclide sampling and laboratory testing in new or existing boreholes, especially replacing drilling and sampling new boreholes in the vadose zone with logging in existing boreholes.

It is estimated that, once successfully developed, it will cost on the order of $1,500 and take about 1 day (0.003 years) to conduct per borehole. Analysis (off-site) of the results will cost about $900 and take about 3 days (0.008 years) to complete per borehole. It has been subjectively assessed that the tool will be acceptable to the regulatory agencies in most cases.

4.1.3 Present Status

The Westinghouse Hanford spectral gamma tool or Radionuclide Logging System (RLS) system has already been developed to a relatively high level and has been tested in a number of Hanford boreholes for its ability to detect gamma-emitting radionuclides.

Confirmatory laboratory results are not yet available, but the tool appears to have a demonstrated effectiveness for this application. Additional calibration studies are necessary to determine the effects of PVC casing, water-filled holes, and grout. Data processing software must be completed to streamline the processing and interpretation of log data. At the present time, data processing and interpretation are done by-hand. Geologic/lithologic applications of the tool have not been field tested. A significant level of effort will be required to develop processing algorithms for assessing adhesion of radionuclides or subtle formation changes.

It is estimated that it will cost on the order of $140,000 and take about 0.6 man-years to complete development of this tool. The probability that such development will be successful, allowing the tool to be applied in the field, has been subjectively assessed to be 0.9, based on judgement.

4.2 GAMMA-GAMMA DENSITY LOGGING TOOL

4.2.1 Potential Application

Gamma-gamma logging employs a gamma-emitting source to irradiate the formation with gamma rays and a detector to subsequently measure back-scattered gamma rays caused by the formation. The attenuation of the gamma rays emitted from the source is related to the electron density of the formation. The intensity of the back-scattered gamma rays is approximately proportional to the bulk density of the formation (Keys and MacCary, 1983).

The tool and analysis techniques are capable of:

- Determining relative bulk density of a formation
- Calculating porosity (given estimates of grain size distributions)
- Evaluating well completion (with respect to the presence and dimensions of air voids, grout, and sand pack)
- Calculating true formation porosity (given the effects of well completion).

The potential applications of the gamma-gamma tool at the Hanford site are for determining formation density in new wells prior to well completion, determining relative formation density in new or existing wells, and evaluating the integrity of existing wells with respect to grout and air-voids (Yearsley et al., 1991).

Gamma-gamma measurements are very sensitive to borehole conditions, and are generally considered unreliable in completed boreholes due to the presence of casing, air voids and grout (Keys 1989). However, a recent feasibility study (Wilson 1991) has shown, through computer simulation that identification of air-voids and grout is possible with some modifications to standard gamma-gamma tool configurations. Corrections for these effects could then be used to determine true formation density in completed wells.

Gamma-gamma logs will also be affected in high background gamma environments, and will require additional measurements to correct for the background effects.

4.2.2 Attributes

The gamma-gamma density tool can potentially satisfy data needs pertaining to lithology, formation uniformity, formation density and porosity in both the vadose and groundwater environments. Hence, application of this tool in new or existing boreholes can potentially substitute for some of the soil sampling for physical property testing and laboratory testing in new boreholes, especially replacing drilling and sampling new boreholes with logging in existing boreholes.

It is estimated that, once successfully developed, it will cost on the order of $500 and take about 0.001 years to conduct, per borehole. Analysis (off-site) of the results will cost about $600 and take about 0.005 years to complete, per borehole. It has been subjectively assessed that the tool will be acceptable to the regulatory agencies in limited applications.

4.2.3 Present Status

The recent feasibility study indicated that, regardless of the application, additional tool and software development activities are necessary to apply gamma-gamma logging at Hanford. Existing "off-the-shelf" technology does not appear sufficient for application at the Hanford site. Two levels of development are possible. Either level requires a tool mock-up, software development, calibration standards, and field evaluation. An initial level of development will provide for relative density measurements and identification of well completion integrity. A comprehensive development program will provide for true density calculations in the presence of well completion effects, and detailed quantitative determination of well completion details.

It is estimated that it will cost on the order of $910,000 and take about 3.7 man-years to complete development of this tool. The probability that such development will be successful, allowing the tool to be applied in the field, has been subjectively assessed to be 0.6, based on judgement.

4.3 NEUTRON-NEUTRON POROSITY LOGGING TOOL

4.3.1 Potential Application

Neutron logging techniques are one of the most useful logs for petroleum and hydrogeologic applications because of their sensitivity to hydrogen. Since saturated formations are normally filled with hydrogen-rich fluids (oil or water), neutron logs can be used to determine formation porosity (Tittman 1986). In addition to determining saturated porosity, neutron-neutron methods are capable of:

- Measuring the presence and quantity of moisture in a formation

It is estimated that it will cost on the order of $1,000,000 and take about 3.7 man-years to complete development of this tool. The probability that such development will be successful, allowing the tool to be applied in the field, has been subjectively assessed to be 0.6, based on judgement

4.4 NEUTRON ACTIVATION LOGGING SYSTEM

4.4.1 Potential Application

Neutron activation tools measure gamma energy emitted when nuclei are excited by the bombardment and capture of thermal neutrons. The gamma spectra emitted via neutron activation reflect the presence and concentration of different elements with large electron capture areas such as chlorine, hydrogen, silicon, calcium, iron, and sulfur (Tittman 1986). Some neutron activation tools can be used as a high resolution spectral gamma tool by shielding, or removing, the neutron generator. In addition, neutron activation tools can also be used as a neutron-porosity tool, similar to standard neutron-neutron logs. Therefore, the neutron activation tool is potentially the most versatile tool for the proposed applications of borehole geophysics at Hanford.

The tool and analysis techniques are capable of:

- Detecting and determining elemental concentrations of elements such as hydrogen, chlorine, silicon, calcium, iron and sulfur
- Determining porosity of the formation by evaluating hydrogen spectra
- Determining the presence and concentration of gamma-emitting radionuclides, similar to the Westinghouse Hanford RLS system
- Identifying and correlating lithologies based on geochemical signatures.

There are potentially three applications for the neutron activation tool:

- Identifying chlorinated organic solvents, nitrate, sulfate or brine which are present in the vadose zone or groundwater, based on characteristic elements in these wastes
- Identifying and quantifying gamma-emitting radionuclides, similar to the WHC RLS system
- Determining relative or true porosity.

Well completion details such as casing, hole diameter, and grout will have a significant effect on the tool response. Corrections for casing and hole diameter are available for these tools. Grout corrections have not been determined. The size of the tool (40-foot length) may limit the number of acceptable holes for logging.

Like standard neutron tools, neutron activation methods are capable of qualitative assessments without calibration standards. However, for quantitative analysis, a calibration facility designed specifically for unconsolidated sediments similar to Hanford sediments is essential.

It should be recognized that the tool detects elemental concentrations, and does not detect actual compounds. Given sufficient calibration and laboratory chemical analyses, a relationship between compound concentration and spectral response could be developed for a specific site.

4.4.2 Attributes

The neutron activation tool can potentially satisfy data needs pertaining to lithology, formation uniformity, presence and concentration of gamma-emitting radionuclides, presence and estimated concentration of chlorinated organic solvents, sulfates, and brines. These data can be obtained in both the vadose and groundwater environments. Moisture content can be determined in the vadose zone, and saturated porosity can be evaluated beneath the water table. Hence, application of this tool in new or existing boreholes can potentially substitute for some of the soil and groundwater sampling for chemistry and laboratory testing in new or existing boreholes, especially replacing drilling and sampling new boreholes in the vadose zone with logging in existing boreholes.

It is estimated that, once successfully developed, it will cost on the order of $2,600 and take about 0.001 years to conduct, per borehole. Analysis (off-site) of the results will cost about $750 and take about 0.005 years to complete, per borehole. It has been subjectively assessed that the tool will be acceptable to the regulatory agencies in many cases.

4.4.3 Present Status

The Westinghouse Hanford Geophysical Team has proposed using a neutron activation tool originally developed by ARCO. This tool was eliminated from ARCO's geophysical program and is available through an independent contractor. It is estimated that up to $5 million was spent in the research and development of this tool. The unique feature of the tool is the Germanium (Ge) detector which provides high resolution spectra. Schlumberger have also developed a Ge detector for their neutron activation tool.

A feasibility study is needed, including field demonstration/application of the existing technology and evaluation of calibration methods, to determine additional development activities and applications.

It is estimated that it will cost on the order of $820,000 and take about 1.9 man-years to complete development of this tool. The probability that such development will be successful, allowing the tool to be applied in the field, has been assessed to be 0.5, based on judgement.

Table 4-1. Borehole Geophysical Tool Attributes.

FACTORS	Spectral Gamma	Gamma-Density	Neutron-Neutron	Neutron Activation
Accuracy in Satisfying Data Requirement:				
Vadose - Geology	4	3	1	4
Vadose - Physical	1	3	4	3
Vadose - Contaminants	5	1	1	4
Vadose - Flux Tests	5	1	1	4
Groundwater - Geology	4	3	3	3
Groundwater - Physical	1	3	1	1
Groundwater - Hydraulic	1	2	4	4
Groundwater - Contaminants	5	1	1	5
Groundwater - Flux Tests	5	1	1	5
Groundwater - Solute Retardation	5	1	1	5
Vadose - Monitoring	5	1	1	5
Groundwater - Monitoring	5	1	1	5
Estimated Development Cost	$135,500	$906,000	$1,025,000	$822,600
Estimated Development Schedule (man-yrs)	0.6	3.7	3.7	1.9
Probability of Successful Development	0.9	0.6	0.6	0.5
Estimated Unit Application Cost (per well)	$1,540	$514	$514	$2,650
Estimated Unit Application Duration (yrs/well)	0.003	0.001	0.001	0.001
Estimated Unit Analysis Cost (per well)	$879	$586	$586	$750
Estimated Unit Analysis Duration (yrs/well)	0.008	0.005	0.005	0.005
Program Compatibility	4	2	3	3
Regulatory Acceptability	4	2	3	3

Scoring Definitions:

Accuracy
1 Not Applicable
2 Poor Data Application/Quality
3 Moderate Data Application/Quality
4 Good Data Application/Quality
5 Excellent Data Application/Quality

Compatibility
1 Not compatible
2 Compatible, in certain applications
3 Compatible, in many applications
4 Compatible, in most applications
5 Highly compatible, complete replacement of present program

Acceptability
1 Not acceptable
2 Acceptable, in limited application
3 Acceptable, in many cases
4 Acceptable, in most cases
5 Highly acceptable, complete acceptance of results

5.0 EVALUATION OF CANDIDATE BHG TOOLS

The development and application of the various candidate BHGs have been evaluated, per the approach presented in Section 2, as discussed below. This evaluation was done in the context of a potential characterization/monitoring program(s). Hence, the role of BHGs within such programs and the basis for evaluating such programs first had to be established. On this basis, the programs (incorporating BHGs) were then evaluated, and the sensitivity of this evaluation to reasonable changes in subjective assessments were determined.

5.1 CHARACTERIZATION/MONITORING PROGRAMS

A variety of programs which satisfy the data requirements are possible. As illustrated in Figure 5-1, the elements of the various programs consist of: drilling new boreholes (if data requirements cannot be met in existing boreholes); obtaining geologic samples in new boreholes and conducting/analyzing lab tests on those samples; obtaining water quality samples in new or existing boreholes and conducting/analyzing lab tests on those samples; conducting other in situ tests in new or existing boreholes and analyzing those tests; possibly conducting BHGs in new or existing boreholes (after BHG development) and analyzing those tests; and finally collecting and interpreting all of the data and comparing it with the data requirements.

A Base Case characterization/monitoring program (which does not include BHGs) was developed from the data review, as described in Section 3 (Table 3-3) and summarized in Table 5-1. The base case program is applicable to about five typical operable units (which is conservative with respect to evaluating the benefits of BHG development and application), and uses the average of the various program elements that were or are being used in the characterization/monitoring of operable units in the 100, 200, 300, and 1100 Areas (Appendix A, Table A-1). Unit cost and time duration of each program element are summarized in Table 5-1, and were developed from interviews with Westinghouse Hanford staff, or were based on assumptions where data were not available. The base case characterization/monitoring program, as well as any assumptions, is described in more detail in Appendix A.

The following conditions were assumed for the Base Case (Program 0):

- Characterization of a total of five "typical" operable units.
- Four drill rigs per operable unit, drilling four borehole types [Vadose (Rad/Non-rad) and Wells (Rad, Non-rad)], for total of 20 drill rigs
- Total of 225 boreholes/wells
- Lab capacity to simultaneously handle 500 soil chemistry tests, 500 soil radiation tests, 500 groundwater chemistry tests, 500 groundwater radiation tests, 100 soil physical properties, and 1 slug test analysis.

A set of five alternative Test Programs which incorporate various combinations of the candidate BHGs and are conservatively equivalent in terms of satisfying the data requirements have been identified, based on the description of the data requirements (Section 3.1), the Base Case Test Program (Section 3.2) and the attributes (vis a vis data requirements) of the various BHGs (Section 4). The alternative programs consisted of the following specific combinations of the candidate BHGs:

- Develop and apply spectral gamma tool (RLS) only
- Develop and apply RLS and gamma-gamma tools
- Develop and apply RLS, gamma-gamma, and neutron tools
- Develop and apply RLS, gamma-gamma, neutron and neutron activation tools
- Develop and apply RLS and neutron activation tools.

In all cases, it was assumed that two spectral gamma tools and one of each of the other BHG tools (gamma-gamma, neutron, and/or neutron activation) would be developed. It was also assumed that two people would be available to develop and analyze each tool.

In addition to BHG development and application, each alternative program consists of different levels of other program elements. For all alternative programs, a percentage of "traditional" program elements (from the Base Case) continue to be implemented in order to confirm and correlate BHG results; i.e., drilling and sampling activities carried out in the Base Case are not completely substituted with BHG. Each alternative characterization/monitoring program is considered to be approximately equivalent to the base case program without BHG in terms of satisfying the data requirements, assuming successful BHG development and application. However, if BHG is intended to be applied, but development is unsuccessful, then it is assumed that the Base Case program would be implemented.

As summarized in Tables 5-1 and 5-2, the five alternative programs were assumed to be identical to the Base Case program, except for the substitution of a percentage of specific samples and analyses in the characterization program. These programs were defined as follows:

- Program 1 substitutes the spectral gamma tool for 50% of the radionuclide samples (either soil or water) and analyses conducted in the base case program.

- Program 2 incorporates Program 1, and in addition substitutes the gamma-gamma density tool for 40% of the soil samples for physical property testing in the Base Case program.

- Program 3 incorporates Program 1, and in addition substitutes the gamma-gamma density and neutron porosity tools for 50% of the physical property test samples and analyses conducted in the base case program.

- Program 4 incorporates Program 3, and in addition substitutes the neutron activation tools for 50% of the chemical (non-radionuclide) samples (either soil or water) and analyses in that program.

- Program 5 incorporates Program 1, and in addition substitutes the neutron activation tool for 50% of the chemical samples and 40% of soil samples for physical property (porosity) testing in that program.

In all of the above programs, the same number of new boreholes were conservatively assumed to be drilled, plus an additional 10 boreholes/wells per operable unit were assumed to be logged to compensate for sampling reductions.

The estimated quantities, unit cost and unit time duration of each program element in the alternative programs, as well as the Base Case program, are presented in Table 5-1. As previously noted, they were developed from interviews with Westinghouse Hanford staff and individuals in other government or private geophysical programs, or were based on assumptions where data were not available, as documented in Appendices A and B.

It should be noted that the estimated quantities, unit costs and durations for each program element are very approximate and intended only for evaluation of the benefits of developing and applying candidate BHGs.

5.2 BASIS FOR EVALUATION OF CHARACTERIZATION/MONITORING PROGRAMS

The various alternative programs containing BHGs which were identified in Section 5.1 have been evaluated as discussed in Section 2. This evaluation consisted of estimating the possible cost and schedule savings associated with each program relative to the Base Case, and separately estimating the "expected" cost and schedule savings (based on the possible cost and savings if BHG development is successful, the probability of successful BHG development, and contingencies if BHG development is unsuccessful), degree of regulatory acceptability, and potential for technology transfer.

Each of the programs consists of a specific combination of elements, each with a quantity, unit cost, and unit duration. The total cost of a program is simply the quantity of each element times its unit cost, summed over all elements. The total duration of a program, however, is the quantity of each element times its unit duration, divided by the number that can be conducted simultaneously, summed over only those elements on the critical path. The critical path was assumed to be the maximum of the following three approximately parallel but interconnected paths, as illustrated in Figure 5-2:

- New Boreholes, including summation of the following:
  - startup
  - drilling, obtaining geologic samples (if any), obtaining water quality samples (if any), and conducting other borehole tests (if any), which can be done in parallel in various boreholes depending on the number of drill rigs available

- the longest development time of the various BHGs (if any) being used (minus drilling, sampling, and testing in the first borehole if less than maximum BHG development time)
- conducting BHGs (if any) in new boreholes, which can be done in parallel in various boreholes depending on the number of tools available, but assuming that the drill rig stays on the hole
- conducting the longest of the last lab tests/analyses (if any)
- combining/interpreting all the data.

- Existing Boreholes, including summation of the following:
  - startup
  - mob/demob of test rigs, obtaining water quality samples (if any), and conducting other borehole tests (if any), which can be done in parallel in various boreholes depending on the number of test rigs available
  - the longest development time of the various BHGs (if any) being used (minus mobilization, sampling and testing in the first borehole if less than maximum BHG development time)
  - conducting BHGs (if any) in new boreholes, which can be done in parallel in various boreholes depending on the number of tools available, but assuming that the test rig stays on the hole
  - conducting the longest of the last lab tests/analyses (if any)
  - combining/interpreting all the data.

- Lab Tests/Analyses, including summation of the following:
  - startup
  - the longest of: (a) longest development time of the various BHGs (if any) being used (minus drilling or mobilization, sampling and testing in the first borehole if less than maximum BHG development time); and (b) the shortest of drilling the first new borehole or setting up a test rig on the first existing borehole of each type, and obtaining the first geologic or water quality sample
  - the maximum of conducting/analyzing all geologic lab tests, conducting/analyzing all water quality tests, analyzing all other borehole tests, and analyzing all BHGs, all of which will be done simultaneously at different facilities and in parallel depending on the combined capacity of those facilities
  - combining/interpreting all the data.

Based on the above, a LOTUS 1-2-3 spreadsheet was developed to estimate the total cost and duration of each program as a function of the quantity, unit cost and unit duration of each element comprising that program, in conjunction with the above schedule logic and specified system capacity. The difference in total cost and duration between each Alternative Test Program and the Base Case was then determined. By focussing on the difference relative to the Base Case, the evaluation is essentially normalized with respect to the Base Case so that potential minor errors in the Base Case assessments are mitigated to a large degree. This spreadsheet is discussed in detail in Appendix C.1.

The spreadsheet determines the program cost and schedule assuming that BHG development is successful. However, such success cannot be guaranteed, i.e., there is a risk that BHG development will not be successful and that BHGs cannot be applied even though they were planned. Hence, a contingency plan (e.g., the Base Case) must be identified and implemented if BHG development is unsuccessful. The "expected" costs and schedule of a BHG program are a function of:

- The program cost and schedule if BHG development is successful;
- The probability that BHG development will be successful; and
- The program cost and schedule if BHG development is unsuccessful (i.e., contingency plan).

Conservative assumptions have been made regarding the probability of success and contingency plans. Details of the probability calculations are included in Appendix C.3.

The overall rating (or "utility") of each BHG Program was subsequently determined as a function of the following factors:

- Expected cost
- Expected schedule
- Technologic capability
- Regulatory acceptance.

Expected cost and schedule are discussed above. Technologic capability was included to reflect the increased characterization and monitoring capabilities afforded by developing BHG, especially at other DOE sites which are expected to have similar data requirements. This is an added benefit of the BHG program, over and above its ability to satisfy the Base Case data requirements at Hanford. Regulatory acceptance, which could be included as part of successful BHG development and thus considered as part of expected cost and schedule, was included separately to recognize that the regulatory agencies might not readily accept some reliance on BHGs. The regulatory acceptance and potential for technology transfer of each program have been subjectively assessed separately on a 0-5 scale, based on judgement and discussions with Westinghouse Hanford personnel, EPA, and Ecology, as discussed in Appendix B.5.

These four factors were incorporated into a weighted overall utility for each program. Individual utility functions were first developed for each factor by identifying approximately equivalent ranges of worst possible to ideal for each. These were then simply converted to a scale of 0 (for worst possible) to 10 (for ideal). Weights can then be applied to the individual utilities to reflect the relative importance of each factor to the decision-maker, consistent with the scales used. The following utility functions and relative weights were assumed:

Factor	Worst	Best	Weight
Cost difference (Mil $)	0	-2.0	1
Schedule Difference (Years)	0	-.5	1
Regulatory Acceptance (0-5)	0	5	1
Technologic Capability (0-5)	0	5	1

This implies that the following are approximately equally preferred; a cost saving of $2 million, a schedule saving of 0.5 year, total regulatory acceptance, and the development of all four BHG tools.

The resulting overall utility, therefore reflects all of the factors relevant to decision making in their appropriate context (i.e., reflecting tradeoffs). On this basis, the various programs can be ranked, with higher ratings preferred. Appendix C.3 contains details of the utility function calculations.

The program evaluation process is summarized in Figure 5-3. As shown, there are program specific and generic components, as well as that part covered within and outside of the spreadsheet.

5.3 RESULTS OF EVALUATION OF CHARACTERIZATION/MONITORING PROGRAMS

The relevant attributes of the various alternative programs were determined, as discussed in Section 5.2. The results of these assessments are presented in detail in Appendix C, and are summarized in Table 5-3. These results indicate the following for the assumptions made herein:

- The probability of successful BHG development decreases as the number of BHG tools increases, assuming success of any one tool is not dependent on success of another. This probability of success ranges from 0.9 for Program 1 (one tool), to about 0.5 for Program 2 and 5 (two tools), to about 0.3 for Program 3 (three tools), and to about 0.2 for Program 4 (four tools).

- All of the alternative programs offer <u>potential</u> cost savings, assuming successful BHG development. Program 5, at $3.6 million, offers the largest potential savings. Programs 1, 4 and 2, at $2.1, $1.8 and $1.2 million, respectively, offer less but still substantial potential savings. Program 3, at $0.1 million, offers insubstantial savings. However, the <u>expected</u> cost savings for each program are moderated from the potential cost savings due to the possibility that BHG development will not be successful. Those programs with the highest probability of success tend to be moderated least. Hence, Program 1, at $1.8 million, offers the largest expected cost savings. Programs 5 and 2, at $0.5 and $0.2 million, respectively, offer some expected cost savings. Programs 3 and 4, however, at -$1.3 and -$1.5 million, respectively, have expected cost penalties, due to their low probability of success and high development cost.

- Conversely, none of the alternative programs offers potential schedule savings, assuming successful BHG development. Programs 1 and 5, at 0.2 and 0.9 years, respectively, have the least potential schedule penalty. Programs 2, 3, and 4, at 1.8, 2.1, and 2.5 years, respectively, have large potential schedule penalties. Similar to costs, however, the expected schedule penalties for each program are moderated from the potential schedule penalties due to the possibility that BHG development will not be successful. Again, those programs with the highest probability of success tend to be moderated least. Hence, Programs 1 and 5, at 0.2 and 0.7 years, respectively, have the least expected schedule penalty. Programs 3, 4 and 2, at 1.2, 1.2, and 1.4 years, respectively, still have large expected schedule impacts.

- All of the alternative programs offer improved technologic capabilities, proportional to the number of tools developed. Hence, Program 4 (four tools) has the highest rating, whereas Program 3 (three tools), Programs 2 and 5 (two tools), and Program 1 (one tool) offer increasingly less.

- Conversely, all of the alternative programs offer decreased regulatory acceptance. Programs 1, 4, and 5 are assumed to offer about 20% less in the way of regulatory acceptance, whereas Programs 2 and 3 are assumed to offer about 40% less.

- Based on the above assessments and on assumed value judgements, tradeoffs were made and an overall rating was developed for each program. It should be noted that the absolute values of these ratings are irrelevant due to the arbitrary scales used in the value judgements. Only comparisons of these ratings are of interest. Based on such comparisons, it can be seen that, based on the assumptions used in this study: only Program 1 has a higher rating than the Base Case, and even so, it is not substantially higher (+12%); Program 5 has the next highest rating, but it is less than the Base Case, although not substantially less (-21%); and Programs 4, 2, and 3 have substantially lower ratings than the Base Case (-60%, -64%, and -69%, respectively).

5.4 SENSITIVITY OF EVALUATION RESULTS OF CHARACTERIZATION/MONITORING PROGRAMS

It is recognized that there is significant uncertainty in many of the evaluation parameters used to develop the results presented in Section 5.3 (Table 5-3). Hence, in order to determine the "robustness" of these results, a sensitivity study was conducted considering the possible range in those evaluation parameters. Where possible, this was done quantitatively. Such sensitivities were determined theoretically to the extent possible (e.g., for those parameters for which the utility function is linear). For parameters for which the utility function is non-linear, those parameters were varied to determine the impact on the attributes and utility and associated ranking of the various programs. Where not possible to determine the sensitivity quantitatively, the sensitivities were discussed qualitatively.

5.4.1 General Sensitivities

Clearly, the ranking of programs is a direct function of their total utility, which in turn is a linear function of the relative weights, utility functions, and program attributes (see Appendix C.3). Hence, as the attributes of a program improve or as the relative importance of those objectives which the program tends to best satisfy increases, the total utility and thus, depending on the differences among programs, the ranking of that program will increase. For example, as presented in Appendix C and summarized in Table 5-4, the total utility for each of the programs considered in Section 5.3 (Table 5-3) has been re-calculated for different relative weights of the objectives. Four weighting combinations were evaluated, each assuming that one factor (cost, for example) is as important as the other three factors combined. This weighting is arbitrary and is meant as an example of the effects of weighting only. However, the following can be observed based on the assumptions (e.g, regarding characterization of five operable units, a nominal 50% BHG substitution rate for samples/lab tests) and assessments used herein:

- Regardless of the relative weights, Program 1 has the highest rating, followed relatively closely by Program 5, with Programs 2, 3, and 4 grouped closely together and substantially behind.

- Only Program 1 has a higher rating than the Base Case, and even it becomes essentially equal to the Base Case when Schedule or Regulatory Acceptance are as important as the other three factors combined.

- Program 5 has a higher rating than the Base Case only if Cost or Technologic Capability are more important than the other three factors combined.

- Programs 2, 3, and 4 would have a higher rating than the Base Case only if Technologic Capability is much more important than the other three factors combined.

The program attributes incorporated in the calculation of total utility include expected cost, expected duration, technologic capability and regulatory acceptance. The effect of changes in each of these attributes on the overall utility will be a function of the relative weights and utility functions used for each. Although technologic capability and regulatory acceptance of a program are assessed directly, the expected cost and expected duration of a program are a function of various other parameters, including:

- estimated quantities of program elements
- estimated unit costs and unit durations of program elements
- the system capacity
- the probability of successful BHG development.

Obviously, as the estimated quantities or unit costs of program elements increase, or as the probability of successful BHG development decreases (assuming potential savings with BHG), the expected program costs will increase. Similarly, as the estimated quantities or unit durations of specific program elements (i.e., those on the critical path) increase, or the system capacity for critical path elements decrease, or the probability of successful BHG development decreases, the expected program schedule will increase. It should be noted, however, that the expected program schedule is unaffected by changes in estimated

quantities, unit durations, or system capacity of non-critical path elements, as long as they remain off the critical path. For example, as the unit costs and unit durations (for critical path elements) associated with drilling, sampling, and lab testing increase, or as the unit costs and unit durations (for critical path elements) associated with BHG development and application decrease, the potential costs and schedule savings, and thus the rating, of an alternative BHG program will increase. As another example, if the system capacity decreases, the duration of the associated elements may increase and the critical path may change.

As another example, as presented in Appendix C and summarized in Figure 5-4, the total program utility for each of the programs considered in Section 5.3 (Table 5-3) has been re-calculated for different probabilities of program success. As can be observed, at probabilities of success greater than about 40% and 90%, respectively, Programs 1 and 5 have a higher rating than the Base Case, whereas Programs 2, 3, and 4 do not have a higher rating than the Base Case for any possible probability of success. Again, this is based on the assumptions (e.g., characterization of five operable units and a 50% BHG substitution rate for samples/lab tests), assessments, and value judgements used herein.

As another example, the attributes and utility for each of the programs considered in Section 5.3 (Table 5-3) have been re-calculated for different quantities of specific elements, i.e., based on higher BHG substitution percentages and/or different Base Case programs, as presented in Appendix C.2 and summarized in Table 5-4. The following can be observed based on the value judgements and assessments used herein:

- As illustrated in Figure 5-5, the rating of each alternative program increases (relative to the Base Case) as the number of operable units in the characterization program increases. Programs 1, 5 and 2 have a higher rating than the Base Case when more than about four, nine and 27 "typical" operable units are considered, respectively. Programs 3 and 4 require substantially more than fifty "typical" operable units to have a higher rating than the Base Case. This is based on a nominal 50% BHG substitution rate for sampling and lab testing.

- Increasing the nominal BHG substitution percentage for sampling and lab testing from 50% to 80% increases the rating for each program, but not substantially. It should be noted the reduction in soil physical property sampling/testing by either the gamma-gamma or neutron activation tools by themselves for the nominal 80% reduction is assumed to be 52%, whereas, if used in conjunction with other tools is assumed to be 80%. Through such an increase, the rating for: Program 1 remains moderately higher than the Base Case; Program 5 becomes essentially equivalent to the Base Case; and Programs 2, 3 and 4 remain substantially below the Base Case. This is based on characterization of five "typical" operable units.

- Substituting BHGs in existing holes for 30% of new holes substantially increases the rating for each program. Through such an increase, the rating for: Program 1 is substantially higher than the Base Case; Program 5 is moderately higher than the Base Case; Program 2 is slightly lower than the Base Case; and Programs 3 and 4 remain substantially below the Base Case. This is based on

characterization of five operable units and a nominal 50% BHG substitution rate for samples and lab testing.

5.4.2 Monitoring Program

If the BHG considered in this study can be successfully developed and used in the Hanford CERCLA characterization programs, there are potentially significant additional benefits to be gained from their use in operational and post-closure monitoring, as suggested by EPA (1991). As BHGs are used in the CERCLA characterization work over the next 10 years, a large amount of data will be available regarding the correlation of BHG logs and both radionuclide and hazardous substance contaminants. This database could potentially allow the use of BHG as a major component of future monitoring programs at the site.

Vadose zone monitoring is currently being conducted at the Tank Farms using gamma-ray logging. The only other currently available method to conduct vadose zone monitoring would involve drilling, sampling, and analyzing soil samples from a new vadose zone borehole at the frequency required by the approved monitoring plan. Operational or post-closure vadose zone monitoring with the spectral gamma system and neutron activation system in either existing or newly installed vadose zone boreholes to monitor any changes in radionuclide or specific chemical contaminant concentrations would clearly have cost-benefits over the drilling alternative. Based on the data presented in Appendix A.4 and Section 4, it is estimated that the cost savings would amount to about $150,000 per well, assuming 10 samples per well. It may be possible to apply BHG to the vadose zone monitoring of approximately 1200 dry boreholes that are used for monitoring waste management facilities (McGhan, 1989).

The benefits of using BHG for conducting groundwater monitoring is not as clear as for vadose zone monitoring. Current groundwater monitoring programs analyze for many chemical constituents that cannot be detected by the spectral gamma or neutron activation system. Still, it may be possible to incorporate BHG into groundwater monitoring programs if the contaminants of concern can be detected by the BHG systems being used, or if the BHG systems can be used as a tool to screen for indicator constituents. Such an application of BHG has the potential to reduce the number of groundwater sample analyses, thereby reducing the overall costs of groundwater monitoring. Based on the data presented in Appendix A.4 and Section 4, it is estimated that the cost savings would amount to about $1,000 and $2,000 per rad well and non-rad well, respectively, assuming 1 sample per well. It may be possible to apply BHG to the groundwater monitoring of approximately 500 to 800 wells being used in current surveillance programs (McGhan, 1989).

The approximate number of vadose zone monitoring boreholes or groundwater monitoring wells which must be replaced in order to provide enough cost savings to increase a program rating to be equal to the Base Case (for characterization of five "typical" operable units and a nominal 50% BHG substitution percentage) can be determined as follows:

- Program 1 has a higher rating than the Base Case without any substitution

- Program 5 must realize an additional $1.05 million savings, which translates to about seven vadose zone monitoring boreholes or about 1,000 groundwater monitoring wells

- Programs 2, 3, and 4 must realize an additional $3.20, $3.45, and $3.00 million savings, respectively, which translates to about 25 vadose zone monitoring boreholes or about 3,500 groundwater monitoring wells.

5.4.3 BHG Program Development Cost and Schedule

It was assumed that, from a management standpoint, the cost and schedule for developing an adequate field test site should be borne by the BHG program, since it would not be developed otherwise. The field test site approach was recommended by EPA in their review of BHG applications at Hanford (EPA 1991). A significant portion of the BHG development cost is related to the development of a borehole test site for field evaluation of the BHG tools. The spreadsheet incorporates cost savings associated with development of multiple tools, since only one field test site will be required for all tools.

Similarly, a portion of the BHG development schedule is related to the number of WHC staff working on BHG development. The duration for tool development was developed in man-years, assuming that two people were able to work on developing hardware and software for any one tool. In many cases, there is a significant schedule savings by increasing staff capabilities in developing BHG tools, or conversely a schedule penalty by decreasing staff capabilities. In addition, a significant portion of the BHG development schedule is related to developing the field test site.

Table 5-1. Summary of Program Elements

PROGRAM ELEMENTS	COST($)	UNIT	(yrs)	PROGRAM:	0	1	2	3	4	5
Work Plan	NA	man-yr	NA	(startup)	0	0	0	0	0	0
Drill/Complete New BH1s	$88,500	each	0.080	N-RAD VADOSE	75	75	75	75	75	75
Drill/Complete New BH2s	$88,500	each	0.080	NON-RAD WELL	50	50	50	50	50	50
Drill/Complete New BH3s	$97,600	each	0.160	RAD VADOSE	50	50	50	50	50	50
Drill/Complete New BH4s	$97,600	each	0.160	RAD WELL	50	50	50	50	50	50
Mob/Demob Test Rig on Old BH1s	$0	each	0.000	N-RAD VADOSE	0	0	50	50	50	50
Mob/Demob Test Rig on Old BH2s	$0	each	0.000	NON-RAD WELL	0	0	50	50	50	50
Mob/Demob Test Rig on Old BH3s	$0	each	0.000	RAD VADOSE	0	50	50	50	50	50
Mob/Demob Test Rig on Old BH4s	$0	each	0.000	RAD WELL	0	50	50	50	50	50
Obtain Geo1 Samples in New BHs	$2,100	each	0.000	SOIL CHEM	625	625	625	625	313	313
Obtain Geo2 Samples in New BHs	$4,460	each	0.000	SOIL RAD	660	330	330	330	330	330
Obtain Geo3 Samples in New BHs	$400	each	0.000	SOIL PHYS	920	920	552	460	460	552
Conduct/Anal Lab Tests (Geo1)	$3,400	each	0.190	SOIL CHEM	625	625	625	625	313	313
Conduct/Anal Lab Tests (Geo2)	$1,400	each	0.410	SOIL RAD	660	330	330	330	330	330
Conduct/Anal Lab Tests (Geo3)	$500	each	0.080	SOIL PHYS	920	920	552	460	460	552
Obtain WQ1 Samples in New BHs	$2,000	each	0.003	GW CHEM	325	325	325	325	163	163
Obtain WQ1 Samples in Old BHs	$2,000	each	0.003	GW CHEM	320	320	320	320	160	160
Obtain WQ2 Samples in New BHs	$2,000	each	0.003	GW RAD	215	108	108	108	108	108
Obtain WQ2 Samples in Old BHs	$2,000	each	0.003	GW RAD	215	108	108	108	108	108
Obtain WQ3 Samples in New BHs	$0	each	0.000		0	0	0	0	0	0
Obtain WQ3 Samples in Old BHs	$0	each	0.000		0	0	0	0	0	0
Conduct/Anal Lab Tests (WQ1)	$3,400	each	0.190	GW CHEM	645	645	645	645	323	323
Conduct/Anal Lab Tests (WQ2)	$1,400	each	0.410	GW RAD	430	215	215	215	215	215
Conduct/Anal Lab Tests (WQ3)	$0	each	0.000		0	0	0	0	0	0
Cond Other BH1 Tests in New BHs	$2,000	per well	0.003	SLUG TEST	100	100	100	100	100	100
Cond Other BH1 Tests in Old BHs	$2,000	per well	0.003	SLUG TEST	50	50	50	50	50	50
Analyze Other BH1 Tests	$2,600	per well	0.019	SLUG TEST	150	150	150	150	150	150
Cond Other BH2 Tests in New BHs	$0	per well	0.000		0	0	0	0	0	0
Cond Other BH2 Tests in Old BHs	$0	per well	0.000		0	0	0	0	0	0
Analyze Other BH2 Tests	$0	per well	0.000		0	0	0	0	0	0
Cond Other BH3 Tests in New BHs	$0	per well	0.000		0	0	0	0	0	0
Cond Other BH3 Tests in Old BHs	$0	per well	0.000		0	0	0	0	0	0
Analyze Other BH3 Tests	$0	per well	0.000		0	0	0	0	0	0
Develop BHG1	$135,500	one	0.600	SPECTRAL	0	1	1	1	1	1
Conduct BHG1 in New BHs	$1,540	per well	0.003	SPECTRAL	0	100	100	100	100	100
Conduct BHG1 in Old BHs	$1,540	per well	0.003	SPECTRAL	0	100	100	100	100	100
Analyze BHG1	$879	per well	0.008	SPECTRAL	0	200	200	200	200	200
Develop BHG2	$906,000	one	3.690	AMMA-GAMMA	0	0	1	1	1	0
Conduct BHG2 in New BHs	$514	per well	0.001	AMMA-GAMMA	0	0	125	125	125	0
Conduct BHG2 in Old BHs	$514	per well	0.001	AMMA-GAMMA	0	0	100	100	100	0
Analyze BHG2	$586	per well	0.005	AMMA-GAMMA	0	0	225	225	225	0
Develop BHG3	$1,025,000	one	3.710	NEUTRON	0	0	0	1	1	0
Conduct BHG3 in New BHs	$514	per well	0.001	NEUTRON	0	0	0	225	225	0
Conduct BHG3 in Old BHs	$514	per well	0.001	NEUTRON	0	0	0	200	200	0
Analyze BHG3	$586	per well	0.005	NEUTRON	0	0	0	425	425	0
Develop BHG4	$822,600	one	1.890	ACTIVATION	0	0	0	0	1	1
Conduct BHG4 in New BHs	$2,650	per well	0.001	ACTIVATION	0	0	0	0	225	225
Conduct BHG4 in Old BHs	$2,650	per well	0.001	ACTIVATION	0	0	0	0	200	200
Analyze BHG4	$750	per well	0.005	ACTIVATION	0	0	0	0	425	425
Combine Data	NA	one	NA	(wrap-up)	0	0	0	0	0	0

Table 5-2. Alternative Test Programs.

TEST PROGRAM	SUBSTITUTION OF BASE CASE ELEMENTS BY BHG (% OF BASE CASE)				
	Soil or water radionuclide sample/analysis by spectral gamma tool	Soil sample/ physical property testing by gamma-gamma tools	Soil sample/ physical property testing by neutron porosity tool	Soil or water chemical sample/ analyses by neutron activation tool	Soil sample/ physical property testing by neutron activation tool
1	50	0	0	0	0
2	50	40	0	0	0
3	50	40	10	0	0
4	50	40	10	50	0
5	50	0	0	50	40

Table 5-3. Evaluation of Test Programs with Respect to Individual Objectives.

TEST PROGRAM	ATTRIBUTES							UTILITY (RATING)
	ΔC (Mil $)	ΔS (Yrs)	T (1-5)	R (1-5)	P[S] (0-1)	E[ΔC] (Mil $)	E[ΔS] (yrs)	$\frac{\Delta U}{U_{BC}}$
0	0	0	1	5	1.0	0	0	0
1	-2.05	+0.2	2	4	0.9	-1.83	+0.2	+0.12
2	-1.22	+1.8	3	3	0.54	-0.18	+1.4	-0.64
3	-0.07	+2.1	4	3	0.27	+1.30	+1.2	-0.69
4	-1.82	+2.5	5	4	0.16	+1.45	+1.2	-0.60
5	-3.57	+0.9	3	4	0.45	-0.46	+0.7	-0.21

Notes:

ΔC = Cost difference (relative to Base Case) (assuming successful BHG development)
ΔS = Schedule difference (relative to Base Case) (assuming successful BHG development)
T = Technologic capability (subjective assessment, rated 0 = worst possible to 5 = ideal)
R = Regulatory acceptance (subjective assessment, rated 0 = worst possible to 5 = ideal)
P[S] = Probability of successful BHG development
E[ΔC] = "Expected" cost difference (relative to Base Case)
E[ΔS] = "Expected" schedule difference (relative to Base Case)
$\frac{\Delta U}{U_{BC}}$ = Fractional difference in total utility, relative to Base Case, where total utility is function of value judgements (utility functions and relative weights). It should be noted that these results represent only one possible but hypothetical set of value judgements, as presented in Appendix C.3. They incorporate equal weighting of cost, schedule, technologic capability and regulatory acceptance, consistent with the individual utility functions. The utility may change for different value judgements.

See Appendix C for details of analyses.

Table 5-4. Sensitivity of Fractional Difference in Program Utility to Various Parameters.

TEST PROGRAM	CHANGED PARAMETER CASE (see Notes)							
	A	B	C	D	E	F	G	H
0	0	0	0	0	0	0	0	0
1	+0.37	-0.04	+0.20	+0.02	-0.31	+2.21	+0.19	+0.69
2	-0.40	-0.99	-0.41	-0.56	-1.90	+0.67	-0.52	-0.07
3	-0.68	-0.96	-0.37	-0.60	-1.95	-0.12	-0.64	-0.38
4	-0.65	-0.88	-0.20	-0.47	-1.88	-0.19	-0.52	-0.40
5	-0.06	-0.43	-0.02	-0.21	-1.02	+1.98	0.00	+0.21

Notes:

A - Cost factor weighted equally to other three summed
B - Schedule factor weighted equally to other three summed
C - Technologic capability factor weighted equally to other three summed
D - Regulatory acceptance factor weighted equally to other three summed
E - Base case program for one operable unit
F - Base case program for fifty operable units
G - BHGs substitutes for 80% of appropriate sampling and testing
H - BHGs substitute for 30% of new boreholes.

See Figure 5-4 for sensitivity of program utility to probability of successful BHG development.

See Appendix C for details of analyses.

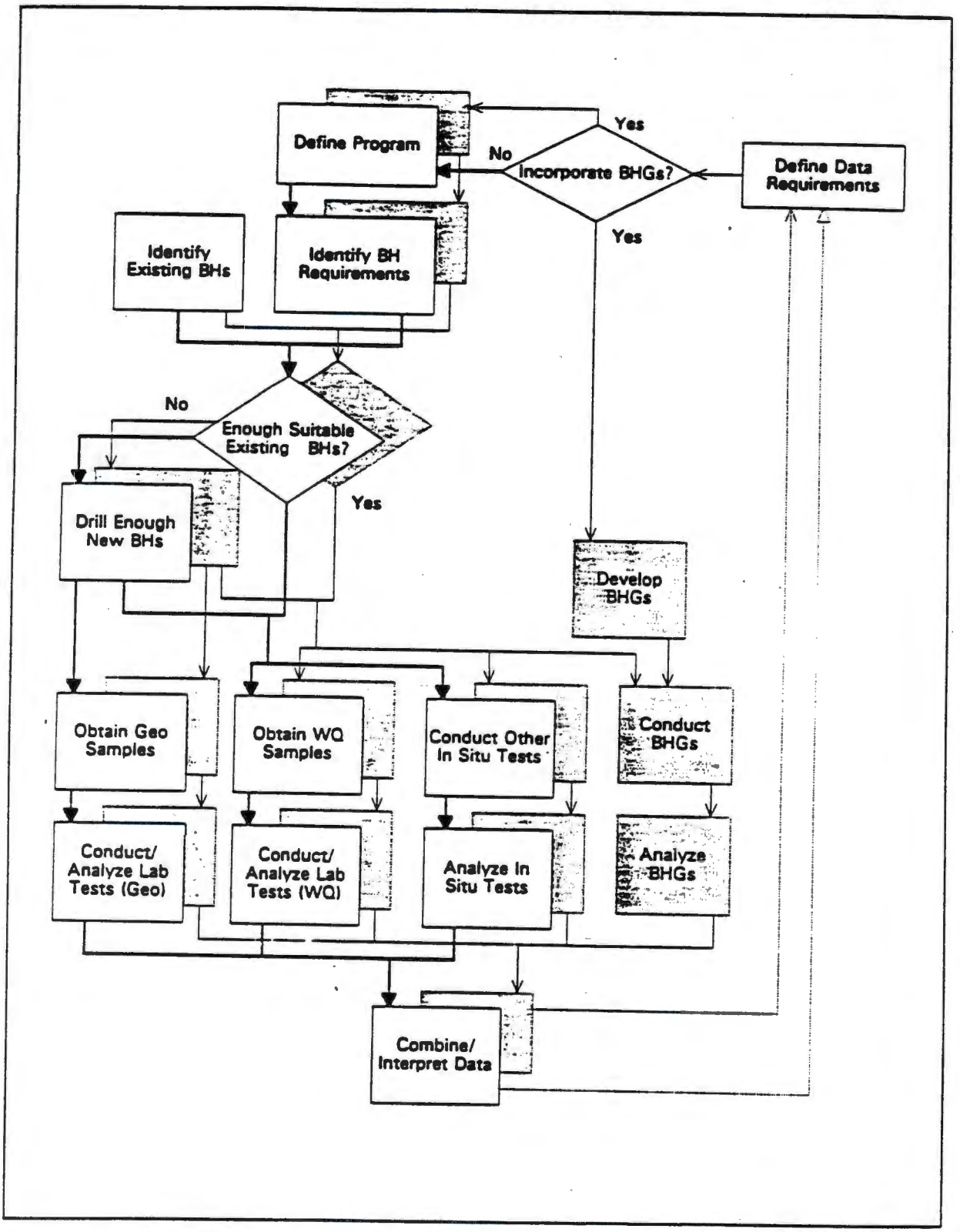

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Figure 5-1. Test Program Development.

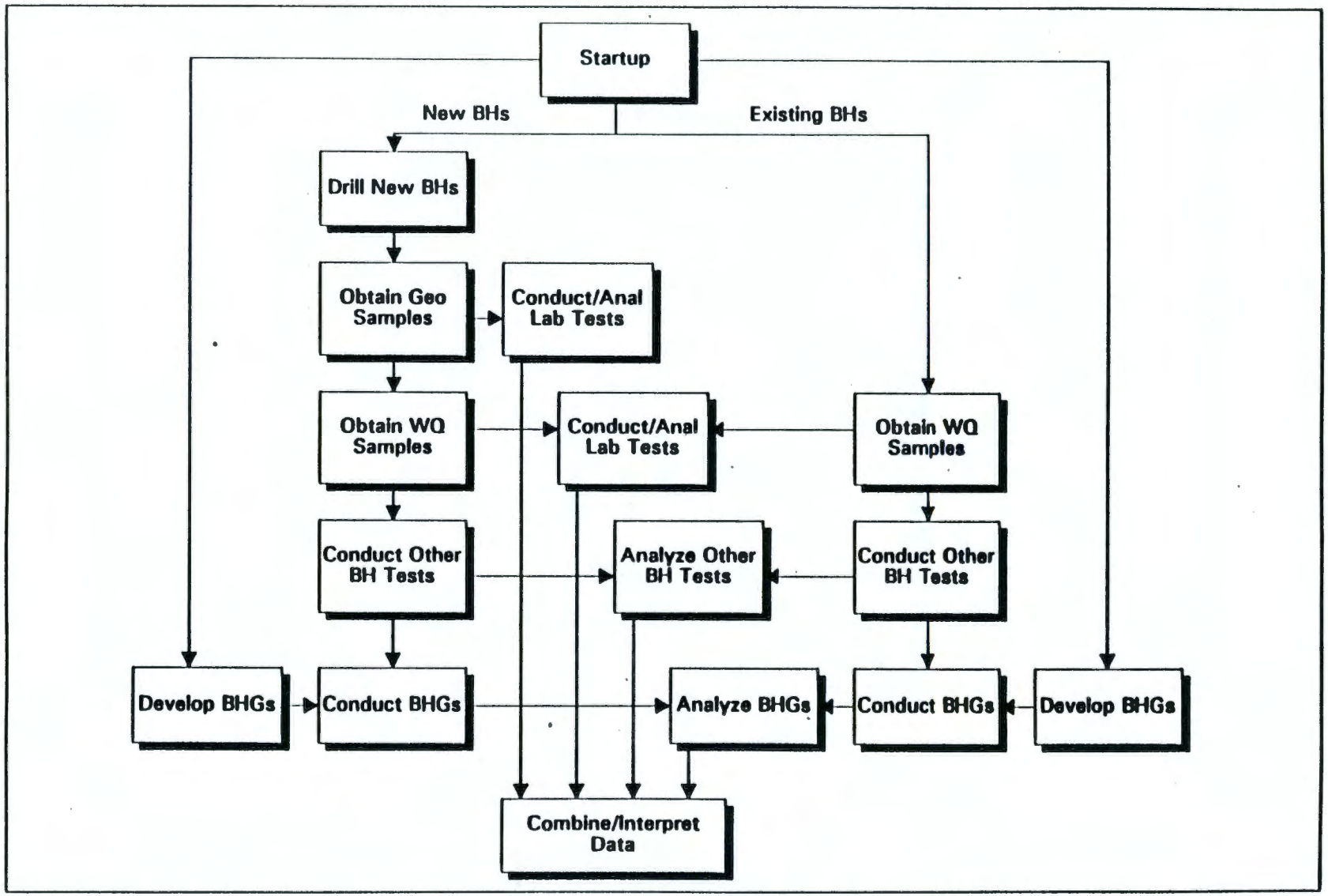

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Figure 5-2. Test Program Schedule Logic.

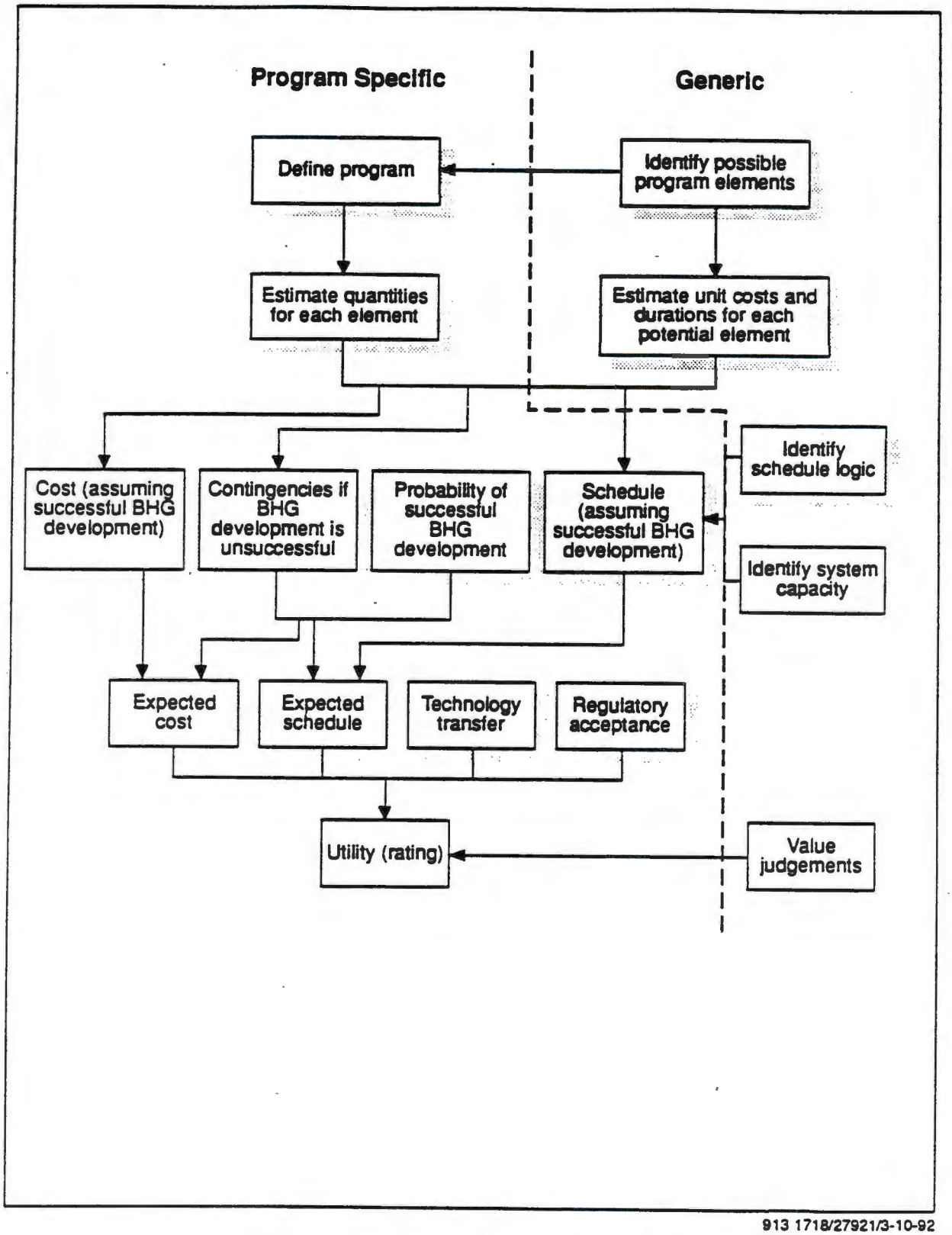

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Figure 5-3. Program Evaluation Process.

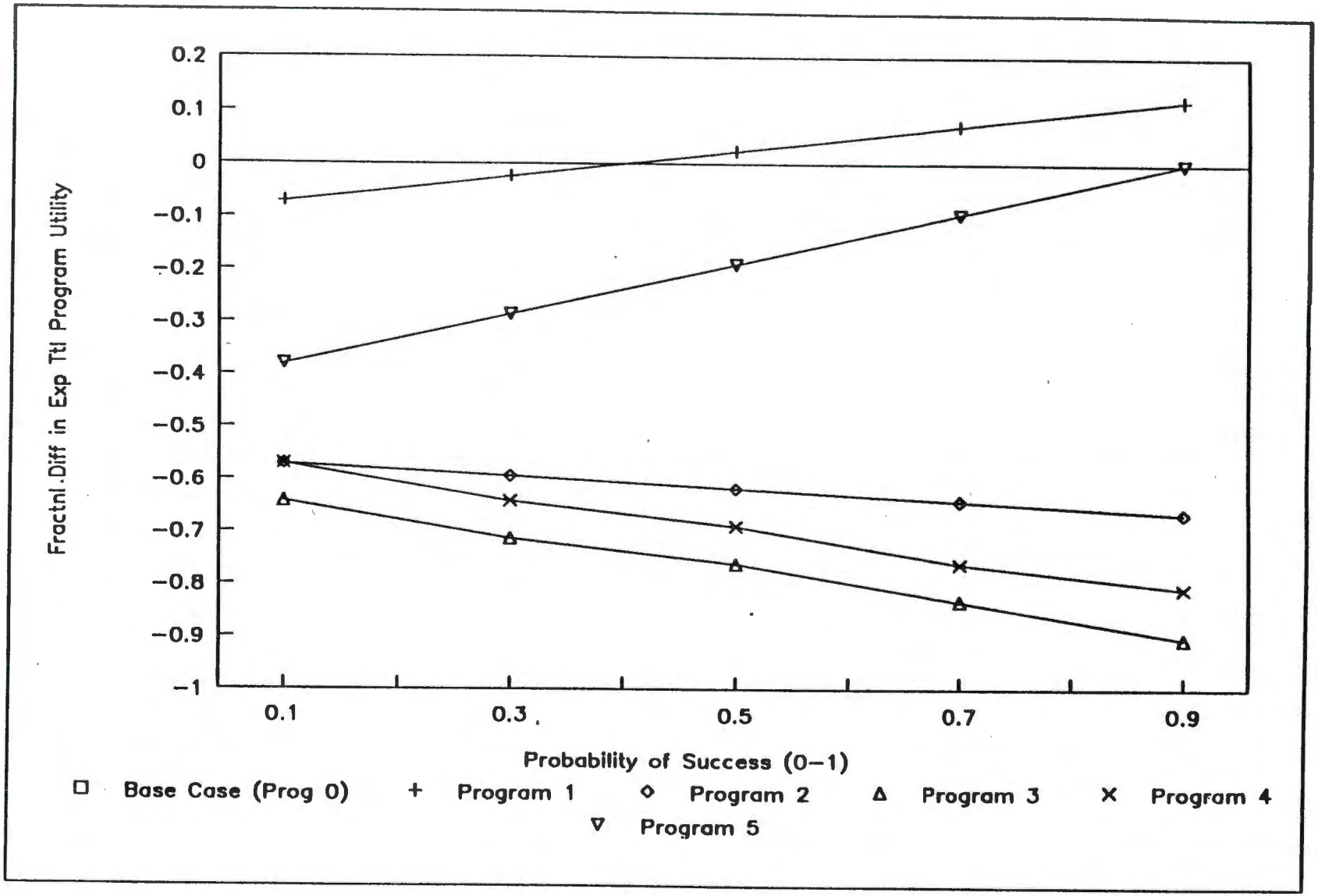

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Figure 5-4. Effect of Probability of Successful BHG Development on Alternative Test Program Utility.

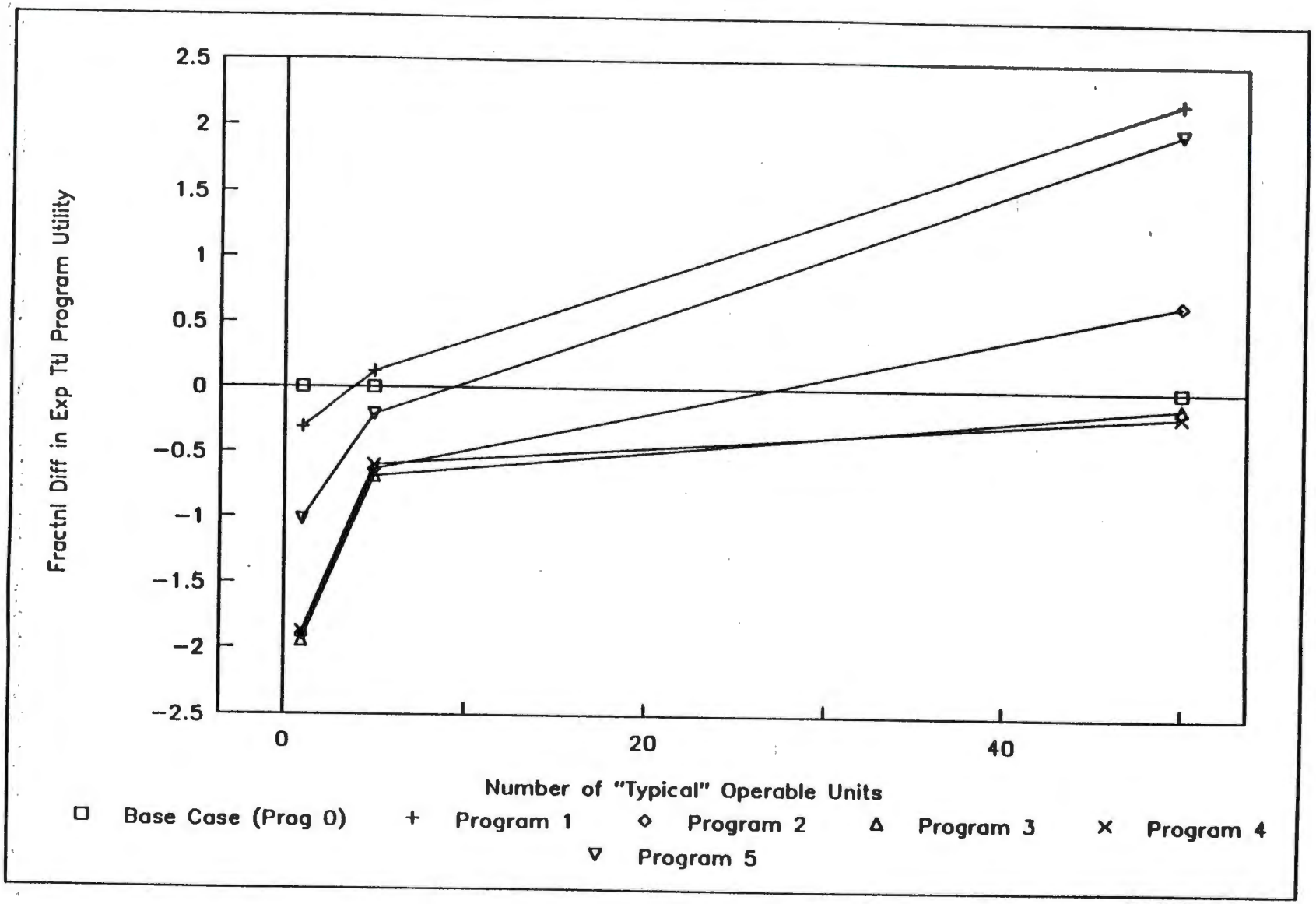

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Figure 5-5. Effect of Number of Operable Units on Alternative Test Program Utility.

6.0 CONCLUSIONS AND RECOMMENDATIONS

Based on the results of this cost-benefit study, specific conclusions and recommendations can be made regarding future development and application of BHGs to Hanford CERCLA programs, as discussed below.

6.1 CONCLUSIONS

A formal cost-benefit study has been conducted to evaluate the economic feasibility and potential benefits of developing and applying specific candidate BHGs to the Hanford CERCLA programs. This cost-benefit study has considered the following for each candidate BHG: its capabilities and limitations in addressing site characterization and monitoring requirements; the cost and duration associated with BHG development and application; its probability of successful development; its likely degree of regulatory acceptance; and its usefulness at DOE sites elsewhere. Each candidate BHG has been evaluated in terms of the entire characterization/monitoring program. The "expected" cost savings and schedule penalties (relative to the current Base Case program), as well as increased technology capabilities and decreased regulatory acceptance, have been estimated for various combinations and application levels of candidate BHG tools (i.e., alternative programs). Generally, conservative assumptions were made regarding the size of the program and the application level of BHGs, which tend to understate the potential benefits. Tradeoffs have then been made among these program attributes in order to collectively rate each program, relative to the Base Case. Sensitivity studies have been conducted to determine the "robustness" of these ratings.

Based on the results of this cost-benefit study, as presented in Section 5, it can be readily concluded that Program 1, incorporating the spectral gamma tool, as defined in Section 5, has a higher rating than the Base Case or any of the other alternative programs for virtually any of the sets of evaluation parameters considered in this study. Although Program 1 has only a slightly higher rating than the Base Case under conservative assumptions regarding the size of the program and the application level of BHGs, this difference becomes substantial for more realistic assumptions. It cannot be concluded, however, that Program 1 would have a higher rating than the Base Case or any other alternative program for <u>any possible</u> set of evaluation parameters. Instead, it can be stated that it is <u>highly likely</u> that Program 1 would have a substantially higher rating that the Base Case or any other alternative program for any <u>reasonable</u> set of evaluation parameters. A possible exception would be that Program 5, also incorporating the neutron activation tool, may have a higher rating for a sufficiently large characterization and monitoring program.

It must be emphasized that the assessments used in this cost-benefit study were made solely for the purpose of comparatively evaluating the potential development and application of specific candidate BHGs within CERCLA characterization/monitoring programs at Hanford. These assessments are considered to be adequate for that purpose, but are not intended to represent program budgets or proposed characterization/monitoring plans.

It must also be emphasized that several additional factors could be considered in this cost-benefit study, but have not been:

- Different levels of BHG development could be considered. For example, gamma-gamma or neutron-neutron tools could be developed (or may even by available "off-the-shelf") at significantly less cost to provide qualitative rather than quantitative information.

- BHGs may provide additional relevant information (e.g., regarding well completion) which is unavailable from other sources. The potential additional benefits of such information has not been considered.

6.2 RECOMMENDATIONS

Based on the above conclusions, it is recommended that:

- The spectral gamma tool is cost effective and thus should continue to be developed and, if successfully developed, be applied in Hanford CERCLA characterization/monitoring programs.

- The Base Case monitoring program should be identified and Programs 1 and 5 evaluated with respect to both characterization and monitoring. In the absence of this evaluation, it is anticipated that, if the monitoring program is sufficiently large, then the neutron activation tool will also be cost effective and thus should also be developed and, if successfully developed, applied in conjunction with the spectral gamma tool in Hanford CERCLA characterization/monitoring programs.

- The gamma-gamma density and neutron-neutron porosity tools are not cost-effective and should not be developed to the levels identified in this report.

7.0 REFERENCES

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APPENDIX A

SITE CHARACTERIZATION/MONITORING DATA REQUIREMENTS AND PROGRAMS DOCUMENTATION

CONTENTS

Appendix A Site Characterization/Monitoring Data Requirements and Programs Documentation

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The site characterization/monitoring data requirements at Hanford, which BHGs might address, and the test programs currently proposed for addressing those requirements have been identified in a broad way to provide a basis for evaluating the candidate BHGs. These data requirements and programs have been identified primarily through a review of RI/FS work plans and an RI report, and discussions with Westinghouse Hanford staff, as documented below. Current cost data for ongoing borehole and well drilling, sampling, and laboratory analyses were provided by Westinghouse Hanford staff, and are in 1992 dollars.

A.1 DATA REQUIREMENTS

The data requirements for site characterization and monitoring of the vadose zone and groundwater in the CERCLA program at Hanford are summarized in Table 3-1. They were compiled from a survey of various Hanford RI/FS work plans and reports. The survey was limited to identifying data requirements that involved the use of vadose zone or deeper boreholes (existing or new) in order to evaluate the candidate BHGs, per the approach presented in Section 2. These work plans were developed in accordance with: the statutory requirements of the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA), as amended; the regulatory requirements of the National Oil and Hazardous Substances Pollution Contingency Plan (NCP); and relevant U.S. Environmental Protection Agency (EPA) guidance documents. Such relevant EPA guidance includes:

Guidance for Conducting Remedial Investigations and Feasibility Studies under CERCLA (EPA 1988)

Data Quality Objectives for Remedial Response Activities (EPA 1987).

The survey included RI/FS work plans for the 100-KR-1, 100-KR-4, 200-BP-1, 300-FF-1 and 300-FF-5 operable units and the 1100-EM-1 Phase 1 RI report (DOE, 1991a, 1991b, 1990a, 1990b, 1990c, 1990d). This survey provides a representative cross section of the types of data needed for characterization and monitoring of operable units across the site.

In addition to the types of data, the data requirements consider data quality, the spatial distribution of data, and the frequency of data collection or analysis. The assignment of codes in Table 3-1 to describe these requirements was based on the survey of the work plans and report described above, and is subjective in nature.

The data quality information provided in Table 3-1 is coded on a 1 to 5 scale, which has been modified after the EPA classification of analytical levels for contaminant data (EPA 1987) to include appropriate categories for non-contaminate data. As data quality goes up on this scale, costs and laboratory turnaround times also increase substantially. The 200-BP-1 RI/FS work plan (DOE 1990a) indicated data completeness and acceptability criteria of 80% for quality level 3 to 5 analytical data. The completeness for level 1 analysis was not considered to be critical; however, it was estimated to be essentially 100% complete because of the ease of repeating the analysis if needed (DOE 1990a).

A.2 CURRENT CHARACTERIZATION/MONITORING PROGRAM

The description of the current vadose zone and groundwater characterization/ monitoring activities within the CERCLA program at Hanford is summarized in Table 3-2 and 3-3. It was compiled from a survey of various Hanford RI/FS work plans and reports, as described in Section A.1. The current program incorporates review of existing data and drilling, sampling, and laboratory analysis of soil and groundwater samples from new boreholes and monitoring wells installed for each operable unit. In the current program, borehole geophysical logging with the spectral-gamma tool is limited to specific requests for logging individual boreholes prior to well construction. Tank farm surveillance also employs a passive gamma-ray logging tool in their monitoring program.

As summarized in Table A-1, recent characterization programs involving drilling and sampling at six operable units include:

100-KR-1 - Twenty-one soil boreholes to be drilled to generally 10 feet below the water table (average hole depth estimated to be 50 feet). Soil samples for physical property testing to be collected every 5 feet or at change in lithology. Soil samples for chemical characterization to be collected every 2 feet to 20 feet depth, then every 5 feet (DOE 1991a).

100-KR-4 - Approximately 10 soil samples for chemical characterization collected from each of 20 monitoring wells. Soil samples for physical property testing collected every 5 feet or at change in lithology. Initial groundwater sampling includes 43 wells. Eleven wells to be sampled monthly for 6 months and 18 wells to be sampled quarterly (assumed for 1 year) (DOE 1991b).

200-BP-1 - Three soil boreholes drilled to 220 feet each. One borehole sampled continuously, the other two holes sampled a 2.5 feet intervals. Soil samples for chemical characterization to be collected every 25 feet. Eleven new monitoring wells with soil samples to be collected every 5 feet or at change in lithology. Thirty-nine monitoring wells to be sampled quarterly for 1 year, then semi-annually until the end of the Feasibility Study (assumed to be 2 years) (DOE 1990a).

300-FF-1 - Fifty soil boreholes with soil samples for physical property tests to be collected at rate of 1 sample per borehole per geologic unit (assumed 1 geologic unit). Soil samples for chemical characterization to be collected every 5 feet resulting in 600 to 700 samples (DOE 1990b).

300-FF-5 - Approximately 40 soil samples for chemical characterization collected from 31 monitoring wells. Eighty-one groundwater samples to be collected quarterly for one year (DOE 1990c).

1100-EM-1 - Drilled 23 soil boreholes and collected approximately 241 soil samples for physical property testing and 242 soil samples for chemical characterization. Installed 16 monitoring wells and analyzed 44 groundwater samples (DOE 1990d).

A summary of existing wells at Hanford is provided by McGhan (1989). As of January 1989, there were over 2900 existing wells at Hanford (McGhan, 1989). It is estimated that approximately 150 additional wells have been installed at Hanford since 1989. Seven hundred Hanford site boreholes were reviewed by Golder Associates (1989) to

evaluate whether they met current Washington Department of Ecology regulations for monitoring wells (WAC 173-160).

The schedule for completion of the RI/FS characterization work is given in the Hanford Federal Facility Agreement and Consent Order (Ecology, EPA, and DOE 1990), which calls for all RI/FS or RFI/CMS work to be completed by September 2005. As of 1990 there were 12 RI/FS work plans submitted and 4 had been approved. The agreement calls for submittal of 20 RI/FS work plans by April 1992, and then submittal of at least 6 work plans per year until all 78 operable units have been submitted (Ecology, EPA, and DOE 1990). There are proposed milestone changes which are pending which would modify some of the numbers and dates given above, but the completion date for the RI/FS work would remain as September 2005.

It is estimated that a new monitoring well in the 200 West Area that would be 270 feet deep would take approximately 3 to 3-1/2 weeks to drill and then 3 to 4 days to construct the well. He also indicated that there are currently 8 to 12 drilling rigs working on RI/FS boreholes and wells and that an assumption of 10 to 14 drilling rigs doing RI/FS borings in the near future was a reasonable estimate.

Current cost data for ongoing borehole and well drilling, sampling, and laboratory analyses were provided by Westinghouse Hanford staff, and are summarized in Table A-2.

A.3 ASSUMED BASE CASE

The description of program elements and associated unit costs, unit time duration, and quantities used to develop the base case characterization program are described below. "New BH" refers to any soil or groundwater borehole or well installed as part of the characterization program for an operable unit. "Old BH" refers to any existing vadose zone or groundwater well that may be used in the characterization program. "Non-rad" refers to borings or wells drilled in areas of relatively low concentrations of hazardous substances or radioactivity, whereas "rad" refers to borings or wells drilled in areas of higher concentrations of hazardous substances or radioactivity.

- Drill/Complete New BH1s - non rad vadose soil borings $88,500 each completed in 4 weeks (0.08 yrs.). Assume 15 borings from average program (Table A-1). The available cost data do not distinguish between the costs for soil boreholes and for soil boreholes completed as monitoring wells.

- Drill/Complete New BH2s - non rad well $88,500 each completed in 4 weeks (0.08 yrs.). Assume 10 wells from average program (Table A-1). The available cost data do not distinguish between the costs for soil boreholes and for soil boreholes completed as monitoring wells.

- Drill/Complete New BH3s - rad vadose soil borings $97,600 each assumed to be completed in 8 weeks (0.16 yr.). Assume 10 borings from average program (Table A-1). The available cost data do not distinguish between the costs for soil boreholes and for soil boreholes completed as monitoring wells.

- Drill/Complete New BH4s - rad well $97,600 each assumed to be completed in 8 weeks (0.16 yr.). Assume 10 wells from average program (Table A-1). The available cost data do not distinguish between the costs for soil boreholes and for soil boreholes completed as monitoring wells.

- Obtain Geo1 Samples in New BHs - Assume chemical soil sample acquisition cost is 90% of ($42,000/(90.5 ft. ave. hole depth/5 ft. sample interval)) which equals $2,100 each. Time to sample is included in drilling time. Assume 125 chemical soil samples of average 257 soil chemistry samples (Table A-1).

- Obtain Geo2 Samples in New BHs - Assume rad soil sample acquisition cost is 90% of ($54,500/(53.3 ft. ave. hole depth/5 ft. sample interval)) which equals $4,460 each. Time to sample is included in drilling time. Assume 132 rad soil samples of average 257 soil chemistry samples (Table A-1).

- Obtain Geo3 Samples in New BHs - Assume soil sample acquisition cost for physical tests is 10% of average cost of collecting Geo1 and Geo2 soil samples (see above) which equals approximately $400 each. Time to sample is included in drilling time. Assume 184 soil samples from average program (Table A-1).

- Conduct/Anal Lab Tests (Geo1) - Used highest cost of $3,400 each for soil chemical analyses. Time to analyze is 50 days plus 21 days for data validation (0.19 yr.). Assume 125 chemical soil samples of average 257 soil chemistry samples (Table A-1).

- Conduct/Anal Lab Tests (Geo2) - Used highest cost of $1,400 for soil rad analyses. This estimate may be low for high rad or specific radionuclide samples. Time to analyze is 130 days plus 21 days for data validation (0.41 yr.). Assume 132 rad soil samples of average 257 soil chemistry samples (Table A-1).

- Conduct/Anal Lab Tests (Geo3) - Used highest cost of $500 for physical testing of soil samples. Time assumed to be 1 month (0.08 yr.). Assume 184 soil samples from average program (Table A-1).

- Obtain WQ1 Samples in New BHs - Assume groundwater sampling cost of $2,000/well and time of 1 day/well (0.003 yr.) for chemical samples. Assume 60% of average program groundwater samples (215, Table A-1) are for chemicals only, and 50% come from new wells, which equals 65 samples.

- Obtain WQ1 Samples in Old BHs - Assume groundwater sampling cost of $2,000/well and time of 1 day/well (0.003 yr.) for chemical samples. Assume 60% of average program groundwater samples (215, Table A-1) are for chemicals only, and 50% come from old wells, which equals 64 samples.

- Obtain WQ2 Samples in New BHs - Assume groundwater sampling cost of $2,000/well and time of 1 day/well (0.003 yr.) for rad samples. Assume 40% of average program groundwater samples (215, Table A-1) are for rad only, and 50% come from new wells, which equals 43 samples.

- Obtain WQ2 Samples in Old BHs - Assume groundwater sampling cost of $2,000/well and time of 1 day/well (0.003 yr.) for rad samples. Assume 40% of average program groundwater samples (215, Table A-1) are for rad only, and 50% come from old wells, which equals 43 samples.

- Conduct/Anal Lab Tests (WQ1) - Same as Conduct/Anal Lab Tests (Geo1). Assume 60% of average program groundwater samples (215, Table A-1) are for chemicals only, which equals 129 samples.

- Conduct/Anal Lab Tests (WQ2) - Same as Conduct/Anal Lab Tests (Geo2). Assume 40% of average program groundwater samples (215, Table A-1) are for rad only, which equals 86 samples.

- Conduct Other BH1 Tests in New BHs - Assume slug testing cost of $2,000/well and time of 1 day/well (0.003 yr.). Assume 20 new wells in average program are tested (Table A-1).

- Conduct Other BH1 Tests in Old BHs - Assume slug testing cost of $2,000/well and time of 1 day/well (0.003 yr.). Assume 10 old wells in average program are tested.

- Analyze Other BH1 Tests - Assume slug test analysis costs $65/hr times 40 hrs each ($2,600) and takes 1 week (0.019 yr.). Assume 30 analyses in average program.

Number of Simultaneous Acts - Defined as the number of samples or analyses which can be run within the time schedule given for the base case program, which was assumed to be:

Geo Labs - Type 1 (Geo1) - 700 chemical analyses in 50 days
Type 2 (Geo2) - 700 rad analyses in 130 days
Type 3 (Geo3) - 100 physical test samples in 1 month

WQ Labs - Type 1 (WQ1) - 700 chemical analyses in 50 days
Type 2 (WQ2) - 700 rad analyses in 130 days

A.4 MONITORING

There is currently insufficient information available to determine a Base Case Monitoring program. However, a list of potential elements of such a monitoring program has bene developed, as summarized in Table A-3. Monitoring in <u>each well in the vadose zone</u> would consist of the following elements:

- Drill and complete non-rad or rad borehole

- Obtain soil chemistry (~18/borehole) or soil chemistry plus radiation (~11/borehole) samples, and conduct associated laboratory tests.

Monitoring in each well in the saturated zone would consist of the following elements:

- Drill and complete non-rad or rad well, or mob/demob on existing non-rad or rad well

- Obtain water chemistry (~1/borehole) or water radiation (~1/borehole) sample, and conduct associated laboratory tests.

The unit costs for each element have been assumed based on discussions with Westinghouse Hanford staff and on judgement, and are summarized in Table A-3.

A.5 APPENDIX A REFERENCES

EPA 1987, Data Quality Objectives for Remedial Response Activities - Development Process, EPA/540/6-87/003, U.S. Environmental Protection Agency Office of Emergency and Remedial Response and Office of Waste Programs Enforcement, Washington, D.C.

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Table A-1. Summary of Hanford RI/FS Drilling and Sampling Programs.

Item	NUMBER PER OPERABLE UNIT								
	100-KR-1	100-KR-4	200-BP-1	300-FF-1	300-FF-5	1100-EM-1	Low	High	Average
New Wells	-	20	11	-	31	16	11	31	20
New Boreholes	21	-	3	50	-	23	3	50	25
Soil - Phys.	210	320	~100	50	-	~241	50	320	184
Soil - Chem.	336	200	~26	600-700	40	~242	26	700	257
GW - Chem.	-	181	312	-	324	44	44	324	215

Notes: - no data or not applicable
~ approximate or estimated number

Soil-Phys. - physical tests on soil samples
Soil-Chem. - chemical and radiological analyses of soil samples
GW-Chem. - chemical and radiological analyses of groundwater samples

References: DOE (1991a, 1991b, 1990a, 1990b, 1990c, 1990d)

Table A-2. Cost Data.

CERCLA Groundwater and Vadose Zone Well Drilling with Non Haz - Non Rad Samples	$1,440/foot or $130,500/well
CERCLA Vadose Zone Well Drilling with Haz - Rad Samples	$2,850/foot or $152,100/well
Laboratory Chemical Analyses (Organics, Inorganics, with CLP deliverable[1])	$3,000 to $3,400/soil or water sample
Laboratory Radionuclide Analyses (with CLP deliv.[1])	$1,200 to 1,400/soil or water sample
Laboratory Chemistry Data Validation[2]	$300 to $400/sample
Laboratory Physical Property Tests[3]	$450 to $500/soil sample[4]

Notes:
1 - 50 day turnaround for chemical results, 100-130 day turnaround for radionuclides
2 - Validation completed within 21 days of receipt of sample results
3 - includes moisture, sieve, density, porosity, specific gravity, hydraulic conductivity; higher price includes hydrometer test.
4 - For high rad samples, costs may be up to twice that shown.

Table A-3. Monitoring Program Elements

PROGRAM ELEMENTS	COST($)	UNIT		QUANTITY/BH
Work Plan	NA	man-yr	(startup)	0
Drill/Complete New BH1s	$88,500	each	NON-RAD VADOSE	1
Drill/Complete New BH2s	$88,500	each	NON-RAD WELL	1
Drill/Complete New BH3s	$97,600	each	RAD VADOSE	1
Drill/Complete New BH4s	$97,600	each	RAD WELL	1
Mob/Demob Test Rig on Old BH1s	$0	each	NON-RAD VADOSE	0
Mob/Demob Test Rig on Old BH2s	$0	each	NON-RAD WELL	0
Mob/Demob Test Rig on Old BH3s	$0	each	RAD VADOSE	0
Mob/Demob Test Rig on Old BH4s	$0	each	RAD WELL	0
Obtain Geo1 Samples in New BHs	$2,100	each	SOIL CHEM	18
Obtain Geo2 Samples in New BHs	$4,460	each	SOIL RAD	11
Obtain Geo3 Samples in New BHs	$400	each	SOIL PHYS	0
Conduct/Anal Lab Tests (Geo1)	$3,400	each	SOIL CHEM	18
Conduct/Anal Lab Tests (Geo2)	$1,400	each	SOIL RAD	11
Conduct/Anal Lab Tests (Geo3)	$500	each	SOIL PHYS	0
Obtain WQ1 Samples in New BHs	$2,000	each	GW CHEM	1
Obtain WQ1 Samples in Old BHs	$2,000	each	GW CHEM	1
Obtain WQ2 Samples in New BHs	$2,000	each	GW RAD	1
Obtain WQ2 Samples in Old BHs	$2,000	each	GW RAD	1
Obtain WQ3 Samples in New BHs	$0	each		0
Obtain WQ3 Samples in Old BHs	$0	each		0
Conduct/Anal Lab Tests (WQ1)	$3,400	each	GW CHEM	1
Conduct/Anal Lab Tests (WQ2)	$1,400	each	GW RAD	1
Conduct/Anal Lab Tests (WQ3)	$0	each		0

APPENDIX B

BOREHOLE GEOPHYSICAL TOOLS DOCUMENTATION

CONTENTS

Appendix B Borehole Geophysical Tools Documentation

B.1 Radionuclide Logging System B-1
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The relevant attributes of the candidate BHGs have been subjectively assessed, based primarily on discussions with WHC staff, as documented below separately for each candidate BHG. In addition, and subsequently discussed, some factors are considered jointly for the various candidate BHGs.

B.1 RADIONUCLIDE LOGGING SYSTEM

Tool: Spectral Gamma Tool (Radionuclide Logging System)

Physical Basis of Measurement:

Spectral gamma techniques have been used for many years, dating back to the 1950's. Modern refinements to spectral gamma tools have greatly increased the resolution and quantitative capabilities of the spectral gamma technique. The traditional oil field application of spectral gamma logs is to identify characteristic spectral signatures of naturally occurring radiation in geologic formations, particularly shales. These characteristic signatures are then used to correlate lithologies as an aid to exploration. The spectral gamma method measures the gamma energy spectra resulting from the natural disintegration of certain radionuclides. The disintegration of radionuclides is statistically precise, such that the measured intensity of the spectra is directly related to the concentration of the gamma-emitting radionuclide. Standard spectral analyses separate the contributions from K, U, and Th series gamma rays (commonly called a KUT-series spectra), and use these ratios to "tag" geologic formations. Research at the WHC borehole geophysics program has produced a method of separating the contributions of other isotopes such as Cs, Co, and Eu, based on the standard KUT spectra.

General Description of Tool:

The tool is 3.63-inches in diameter and approximately 7 feet long. It is operated from the WHC logging truck, using quick connects so that other tools may be used with the truck. There are two gamma-ray detectors spaced approximately 6-inches apart. One detector is a high sensitivity Germanium (Ge) detector capable of very high resolution spectral response. The second detector is a standard Sodium Iodide (NaI) detector capable of moderate resolution spectral response.

The tool takes approximately 1 to 2 hours to set up over a borehole and perform field calibration checks. The tool can be deployed in a "continuous" mode at a rate of approximately 10 feet per hour, or it can be used in a "station" mode, where the tool remains stationary for a period of time at a specified interval (6-inches or more). The detection level and vertical resolution of the tool is a function of the operating mode.

Capabilities of Tool:

The tool and analysis techniques are capable of:

- Detecting gamma-emitting radionuclides including Cs, Co, Eu, Al, Am, K, U, and Th.
- Calculating actual concentrations of gamma-emitters to accuracies measured in pCi/g.
- Identifying characteristic spectra or "tags" for specific formations or lithologies (particularly clays and silts);
- Identify the distribution of gamma-emitting radionuclide away from the borehole (i.e., adhered to casing or distributed in formation) with a penetration of 1 to 1.5 feet outside the borehole casing;
- Correcting for borehole effects such as hole diameter, borehole fluid, and casing based on physical models and field trials;
- Repeatable measurements to detection accuracy.

Application of Tool At Hanford

The spectral gamma system, or RLS, has a number of potential applications including:

- Detection of gamma emitting radionuclides (such as Cs, Co, Eu) in new or existing vadose zone, or groundwater monitoring wells. In newly drilled wells (prior to well completion), the true concentration and vertical extent of radionuclides could be determined very accurately. The accuracy in existing wells will depend partly on well completion effects. The frequency of soil sampling activities in radioactive areas could be greatly reduced through the use of the RLS. Additionally, the frequency of sampling groundwater wells, and the necessity to drill additional vadose zone wells could be reduced.
- Identification and correlation of lithologies (particularly silts and clays) in new or existing vadose zone or groundwater monitoring wells. This is the typical application of spectral tools, and would provide an objective, quantitative means of identifying and correlating lithologic units at the Hanford site.

The RLS has already been developed to a relatively high level and has been tested in a number of boreholes for its ability to detect gamma-emitting radionuclides. Confirmatory laboratory results are not yet available, but the tool appears to have a demonstrated effectiveness for this application. Geologic/lithologic applications have not been field tested yet.

Factors Affecting Tool Performance:

Completion Effects

Well Casing

The effects and appropriate corrections in carbon steel cased holes have been demonstrated. The effects of PVC and stainless steel casings are likely to be similar or less than those for carbon steel. Additional calibration studies are planned for PVC casing.

Well Screen/Perforations

The effects of screen or perforations have not been demonstrated, but the effect will fall between an uncased response and a fully cased response. At low energies, the effect would be reduced by a factor of 1 to 2, while at high energies, the effect may be reduced by a factor of 4 to 6.

Hole Diameter

The minimum hole diameter is 4-inches, and the maximum hole diameter is 24-inches. Hole diameter corrections are well known.

Grout

Some grouts may contain naturally occurring gamma-emitters in the clay minerals. No corrections for grout type or thickness have yet been developed, and the magnitude of the effect is not yet known.

Sand Pack

Sand pack will have some effect on the tool response if the gamma-emitting radionuclides are present in the formation behind a sand pack. A sand pack will most likely be encountered in a water-bearing zone. If radionuclides are present in the groundwater, there would be no correction needed for the sand pack since it should contain a similar concentration of radionuclides. This ignores the effect of adsorption onto the sand pack.

Air Voids

Air voids do not affect the tool.

Water Filled Bore

The effect of a water filled borehole has not been demonstrated, and a correction for this effect has not yet been developed.

Air Filled Bore

This is the ideal borehole condition for this tool.

Formation Effects

Uniformity

The response of the tool to this parameter is a second or third order effect and is not deemed significant. Calculation of gamma-emitter concentrations are independent of the bulk density of the formation. However, characteristic spectra may be useful formation "tags" which could be used for stratigraphic correlation. Sophisticated processing techniques may enable identification of subtle changes in formation characteristics.

Cobbles/Boulders

The effect of cobbles or boulders have not been demonstrated. The technique assumes a uniform distribution of materials around the borehole, in all dimensions.

Moisture

The effect of non-gamma-emitting moisture is small, but has not been demonstrated.

Saturation

The effect of non-gamma-emitting formation saturation is small, but has not been demonstrated.

Background Effects

High concentrations of man-made waste saturate the detector and prevent quantitative interpretation. A concentration threshold has not been determined. High concentrations of Strontium-90 (a non-gamma-emitting radionuclide) can cause a Bremstrallen signal, which can be mis-interpreted as a gamma signal.

Target Compounds

Concentration

High concentrations of man-made waste saturate the detector and prevent quantitative interpretation. A concentration threshold has not been determined.

Compound Suite

High concentrations of Strontium 90 (a non gamma-emitting radionuclide) can cause a Brenstrallen signal, which can be mis-interpreted as a gamma signal.

Adhesion/Distribution

The effects of adhesion of compounds to the casing and the distribution of compounds around the borehole have not been demonstrated. Theoretically, an algorithm could be developed to identify and correct for these effects, but this would require a significant level of effort.

Tool Design

Source Type

There is no source for this tool.

Detector Type

The Germanium (Ge) and sodium-iodide (NaI) detectors are the most widely used detectors.

Detector Spacing

There is no effect caused by the spacing of detectors.

Data Processing Techniques

Raw Data

It is possible to identify the type of gamma-emitting radionuclide on-site using field data. Quantitative interpretation requires data processing.

Standard Level of Processing

Data corrections, element identification and concentration calculations are presently done by hand. Development of a standardized computer processing package is a high priority/moderate effort activity.

Sophisticated Processing

Additional processing algorithms to evaluate adhesion and formation uniformity are possible. Additional theoretical and field data are needed to develop to this level.

Availability of Other Data

Geophysical Data

No other geophysical data is necessary for interpretation.

Chemical Data

No other chemical data is necessary for interpretation. The correlation between lab chemical concentrations and geophysically calculated concentrations has not been determined.

Physical/Geologic Data

No other geologic data is necessary for interpretation. Mineralogy, water content, and density may have a small effect on calculations.

B.2 GAMMA-GAMMA DENSITY

Tool: Gamma-Gamma

Physical Basis of Measurement:

Gamma-gamma logging employs a gamma-emitting source to irradiate the formation with gamma rays and then subsequently measures back-scattered gamma-rays caused by the formation. The measurement utilizes what is called the Compton region of electron absorption energies, which insures that the measured electron density is independent of the atoms in which the electrons are bound. This, therefore enables measurement of density of most sedimentary formations, independent of its composition.

General Description:

Gamma-gamma tools vary in size and configuration depending on the application. A tool appropriate for the Hanford site would require hardware development which has not yet been carried out. Design features which would be incorporated into a Westinghouse Hanford gamma-gamma tool would include 3.6-inch diameter for use in 4-inch boreholes, multiple detector spacings with the ability to choose appropriate source-detector spacings, tool connectors compatible with the Westinghouse Hanford logging truck, gamma source suitable for logging at speeds of 2 to 5 feet per minute, and suitable shielding for a Cobalt gamma source.

Capabilities of Tool:

The tool and analysis techniques are capable of:

- Measuring relative bulk density of a formation
- Calculate porosity given estimates of grain density
- Evaluating well completion with respect to the presence and dimensions of air voids, grout, and sand pack
- Correcting for the effects of well completion (i.e. air voids, grout) to calculate true formation porosity.

Tool Application:

There are two potential applications of the gamma-gamma tool at the Hanford site:

- Determination of formation density in new wells prior to well completion
- Evaluation of the integrity of existing wells with respect to grout and air-voids.

Formation densities determined with the geophysical logging would be used in conjunction with lithologic samples collected during drilling. The required number of density tests in a given borehole could be reduced based on the application of gamma-gamma logging. Alternatively, the method of drilling could be modified to improve drilling

production (i.e., air rotary versus cable tool). Geophysical logging (gamma-gamma or spectral gamma) of rotary-drilled holes would provide an accurate determination of major lithologic contacts (i.e., Hanford/Ringold/Basalt).

There is no direct method of determining the integrity of existing wells. Gamma-gamma logging provides an excellent means of evaluating well integrity at either a qualitative or quantitative level.

Factors Affecting Tool Performance:

Completion Effects

Well Casing

Casing effects have been evaluated through computer modeling, and a range of responses for steel casings used at Hanford has been determined. PVC casing has not yet been evaluated.

Well Screen/Perforations

Well screen and perforations will have an effect intermediate between cased and uncased conditions.

Hole Diameter

Minimum hole diameter is 4 inches.

Grout

Dense grout will affect the tool response. A range of responses for grout thicknesses to 1-foot have been determined through computer modeling. Variable grout thickness in existing wells will limit the ability of the tool to identify changes in formation density.

Air Voids

Air voids have also been addressed through computer simulation and a method has been developed for identifying and quantifying the effect of air voids. The presence and distribution of air voids in existing completions may limit the ability of the tool to identify changes in formation density.

Water Filled Bore

Water-filled boreholes affect the transport of gamma energy in the borehole. Corrections for water filled boreholes must be applied.

Air Filled Bore

This is the ideal condition for this tool.

Formation Effects

Uniformity

The uniformity of the formation is a major factor in the gamma-gamma response, and is a parameter of interest for this type of measurement.

Cobbles/Boulders

Cobbles and boulders are problematic because of the large density contrast.

Moisture

The response is not sensitive to moisture in the formation

Saturation

Saturation changes the density of the formation, and therefore affects the response of the tool.

Background Effects

Background noise can be problematic in high gamma energy environments. Background can be subtracted by logging several boreholes using detectors only, and using that energy level as background.

Target Compounds

Concentration

This technique does not provide information on target compounds. High gamma energy environments will cause high background noise. Non gamma emitting elements do not affect the measurement.

Compound Suite

This technique does not provide information on target compounds. High gamma energy environments will cause high background noise. Non gamma emitting elements do not affect the measurement.

Tool Design

Source Type

A Cobalt gamma source has been identified in computer modeling studies as being superior for logging steel cased boreholes similar to those at the Hanford site. Traditional Cesium sources, used in most commercial applications, are not adequate.

Detector Type

Detector types have not been evaluated but different detectors are not likely to result in a significant improvement in tool response.

Detector Spacing

Detector spacings have been shown to have a significant effect on the tool's response under certain conditions. For example, detector spacing has been shown to have a significant effect on determining the energy at which the effect of formation density can be decoupled from the effects of an air-gap behind the casing. Field and lab studies are required to determine optimum detector spacing for different applications.

Data Processing Techniques

Raw Data

Raw gamma count data cannot be interpreted in terms of density, or location of grout, air voids, or sand pack.

Standard Level of Processing

A first level of data processing would involve algorithms that could be programmed into the acquisition hardware to determine relative density. This would allow gross identification of well completion details, and the location and magnitude of formation density changes.

Sophisticated Processing

Detailed data processing would include evaluation of grout thickness, air voids, sand pack, and casing effects, and corrections for these factors to accurately determine true formation density. Studies have shown that a spectral ratio method can provide measurement of air gap thickness up to 4-inches, and can be combined with multiple detector count rates to provide an air-gap compensated density log. However, additional work is required to determine the best implementation and processing methods to perform detailed "production" logging with this tool.

Potential Development Program

Feasibility studies on the application of gamma-gamma logging at Hanford have focused the program development needs. Existing "off-the-shelf" technology is not sufficient for application at the Hanford site. Two levels of development are possible. Either level requires a tool mock-up, software development, calibration standards, and field evaluation. An initial level of development will provide for relative density measurements and identification of well completion integrity. A comprehensive development program will provide for true density calculations in the presence of well completion effects, and detailed quantitative determination of well completion details.

B.3 NEUTRON-NEUTRON LOGGING TOOL

Tool: Neutron

Physical Basis of Measurement:

Neutron logging measures the neutron moderation properties of the formation, based on diffusion theory. Hydrogen atoms strongly affect neutron moderation and, since saturated formations are normally filled with hydrogen-rich fluids (oil or water), can be used to determine formation porosity. Neutron tools measure the count rates of emitted neutrons at an initial energy state and subsequently diffused thermal or epithermal neutrons at lower energy states. This ratio is characteristic of the diffusion length, or slowing-down length. Hydrogen atoms have a large neutron capture cross-section and can therefore "slow-down" neutrons very effectively. Neutron transport is also affected by the chemical composition of the formation. Therefore, identical measured neutron count rates in, for example, sandstone and limestone, do not indicate similar porosities. In the oil industry, corrections for lithology are applied so that a direct relationship between measured counting rates and slowing down length can be established for calculation of saturated porosity. The American Petroleum Institute calibration standard is to a Gulf Coast limestone formation.

General Description:

Neutron logs are one of the most useful logs for petroleum and hydrogeologic applications because of their sensitivity to hydrogen, which can then be related to saturated formation porosity. Quantitative interpretation of neutron logs is commonplace in the petroleum industry where theoretical and empirical correction factors have been developed for common oil-bearing formations (primarily sandstone and limestone). However, similar calibration standards have not been determined for unconsolidated sediments, which are of primary interest at the Hanford site. This does not limit the ability of the tool to detect relative porosity.

Capabilities of Tool:

The tool and analysis techniques are capable of:

- Measuring the presence and quantity of moisture in a formation
- Identifying diffuse soil moisture, percolation fronts, capillary fringe, and full formation saturation
- Measuring formation porosity of saturated formations.

Tool Application:

Neutron logging would be applied at the Hanford site to determine the porosity of saturated formations and the moisture content of unsaturated formations.

Formation porosities determined with the geophysical logging would be used in conjunction with lithologic samples collected during drilling. The required number of porosity tests in a given borehole could be reduced based on the application of neutron

logging. The application of neutron logging in existing holes will be highly dependent on the type and condition of the well completion.

Factors Affecting Tool Performance:

Completion Effects

Well Casing

Corrections for neutron moderation in steel casing are well established in oil field applications. PVC casing may have an effect due to the presence of chlorine, which has a large thermal neutron capture area.

Well Screen/Perforations

Well screen and perforations will have an effect intermediate between cased and uncased conditions.

Hole Diameter

The minimum hole diameter is 4 inches, and the maximum hole diameter is 20 inches. Hole diameter corrections are well known.

Grout

Water bound in grout will affect the measurement and will likely limit its use in grouted holes.

Sand Pack

The porosity of the surrounding sand pack will affect the measurement, but may be compensated by varying detector spacings and source strengths.

Air Voids

Air voids do not affect the tool.

Water Filled Bore

Water filled boreholes have a large effect on the response of the tool, but there are well established correction techniques for quantitative analysis.

Air Filled Bore

Appropriate for moisture content measurements, but inappropriate for porosity measurements.

Formation Effects

Uniformity

The uniformity of the formation is a major factor controlling the tool response.

Cobbles/Boulders

Cobbles and boulders are problematic because of the large porosity contrast.

Moisture

The tool is very sensitive to moisture, and should be able to detect low moisture content. A threshold moisture content has not been established.

Saturation

In saturated conditions, the tools response is a function of the amount of water within the pore spaces, and hence formation porosity.

Background Effects

Formation mineralogy or water chemistry can be important if they have significant neutron moderating characteristics (i.e., high chlorine, iron or silica). Under most conditions, hydrogen bound in water molecules controls most of the neutron moderation.

Target Compounds

Concentration

Formation mineralogy or water chemistry can be important if they have significant neutron moderating characteristics (i.e., high chlorine, iron or silica). Under most conditions, hydrogen bound in water molecules controls most of the neutron moderation.

Compound Suite

Formation mineralogy or water chemistry can be important if they have significant neutron moderating characteristics (i.e., high chlorine, iron or silica). Under most conditions, hydrogen bound in water molecules controls most of the neutron moderation.

Tool Design

Tool design could be a major factor in detailed quantitative application of neutron tools at the Hanford site.

Source Type

The type of neutron source used has a significant effect on the strength and type of neutrons bombarding the formation. An evaluation of thermal versus epithermal neutrons would be necessary to determine the sensitivity of the source type to various formation and casing conditions at the Hanford site.

Detector Type

The detector type determines whether thermal or epithermal neutrons are detected.

Detector Spacing

Detector spacing can be important in hole conditions that include a sand pack or grout. Detector spacing is also important in moisture content measurements.

Data Processing Techniques

Raw Data

Raw neutron count rate data will provide a qualitative evaluation of relative porosity under saturated conditions, and a qualitative evaluation of moisture content in unsaturated conditions. Comparison to other boreholes or sites cannot be accomplished without data processing.

Standard Level of Processing

Standard processing would involve using existing processing packages to produce American Petroleum Institute (API) standard porosity estimates. These measurements would be based on calibration standards established for API limestone pits in Houston, Texas. Corrections for well completion effects would also be carried out. The relative magnitudes of porosity changes between locations would be fairly reliable, but, because the calibration standards are based on limestone, the actual true porosity values would not be reliable.

Sophisticated Processing

Detailed processing algorithms could be developed specifically for the Hanford site which would be based on calibration standards established for Hanford sediments. Measurements based on these calibration standards would be very reliable in measuring true porosity and actual moisture content in Hanford sediments.

Potential Development Program:

Available production neutron logging tools are appropriate to apply at the Hanford site as a feasibility study for its potential application. Detailed estimates of additional development costs cannot be determined until a feasibility study has been performed, including computer evaluation of neutron source and detector effects, identifying methods for developing calibration standards and field application of existing technology at the Hanford site.

B.4 NEUTRON ACTIVATION LOGGING SYSTEM

Tool: Neutron Activation

Physical Basis of Measurement:

Neutron activation tools measure gamma energy emitted when nuclei are excited by the capture of thermal neutrons. The gamma spectra emitted via neutron activation reflect the presence of different elements with large electron capture areas such as chlorine, hydrogen, silicon, calcium, iron, and sulfur. Thermal neutron capture spectra do not contain carbon or oxygen lines. The principal limitations of the measurement are in the true determination of atom ratios because of the observed spectra are dependent on complex neutron and gamma-ray transport properties.

General Description:

Much of the information on the tool proposed for use at the Hanford site was provided by Mr. Gary Meyers who was involved in the research and development of the tool. The neutron activation tool was originally developed by ARCO, but the program was cut for budgetary reasons. It is estimated that up to $5 million was spent in the research and development of this tool. After the program was cut, several of the tool's developers formed an independent logging company and bought the tool. The tool was developed for the rugged oil exploration environment and is a highly complicated instrument containing numerous back-up modules. The tool was designed to operate for 12 hours at 100° C and has standard 7-conductor connectors suitable for integration to the Westinghouse Hanford borehole logging truck. The tool has been used in Arctic wellfields to depths of 20,000 feet. The unique feature of the tool is the Germanium detector used to measure gamma spectra. Other neutron activation tools use a standard NaI detector, which significantly limits the resolution of other tools. The Ge detector is used in the Westinghouse Hanford spectral gamma tool. The neutron activation tool can therefore be used as a high resolution spectral gamma tool by shutting off, or removing, the neutron generator. Unlike the Westinghouse Hanford system, the Ge detector for the neutron activation tool is cooled with freon and does not require a vented wireline. In addition to its ability to measure gamma spectra, the neutron activation tool can also be used as a porosity tool, similar to standard neutron-neutron logs. Therefore, the neutron activation tool is potentially the most versatile tool for the proposed applications of borehole geophysics at Hanford.

Capabilities of Tool:

The tool and analysis techniques are capable of:

- Detecting elements with large thermal neutron capture cross sections including hydrogen, chlorine, silicon, calcium, iron and sulfur. May also detect presence of elements with smaller cross-sections such as nitrogen, and sodium.

- Determining elemental concentrations based on magnitude of spectral peaks and/or data processing techniques.

- Determining porosity of formation by evaluating hydrogen spectra to determine water content for formation.

- Determining the presence and concentration of gamma-emitting radionuclides, by using the Ge detector only, and shutting off the neutron generator. The tool would then be similar to the Westinghouse Hanford RLS system.

- Identification and correlation of lithologies (particularly silts and clays) in new or existing vadose zone or groundwater monitoring wells. This is the typical application of spectral tools, and would provide an objective, quantitative means of identifying and correlating lithologic units at the Hanford site.

Tool Applications:

There are potentially three applications for the neutron activation tool:

- Identification of organic solvents, nitrate, sulfate or brine which are present in the vadose zone or groundwater

- Identification and quantification of gamma-emitting radionuclides, similar to the WHC Spectral gamma system

- Determination of relative or true porosity.

It should be recognized that the tool detects elemental concentrations, and does not detect actual compounds. Given sufficient field calibration to laboratory chemical analyses, the neutron activation tool could be used as a substitute for some percentage of sampling activities. The results would be used to infer actual concentrations between lab sample points, based on field calibration between tool response and lab analyses at a given site.

Factors Affecting Tool Performance:

Completion Effects

Well Casing

Steel casing moderates gamma energy returning from the formation, but has no effect on the neutrons transmitted from the borehole to the formation. The effects of steel casing have been addressed by petroleum well log analysts. PVC casing will have a very small effect in terms of energy moderation, but will cause a distinct chlorine spectra which is not caused by the formation.

Well Screen/Perforations

Well screen and perforations will have an effect intermediate between cased and uncased conditions. Corrections for these conditions have not been determined.

Hole Diameter

Hole diameter has a significant effect on the tool. Correction factors for the tool have been determined in accordance with the Society of Petroleum Well Log Analysts. A minimum hole depth of 100 feet is required due to the length of the tool (40 feet).

Grout

Grout could have a significant effect on the spectral response due to bound water in the grout, and other chemical characteristics of the grout.

Sand Pack

The sand pack will not affect the response of the tool unless it is applied as a neutron porosity tool.

Air Voids

Air voids have no effect on the response of the tool.

Water Filled Bore

Water-filled boreholes will have a different response than air filled boreholes in the same formation. Corrections for borehole fluid chemistry have not been determined. Presumably, however, the chemistry of the water in the borehole is related to formation water quality and is therefore of interest.

Air Filled Bore

Air-filled boreholes are the ideal condition for this tool.

Formation Effects

Uniformity

Uniformity of the formation does not have a first-order effect on the response of the tool, except for hydrogen, which would be used to determine porosity.

Cobbles/Boulders

Cobbles and boulders will have some effect on the tool response due to chemical and porosity differences.

Moisture

Moisture tends to moderate the capture of neutrons which increases the sensitivity of tool response. The tool will readily detect moisture around the borehole.

Saturation

Saturation is detected by the tool as an increase in hydrogen response. In saturated conditions, the hydrogen response is a function of formation porosity.

Background Effects

Noise caused by background gamma emitters will not likely affect the interpretation of the response. The high resolution Ge detector is sensitive enough to distinguish gamma emitting elements from other compounds of interest. If high concentrations of other neutron moderating elements, such as chlorine and iron, are present, porosity calculations based on hydrogen spectra only may be inaccurate.

Target Compounds

Concentration

The concentration of target elements is unlikely to have an effect on the tools ability to detect those elements.

Compound Suite

The suite of target elements is unlikely to have an effect on the tools ability to detect those elements, particularly when using the high resolution Ge detector.

Tool Design

The tool proposed for use is the present state-of-the-art. No additional refinements or modifications are possible at this time.

Source Type

The type of neutron source used has a significant effect on the strength and type of neutrons bombarding the formation. An evaluation of thermal versus epithermal neutrons would be necessary to determine the sensitivity of the source type to various formation and casing conditions at the Hanford site.

Detector Type

The Germanium detector is the state-of-the-art detector.

Detector Spacing

Detector spacing can be important when using the tool to determine porosity in hole conditions that include a sand pack or grout.

Data Processing Techniques

Raw Data

Raw data produced in the field consists of a calibrated energy spectra, from which the type of elements present can be determined. If count rates are sufficient and there are no overlapping spectral peaks, then the concentration can be estimated based on the "peak area" of the spectral response.

Standard Level of Processing

A first level of processing would entail corrections for neutron efficiency and simple spectral ratio evaluations of various spectra. Efficiency versus energy corrections are relatively simple, and could be incorporated in the field software. Ratio methods are potentially very powerful if there is a constant spectral signal, such as silicon, throughout the area of investigation. This "constant" signal would be used to normalize the responses of other spectra, providing for better interpretation of spectral variations with depth or location. Processing for spectral gamma applications would be similar to the requirements for the existing Westinghouse Hanford RLS system. Processing requirements for determining relative porosity would be similar to the requirements for developing a neutron-neutron tool.

Sophisticated Processing

Detailed processing entails corrections to remove the effects of casing, neutron efficiency, and received gamma energy. Lab model studies, or benchmarks, as well as computer simulations are required to develop adequate benchmarks to describe possible neutron paths and energies for detailed quantitative analysis. Advanced processing for the spectral gamma application would be similar to the requirements for the existing WHC RLS system. Advanced processing requirements for determining true porosity would be similar to the requirements for developing a neutron-neutron tool, including lab model studies and computer simulations.

Availability of Other Data

Geophysical Data

No other geophysical data is necessary for interpretation. However, confirmatory logs using standard neutron-neutron, or spectral gamma logs would be useful, depending on the application.

Chemical Data

No other chemical data is necessary for interpretation. The correlation between lab chemical concentrations and geophysically calculated concentrations has not been determined.

Physical/Geologic Data

No other geologic data is necessary for interpretation. Mineralogy, water content, and density may have a small effect on calculations.

Potential Development Program:

The available technology associated with neutron-activation logging appears sufficient to apply at the Hanford site with a minimum of initial testing or modeling. It is estimated that up to $5 million has already been invested in developing the proposed tool to its present level of application. Estimates of additional development costs cannot be determined until a feasibility study has been performed, including field application of the existing technology at the Hanford site. Recommendations regarding additional

development activities, future applications and immediate applications could be put forth after the feasibility study.

B.5 JOINT FACTORS

Several additional factors must be considered regarding the potential development and application of combinations of BHGs: development costs and success, regulatory acceptance, and technology transfer.

B.5.1 Development Costs and Success

Significant cost savings might be achieved over the combined cost of developing several BHGs independently if such development was coordinated. For example, a single test facility might be used for several BHGs. The estimated cost savings in such coordinated development of specific combinations of BHGs have been estimated to be as follows:

- combining spectral gamma tool and neutron activation tool development - no savings
- combining spectral gamma tool and gamma-gamma tool development - no savings
- combining spectral gamma tool, gamma-gamma tool, and neutron-neutron tool development - $260,000 savings
- combining spectral gamma tool, gamma-gamma tool, neutron-neutron tool and neutron activation tool - $812,000 savings.

The probability of successful development, P[S], of combinations of BHGs is a function of the P[S] of each BHG independently and any correlation among those BHGs. If it can be assumed that the P[S] of any one BHG is independent of the successful development of the other BHGs, then the P[S] of the combination of BHGs is simply the product of the P[S] for each of the BHGs. For example, the P[S] for all four candidate BHGs would be (0.9)(0.6)(0.6)(0.5) = 0.16, if they were independent with those individual P[S]'s.

The P[S] for any one BHG, in turn, can be estimated as follows:

- identify the sequence of activities <u>required</u> for successful development
- assess the probability of successful completing each critical activity, assuming that all preceding critical activities (if any) have been successfully completed.
- multiply all of the conditional probabilities of successfully completing each of the critical activities together.

This was done implicitly and subjectively in determining the following P[S] for each BHG:

- P[S] = 0.9 for spectral gamma tool
- P[S] = 0.6 for gamma-gamma tool
- P[S] = 0.6 for neutron-neutron tool
- P[S] = 0.5 for neutron activation tool

Based on these assessments, and assuming independence among development of BHGs, the P[S] for specific combinations of BHGs have been estimated to be as follows:

- Combining spectral gamma tool and neutron activation tool development - P[S] = 0.45

- Combining spectral gamma tool an l gamma-gamma tool development - P[S] = 0.54

- Combining spectral gamma tool, gamma-gamma tool, and neutron-neutron tool development - P[S] = 0.32

- Combining spectral gamma tool, gamma-gamma tool, neutron-neutron tool, and neutron activation tool - P[S] = 0.16

B.5.2 Regulatory Acceptance

Insight into the potential regulatory acceptance of BHG in the Hanford CERCLA programs was gained from discussions with EPA and Ecology personnel and from the summary of a December 1990 review meeting of the Westinghouse Hanford and Pacific Northwest Laboratory (PNL) geophysical logging activities (EPA 1991). The review meeting cover letter stated:

> "The U.S. Environmental Protection Agency (EPA) considers the use of down-hole geophysical logging to be an important tool for meeting the long-term goals of Hanford cleanup. These techniques are extremely well suited to the investigation of the unsaturated zone at Hanford, since much of the radioactive and hazardous substance inventory remains in the soil column above the water table. EPA believes that the use of geophysical logging can yield significant reductions in the overall cost of site characterization, operational monitoring, and post-closure monitoring. This capability is especially attractive since thousands of boreholes were installed to monitor liquid disposal sites and tank leaks as a standard practice. These boreholes provide access to valuable information on stratigraphy, moisture distribution, and hazardous substance and radionuclide distributions without additional drilling. Used in conjunction with core sampling, down-hole geophysics can enhance our understanding of contaminant mobility and focus sampling and analysis plans on selected constituents." (EPA 1991)

The review goes on to state:

> "The proper application of borehole geophysics has the potential to maximize the amount of information provided by new and existing Hanford Site boreholes and reduce the total amount of drilling required and, therefore, the total cost of site characterization. It should be noted, however, that geophysical logging cannot replace borehole sampling completely. Detailed borehole sample data are needed for each study area to aid log analysis. The borehole samples provide a precise analysis of physical properties, and logs--when correlated with the samples--give a high resolution vertical distribution of these properties along the borehole and a horizontal distribution of the properties in adjacent boreholes. The combination of samples and logs provides superior results that cannot be obtained by either method alone". (EPA 1991)

Regarding the WHC spectral-gamma-ray logging system, the review stated:

> "The spectral gamma logs should provide valuable site characterization information on the present distribution of radionuclides in the subsurface and should be one of the few techniques capable of providing insitu data for post-closure monitoring of remedial-action performance assessment. Post-closure monitoring is likely to be an important component of most operable unit RODs, and developing and demonstrating the capability to conduct post-closure monitoring within both the saturated and unsaturated zones should be a very high priority and fully supported activity". (EPA 1991)

The geophysical logging review (EPA 1991) stressed the need to develop an exact understanding of the gamma-gamma and neutron-neutron log response to the physical properties of the sediments on the Hanford Site through a field testing, demonstration, and development program that involved collateral geologic studies of core samples. The review concluded:

> "This activity should also conclusively determine the type and quality of data that borehole geophysics are able to yield at Hanford, and in which areas of the site we can expect successful results, thereby providing guidance to the authors and reviewers of RI/FS work plans as to how borehole geophysical techniques should be included as a site characterization tool". (EPA 1991)

The review suggested that if the geophysical logs matched the physical formation properties measured in the field test boreholes then the geophysical logs should provide acceptable and defensible results for Hanford Site remedial investigations (EPA 1991).

The geophysical logging review (EPA 1991) also indicated that neutron-activation logging can provide information on the distribution of non-gamma emitting radionuclides, such as uranium 238, carbon-14, strontium-90, and technetium-99, as well as other stable isotopes. Many other contaminants of concern at Hanford including nitrate, chromium, cadmium, copper phosphates, cyanides and other substances can be identified and quantified using neutron-activation logging. The review indicated that if neutron-activation logging can be shown to provide defensible data on the distribution of non-gamma emitting radionuclides and other contaminants of concern in the Hanford subsurface environment, a significant data need will be fulfilled (EPA 1991).

It seems apparent from the above discussion that the application of BHG in the Hanford CERCLA programs would be supported by the regulatory agencies, provided that the technology is applied by competent staff that are equipped with logging tools that are designed for specific applications and are calibrated to yield predictable and quantifiable responses to variations in physical properties. Discussions with both EPA and Ecology indicated that the regulators do not expect BHG to provide the same quality of data provided by an analytical laboratory using CLP protocols, and that the acceptance of quantitative BHG data will depend on the quality of the BHG calibration and the field verification testing. As stated during the review (EPA 1991), it appears that a combination of both BHG and laboratory analysis of samples will provide better results than can be obtained by either method alone.

The level of BHG application that may be acceptable to the regulators cannot be defined at the present time with any certainty, and will obviously depend on site-specific factors such as the type of contaminants present, the location, depth and suitability of existing boreholes in which to obtain BHG data that might provide data on the extent of contamination, how well BHGs work in specific areas of the Hanford Site, etc. However, in certain operable units within the 200 Area, EPA personnel suggested that it may be appropriate to characterize the site with 100% BHG if the nature of the wastes, the site operation that produced the wastes, and the geology are similar to other 200 Area operable units that have been characterized using traditional drilling, sampling, and laboratory analysis methods. Ecology personnel felt that the current level of sample collection and laboratory analysis could be reduced quite a bit through the use of BHG, which would provide a continuous log of the borehole environment.

The EPA and Ecology personnel also felt that the greatest benefit would be gained from BHG logging in existing boreholes which would provide data on the geology and possibly depth of potential contamination which could then be used to better select the location and depth for any new boreholes, thereby reducing the number and/or depth of new boreholes needed for site characterization. When new boreholes are drilled and sampled, BHG logging of the holes before they are completed (in the case of monitoring wells) could allow selection of soil samples to be submitted for laboratory analyses based on log response, thereby reducing the overall laboratory analytical costs.

B.5.3 Technology Transfer

It has been assumed that each BHG, if successfully developed, will be equally and independently useful at other DOE sites. Hence, on a scale of 1 to 5, successful development of any single tool has a value of 2, successful development of any pair of tools has a value of 3, successful development of any three tools has a value of 4, and successful development of all four tools has a value of 5.

ASSUMED FIELD TEST SITE REQUIREMENTS			NOTES/REFERENCES
New wells for testing	0	wells	EPA Recommendation
Existing wells for testing	0	wells	(Fassett, 1992, Pers. Comm.)
Non-geophysical costs			
Drill Borehole	$130,500	each	See Appendix A
Chemistry (Rad + Non-rad)	$4,500	sample	See Appendix A
Physical Soils Tests	$500	sample	See Appendix A
Chem Samples (new wells)	10	per/well	See Appendix A
Chem Samples (exist wells)	1	per/well	See Appendix A
Soil Samples	10	per/well	See Appendix A
Total Lab + Drilling Costs	$0		
Non-geophysical schedule			
Drilling + Sampling	0.00	yrs	See Appendix A
Lab	0.00	yrs	See Appendix A
Total Schedule	0.00	years	

SPECTRAL GAMMA TOOL			
Geophysical Application Costs			
Labor	$107,000	year	(Fassett, 1992, personal communication)
Log Borehole	$200	well	(Fassett, 1992, personal communication)
Schedule			
Logging Production Rate	30	hrs/well	(Fassett, 1992, personal communication)
Logging Evaluation/report	3	days/well	Estimate

COMPONENT	CAPITAL COST (1991 $)	LABOR COST (man-yrs)	SCHEDULE	NOTES/REFERENCES (Unless noted, all costs based on dicussions with WHC geosciences staff)
FEASIBILITY STUDIES	$0	$0		
	$0	0.00	0.00	
SYSTEM MODIFICATIONS	$0	$71,333	0.00	
Repair NaI Detector	$0	0.17	0.17	Back-up Ge Detector purchased
Hardware/facilities	$0	0.00	0.00	
Software	$0	0.50	0.50	Production and deconvolution dvlpmnt
SYSTEM CALIBRATION	$0	$37,450	0.35	
Add'l Calibration Studies	$0	0.10	0.10	Trip to complete calibration studies
Reports	$0	0.25	0.25	Final Calibration Report
FIELD STUDIES	$0	$26,750	0.25	
Non-geophysical	$0	0.00	0.00	See test site program
Geophysical Logging	$0	0.00	0.00	Log new wells prior and after well completion
System Modifications	$0	0.00	0.00	None anticipated
Reports	$0	0.25	0.25	Final Reports
TOTAL DEVELOPMENT COSTS	$0	$135,533	0.60	
GRAND TOTAL	$135,533			
APPLICATION COSTS				
Cost per well (logging only)	$200	$1,543	0.03	
Cost per well (analysis)	$0	$879		
Maintenance	$8,000	$12,000	0.03	(Fassett, 1992, Personal communication)

ASSUMED FIELD TEST SITE REQUIREMENTS			NOTES/REFERENCES
New wells for testing	2	wells	EPA Recommendation
Existing wells for testing	0	wells	(Fassett, 1992, Pers. Comm.)
Non-geophysical costs			
Drill Borehole	$130,500	each	See Appendix A
Chemistry (Rad + Non-rad)	$4,500	sample	See Appendix A
Physical Soils Tests	$500	sample	See Appendix A
Chem Samples (new wells)	0	per/well	See Appendix A
Chem Samples (exist wells)	0	per/well	See Appendix A
Soil Samples	20	per/well	See Appendix A
Total Lab + Drilling Costs	$281,000		
Non-geophysical schedule			
Drilling + Sampling	0.12	yrs	See Appendix A
Lab	0.08	yrs	See Appendix A
Total Schedule	0.12	years	

GAMMA-GAMMA TOOL			
Geophysical Application Costs			
Labor	$107,000	year	(Fassett, 1992, personal communication)
Log Borehole	$200	well	(Fassett, 1992, personal communication)
Schedule			
Logging Production Rate	10	hrs/well	(Fassett, 1992, personal communication)
Logging Evaluation/report	1	days/well	Estimate

COMPONENT	CAPITAL COST (1991 $)	LABOR COST (man-yrs)	SCHEDUL	NOTES/REFERENCES (Unless noted, all costs based on dicussions with WHC geosciences staff)
FEASIBILITY STUDIES	$0	$0	0.00	
	$0	0.00	0.00	
SYSTEM MODIFICATIONS	$70,000	$160,500	1.50	
Tool Mock-up	$60,000	1.00	1.00	Estimate for tool components
Hardware/facilities	$10,000	0.00	0.00	Estimate for facilities & equipment
Software	$0	0.50	0.50	Implement well completion corrections
SYSTEM CALIBRATION	$150,000	$142,667	1.33	
Build and Test Models	$150,000	1.00	1.00	(J. Hearst, 1992, pers. comm.)
Reports	$0	0.33	0.33	Calibration Report
FIELD STUDIES	$291,800	$91,224	0.85	
Non-geophysical	$281,000	0.00	0.00	See test program
Geophysical Logging	$800	0.02	0.02	Log new wells prior and after well completion
System Modifications	$10,000	0.50	0.50	Assume some modification
Reports	$0	0.33	0.33	Field Testing Report
TOTAL DEVELOPMENT COSTS	$511,800	$394,391	3.69	
GRAND TOTAL	$906,191			
APPLICATION				
Cost per well (logging only)	$200	$514	0.03	
Cost per well (analysis)	$0	$293		
Maintenance	$8,000	$12,000	0.03	(Fassett, 1992, Personal communication)

ASSUMED FIELD TEST SITE REQUIREMENTS			NOTES/REFERENCES
New wells for testing	2	wells	EPA Recommendation
Existing wells for testing	5	wells	(Fassett, 1992, Pers. Comm.)
Non-geophysical costs			
Drill Borehole	$130,500	each	See Appendix A
Chemistry (Non-rad)	$3,400	sample	See Appendix A
Physical Soils Tests	$500	sample	See Appendix A
Chem Samples (new wells)	10	per/well	See Appendix A
Chem Samples (exist wells)	1	per/well	See Appendix A
Soil Samples	10	per/well	See Appendix A
Total Lab + Drilling Costs	$356,000		
Non-geophyical schedule			
Drilling + Sampling	0.16	yrs	See Appendix A
Lab	0.14	yrs	See Appendix A
Total Schedule	0.16	years	

NEUTRON-NEUTRON TOOL			
Geophysical Application Costs			
Labor	$107,000	year	(Fassett, 1992, personal communication)
Log Borehole	$200	well	(Fassett, 1992, personal communication)
Schedule			
Logging Production Rate	10	hrs/well	Estimate
Logging Evaluation/report	2	days/well	Estimate

COMPONENT	CAPITAL COST (1991 $)	LABOR COST (man-yrs)	SCHEDUL	NOTES/REFERENCES (Unless noted, all costs based on dicussions with WHC geosciences staff)
FEASIBILITY STUDIES	$30,000	$21,400		
	$30,000	0.20	0.20	Feasibility using existing technology
SYSTEM MODIFICATIONS	$65,000	$160,500	1.50	
Tool Mock-up	$60,000	1.00	1.00	Assume tool modification necessary
Hardware/facilities	$5,000	0.00	0.00	
Software	$0	0.50	0.50	Neutron transport modeling
SYSTEM CALIBRATION	$150,000	$142,667	1.33	
Build and Test Models	$150,000	1.00	1.00	(J. Hearst, 1992, pers. comm.)
Reports	$0	0.33	0.33	Calibration Report
FIELD STUDIES	$362,800	$93,440	0.87	
Non-geophysical	$356,000	0.00	0.00	See test program
Geophysics	$1,800	0.04	0.04	Log new wells prior and after well completion
System Modifications	$5,000	0.50	0.50	Assume some modifications
Reports	$0	0.33	0.33	Field Testing Report
TOTAL DEVELOPMENT COSTS	$607,800	$418,006	3.71	
GRAND TOTAL	$1,025,806			
APPLICATION				
Cost per well (logging only)	$200	$514	0.03	
Cost per well (analysis)	$0	$586		
Maintenance	$8,000	$12,000	0.03	(Fassett, 1992, Personal communication)

ASSUMED FIELD TEST SITE REQUIREMENTS			NOTES/REFERENCES
New wells for testing	2	wells	EPA Recommendation
Existing wells for testing	0	wells	(Fassett, 1992, Pers. Comm.)
Non-geophysical costs			
Drill Borehole	$130,500	each	See Appendix A
Chemistry (Rad + Non-rad)	$4,500	sample	See Appendix A
Physical Soils Tests	$500	sample	See Appendix A
Chem Samples (new wells)	10	per/well	See Appendix A
Chem Samples (exist wells)	1	per/well	See Appendix A
Soil Samples	10	per/well	See Appendix A
Total Lab + Drilling Costs	$361,000		
Non-geophysical schedule			
Drilling + Sampling	0.12	yrs	See Appendix A
Lab	0.14	yrs	See Appendix A
Total Schedule	0.14	years	

NEUTRON ACTIVATION TOOL			
Geophysical Application Costs			
Labor	$135,000	year	(Fassett, personal communication)
Log Borehole	$2,000	per well	Estimated Outside Contractor Cost
Schedule			
Logging Production Rate	10	hrs/well	Estimate
Logging Evaluation/report	2	days/well	Estimate

COMPONENT	CAPITAL COST (1991 $)	LABOR COST (man-yrs)	SCHEDUL	NOTES/REFERENCES (Unless noted, all costs based on dicussions with WHC geosciences staff)
FEASIBILITY STUDIES	$30,000	$27,000		
	$30,000	0.20	0.20	Feasibility w/existing technology
SYSTEM MODIFICATIONS	$0	$27,000	0.20	
Tool Mock-up	$0	0.00	0.00	Assume contractor tools sufficient
Hardware/facilities	$0	0.00	0.00	No Modifications
Software	$0	0.20	0.20	Minor software modifications
SYSTEM CALIBRATION	$150,000	$180,000	1.33	
Build and Test Models	$150,000	1.00	1.00	(J. Hearst, 1992, pers. comm.)
Reports	$0	0.33	0.33	Calibration Report
FIELD STUDIES	$361,000	$47,596	0.35	
Non-geophysical	$361,000	0.00	0.00	See test program
Geophysics	$0	0.02	0.02	Log new wells prior and after well completion
System Modifications	$0	0.00	0.00	
Reports	$0	0.33	0.33	Field Testing Report
TOTAL DEVELOPMENT COSTS	$541,000	$281,596	1.89	
GRAND TOTAL	$822,596			
APPLICATION				
Cost per well (logging only)	$200	$649	0.03	
Cost per well (analysis)	$0	$740		
Maintenance	$8,000	$12,000	0.03	(Fassett, 1992, Personal communication)

SPECTRAL GAMMA TOOL

SCORING CHARACTERISTICS		CATEGORY DEFINITION
Not applicable	1	1 Grouted/Existing Borehole
Applicable/poor data quality	2	2 New or Ideal Borehole (i.e. Vadose borehole)
Applicable/moderate data quality	3	
Ideal/good data quality	4	
Ideal/Excellent data quality	5	

DATA NEEDS EVALUATION	Category 1	Category 2	Notes
VADOSE ZONE			
GEOLOGY			
Lithology	2	4	
Physical Character	1	1	
Uniformity	1	3	
PHYSICAL PROPERTIES			
Permeability	1	1	
Porosity	1	1	
Density	1	1	
Moisture	1	2/1	
Grain Size	1	1	
CONTAMINATION TYPE			
Radionuclides (emitting)	5/2	5/5	Detect/Quantify
Radionuclides (non-emitting)	1	1	
Organics	1	2/2	
Inorganics	1	1	
FLUX TESTS			
Radionuclides (emitting)	5/2	5/5	Detect/Quantify
Radionuclides (non-emitting)	1	1	
Organics	1	2/2	
Inorganics	1	1	
CONTAMINANT EXTENT			
Vertical	5/2	5/5	
Horizontal	2	2	
HYDROGEOLOGY/GROUNDWATER			
GEOLOGY			
Lithology	1	4	
Physical Character	1	1	
Uniformity	1	3	
PHYSICAL PROPERTIES			
Density	1	1	
Grain Size	1	1	
HYDRAULIC PROPERTIES			
Permeability	1	1	
Porosity	1	4	
CONTAMINATION TYPE			
Radionuclides (emitting)	5/2	5/5	Detect/Quantify
Radionuclides (non-emitting)	1	1	
Organics	1	4/2	
Inorganics	1	1	

SPECTRAL GAMMA TOOL

SCORING CHARACTERISTICS		CATEGORY DEFINITION	
Not applicable	1	1	Grouted/Existing Borehole
Applicable/poor data quality	2	2	New or Ideal Borehole (i.e. Vadose borehole)
Applicable/moderate data quality	3		
Ideal/good data quality	4		
Ideal/Excellent data quality	5		

DATA NEEDS EVALUATION	Category 1	Category 2	Notes
FLUX TESTS			
Radionuclides (emitting)	5/2	5/5	Detect/Quantify
Radionuclides (non-emitting)	1	1	
Organics	1	4/2	
Inorganics	1	1	
CONTAMINANT EXTENT			
Vertical	1	3	
Horizontal	1	2	
SOLUTE RETARDATION			
Radionuclides (emitting)	5/2	5/5	Detect/Quantify
Radionuclides (non-emitting)	1	1	
Organics	1	4/2	
Inorganics	1	1	
OPERATIONAL/POST-CLOSURE MONITORING			
VADOSE ZONE - CONTAMINATION TYPE			
Radionuclides (emitting)	5/2	5/5	Detect/Quantify
Radionuclides (non-emitting)	1	1	
Organics	1	4/2	
Inorganics	1	1	
GROUNDWATER - CONTAMINATION TYPE			
Radionuclides (emitting)	5/2	5/5	Detect/Quantify
Radionuclides (non-emitting)	1	1	
Organics	1	4/2	
Inorganics	1	1	

GAMMA–GAMMA DENSITY TOOL

SCORING CHARACTERISTICS		CATEGORY DEFINITION	
Not applicable	1	1	Completion Details/Existing Well
Applicable/poor data quality	2	2	New Wells
Applicable/moderate data quality	3	3	High Gamma Environment
Ideal/good data quality	4		
Ideal/Excellent data quality	5		

DATA NEEDS EVALUATION	Category 1	2	3	Notes
VADOSE ZONE				
GEOLOGY				
Lithology	2	4	2	
Physical Character	1	1	1	
Uniformity	2	4	2	
PHYSICAL PROPERTIES				
Permeability	1	1	1	
Porosity	1	1	1	
Density	2	4	2	
Moisture	1	1	1	
Grain Size	1	1	1	
CONTAMINATION TYPE				
Radionuclides (emitting)	1	1	1	
Radionuclides (non–emitting)	1	1	1	
Organics	1	1	1	
Inorganics	1	1	1	
FLUX TESTS				
Radionuclides (emitting)	1	1	1	
Radionuclides (non–emitting)	1	1	1	
Organics	1	1	1	
Inorganics	1	1	1	
CONTAMINANT EXTENT				
Vertical	1	1	1	
Horizontal	1	1	1	
HYDROGEOLOGY/GROUNDWATER				
GEOLOGY				
Lithology	2	4	2	
Physical Character	1	1	1	
Uniformity	2	4	2	
PHYSICAL PROPERTIES				
Density	2	4	2	
Grain Size	1	1	1	
HYDRAULIC PROPERTIES				
Permeability	1	1	1	
Porosity	1	3	2	
CONTAMINATION TYPE				
Radionuclides (emitting)	1	1	1	Detect/Quantify
Radionuclides (non–emitting)	1	1	1	
Organics	1	1	1	
Inorganics	1	1	1	

GAMMA–GAMMA DENSITY TOOL

SCORING CHARACTERISTICS		CATEGORY DEFINITION
Not applicable	1	1 Completion Details/Existing Well
Applicable/poor data quality	2	2 New Wells
Applicable/moderate data quality	3	3 High Gamma Environment
Ideal/good data quality	4	
Ideal/Excellent data quality	5	

DATA NEEDS EVALUATION	Category 1	2	3	Notes
FLUX TESTS				
Radionuclides (emitting)	1	1	1	Detect/Quantify
Radionuclides (non–emitting)	1	1	1	
Organics	1	1	1	
Inorganics	1	1	1	
CONTAMINANT EXTENT				
Vertical	1	1	1	
Horizontal	1	1	1	
SOLUTE RETARDATION				
Radionuclides (emitting)	1	1	1	Detect/Quantify
Radionuclides (non–emitting)	1	1	1	
Organics	1	1	1	
Inorganics	1	1	1	
OPERATIONAL/POST–CLOSURE MONITORING				
VADOSE ZONE – CONTAMINATION TYPE				
Radionuclides (emitting)	1	1	1	Detect/Quantify
Radionuclides (non–emitting)	1	1	1	
Organics	1	1	1	
Inorganics	1	1	1	
GROUNDWATER – CONTAMINATION TYPE				
Radionuclides (emitting)	1	1	1	Detect/Quantify
Radionuclides (non–emitting)	1	1	1	
Organics	1	1	1	
Inorganics	1	1	1	

NEUTRON–NEUTRON TOOL

SCORING CHARACTERISTICS	CATEGORY DEFINITION	
Not applicable	1	1 Without Feasibility/Calibration Study
Applicable/poor data quality	2	2 With Feasibility/Calibration Study
Applicable/good data quality	3	
Ideal/good data quality	4	
Ideal/Excellent data quality	5	

DATA NEEDS EVALUATION	Category 1	2
VADOSE ZONE		
GEOLOGY		
Lithology	1	1
Physical Character	1	1
Uniformity	1	1
PHYSICAL PROPERTIES		
Permeability	1	1
Porosity	1	1
Density	1	1
Moisture	3	4
Grain Size	1	1
CONTAMINATION TYPE		
Radionuclides (emitting)	1	1
Radionuclides (non–emitting)	1	1
Organics	1	2
Inorganics	1	1
FLUX TESTS		
Radionuclides (emitting)	1	1
Radionuclides (non–emitting)	1	1
Organics	1	2
Inorganics	1	1
CONTAMINANT EXTENT		
Vertical	1	3
Horizontal	1	2
HYDROGEOLOGY/GROUNDWATER		
GEOLOGY		
Lithology	1	1
Physical Character	1	1
Uniformity	1	4
PHYSICAL PROPERTIES		
Density	1	1
Grain Size	1	1
HYDRAULIC PROPERTIES		
Permeability	1	1
Porosity	4	5
CONTAMINATION TYPE		
Radionuclides (emitting)	1	1
Radionuclides (non–emitting)	1	1
Organics	1	2
Inorganics	1	1
FLUX TESTS		
Radionuclides (emitting)	1	1
Radionuclides (non–emitting)	1	1
Organics	1	2

NEUTRON–NEUTRON TOOL

SCORING CHARACTERISTICS	CATEGORY DEFINITION	
Not applicable	1	1 Without Feasibility/Calibration Study
Applicable/poor data quality	2	2 With Feasibility/Calibration Study
Applicable/good data quality	3	
Ideal/good data quality	4	
Ideal/Excellent data quality	5	

	Category	
DATA NEEDS EVALUATION	1	2
Inorganics	1	1
CONTAMINANT EXTENT		
Vertical	1	3
Horizontal	1	2
SOLUTE RETARDATION		
Radionuclides (emitting)	2	5
Radionuclides (non–emitting)	1	1
Organics	1	1
Inorganics	1	1
OPERATIONAL/POST–CLOSURE MONITORING		
VADOSE ZONE – CONTAMINATION TYPE		
Radionuclides (emitting)	1	1
Radionuclides (non–emitting)	1	1
Organics	1	2
Inorganics	1	1
GROUNDWATER – CONTAMINATION TYPE		
Radionuclides (emitting)	1	1
Radionuclides (non–emitting)	1	1
Organics	1	2
Inorganics	1	1

NEUTRON ACTIVATION TOOL

SCORING CHARACTERISTICS		CATEGORY DEFINITION
Not applicable	1	1 Grouted/Existing Borehole – No feasibility/calibration
Applicable/poor data quality	2	2 New Borehole – No feasibility/calibration
Applicable/moderate data quality	3	3 New Borehole – Feasibility/calibration
Ideal/good data quality	4	
Ideal/Excellent data quality	5	

DATA NEEDS EVALUATION	Category 1	2	3	Notes
VADOSE ZONE				
GEOLOGY				
Lithology	1	4	4	Spectral gamma mode
Physical Character	1	1	1	
Uniformity	1	3	3	Spectral gamma mode
PHYSICAL PROPERTIES				
Permeability	1	1	1	
Porosity	1	1	1	
Density	1	1	1	
Moisture	1	2/1	4/4	Detect/Quantify
Grain Size	1	1	1	
CONTAMINATION TYPE				
Radionuclides (emitting)	5/2	5/5	5/5	Detect/Quantify
Radionuclides (non–emitting)	1	1	1	
Organics	2/1	2/2	3/3	Detect/Quantify
Inorganics	1	1	1	
FLUX TESTS				
Radionuclides (emitting)	5/2	5/5	5/5	Detect/Quantify
Radionuclides (non–emitting)	1	1	1	
Organics	2/1	2/2	3/3	Detect/Quantify
Inorganics	1	1	1	
CONTAMINANT EXTENT				
Vertical	1	4/2	4/3	Radionuclide/Organics
Horizontal	1	2	2	
HYDROGEOLOGY/GROUNDWATER				
GEOLOGY				
Lithology	1	4	4	Spectral gamma mode
Physical Character	1	1	1	
Uniformity	1	3	3	Spectral gamma mode
PHYSICAL PROPERTIES				
Density	1	1	1	
Grain Size	1	1	1	
HYDRAULIC PROPERTIES				
Permeability	1	1	1	
Porosity	1	4	5	Hydrogen porosity
CONTAMINATION TYPE				
Radionuclides (emitting)	5/2	5/5	5/5	Detect/Quantify
Radionuclides (non–emitting)	1	1	1	
Organics	2/1	4/2	5/3	Detect/Quantify
Inorganics	1	1	1	

NEUTRON ACTIVATION TOOL

SCORING CHARACTERISTICS	
Not applicable	1
Applicable/poor data quality	2
Applicable/moderate data quality	3
Ideal/good data quality	4
Ideal/Excellent data quality	5

CATEGORY DEFINITION

1 Grouted/Existing Borehole – No feasibility/calibration
2 New Borehole – No feasibility/calibration
3 New Borehole – Feasibility/calibration

DATA NEEDS EVALUATION	Category 1	2	3	Notes
FLUX TESTS				
Radionuclides (emitting)	5/2	5/5	5/5	Detect/Quantify
Radionuclides (non–emitting)	1	1	1	
Organics	2/1	4/2	5/3	Detect/Quantify
Inorganics	1	1	1	
CONTAMINANT EXTENT				
Vertical	1	3	3	
Horizontal	1	2	2	
SOLUTE RETARDATION				
Radionuclides (emitting)	5/2	5/5	5/5	Detect/Quantify
Radionuclides (non–emitting)	1	1	1	
Organics	2/1	4/2	5/3	Detect/Quantify
Inorganics	1	1	1	
OPERATIONAL/POST–CLOSURE MONITORING				
VADOSE ZONE – CONTAMINATION TYPE				
Radionuclides (emitting)	5/2	5/5	5/5	Detect/Quantify
Radionuclides (non–emitting)	1	1	1	
Organics	2/1	4/2	5/3	Detect/Quantify
Inorganics	1	1	1	
GROUNDWATER – CONTAMINATION TYPE				
Radionuclides (emitting)	5/2	5/5	5/5	Detect/Quantify
Radionuclides (non–emitting)	1	1	1	
Organics	2/1	4/2	5/3	Detect/Quantify
Inorganics	1	1	1	

APPENDIX C

PROGRAM EVALUATIONS

CONTENTS

Appendix C Program Evaluations

C.1 Spreadsheet C-1
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FIGURES

C-1. Spreadsheet Critical Path Schedule Logic C-9

The costs and schedules of various potential characterization/monitoring programs, which include BHGs of different types and to various degrees, have been estimated and compared to various possible base cases. The spreadsheet for making these estimates is presented in Appendix C.1, and the results are presented in Appendix C.2. It should be noted that only the characterization part of the program has been focussed on in this study.

The estimates of "expected" costs and schedule for each of the programs, which also consider the probability of successful BHG development and contingencies if BHG development is unsuccessful, is discussed in Appendix C.3. The determination of an overall rating for each program, based on tradeoffs among the expected costs and schedule, regulatory acceptability, and potential for technology transfer, is also discussed in Appendix C.3.

C.1 SPREADSHEET

A LOTUS 1-2-3 spreadsheet has been developed to estimate the total cost and duration of each program as a function of the quantity, unit cost and duration of that program's elements, as well as the sequence of those elements and the capacity of the system to complete elements simultaneously. A common set of elements has been identified which can be combined in various ways to achieve any program of interest. The program is divided into characterization and monitoring, with the same types of elements comprising both. The unit cost and duration is specified for each element. The quantity of each element may vary among the various programs. A Base Case program is specified and alternative programs, consisting of some combination of BHG tools, are used to substitute for a specified percentage of sampling and/or boreholes assumed in the Base Case. BHG tools are only used in the alternative programs. Up to ten programs plus the Base Case can be considered simultaneously in the spreadsheet. Differences between each program and the Base Case are the focus of the evaluation.

C.1.1 Cost

The cost for the characterization part of the program is determined simply as the product of the quantity of each element and the unit cost of that element, summed over all of the possible elements. Quantities of many of the elements may be zero for some programs. Development of BHG tools is assumed only if such tools are intended to be used (whether or not such development is ultimately successful). Additional cost savings may result if more than one BHG tool is developed at the same time, depending on the specific combination of BHGs.

The cost for the monitoring part of the program is similarly determined. However, if a BHG tool was developed during characterization it is recognized that it would not be redeveloped if intended to be used during monitoring. On the other hand, if it was not developed during characterization, it would be developed during monitoring if intended to be used.

The total cost for a program is simply the summation of the cost for the two parts, characterization and monitoring. As previously noted, however, monitoring costs have not been evaluated in this study.

The difference in costs (total or for either part) between a program and the Base Case is determined simply by subtraction.

For the analyses in this study, start-up and wrap-up costs, as well as monitoring programs, were assumed to be identical for all programs. Since the difference between programs was of primary interest, these costs were assumed to be zero.

C.1.2 Duration

Only the duration of the characterization part of the program is considered, since monitoring is a subsequent and continuous activity, which is assumed not to be duration controlled. In considering the duration of this part of the Program, it is necessary to consider that the activities may occur in specific sequences and that many activities may be occurring simultaneously. Hence, the critical path must first be identified and then the durations of those activities can be determined and summed. However, the critical path may vary for different programs. Rather than evaluating each possible program in detail, several general assumptions have been made in order to reasonably approximate the critical path in the spreadsheet, as illustrated in Figure C-1 (see also Figure 5-2):

- Any critical path will include startup at the beginning and data compilation/interpretation at the end of the program. For the analyses presented in this study, start-up and wrap-up schedules were assumed to be identical for all programs. Since the difference between programs was of primary interest, these start-up and wrap-up durations were assumed to be zero.

- Various types of drill rigs will drill various types of new boreholes, possibly obtain various types of geologic and/or water quality samples, possibly conduct various types of other borehole tests and/or BHG, and then complete the borehole prior to moving to the next borehole. Assuming that each drill rig had all of the necessary equipment and there was no delay between holes, the total duration of this would equal the maximum (over the various types of boreholes) of: the number of boreholes of a specific type times the duration to accomplish everything for each borehole of that type divided by the number of drill rigs being used for that type of borehole. For example, if there were 100 Type 1 boreholes which take 0.2 years each to complete, then it would take 2 years for 10 drill rigs to complete this part of the program. If another borehole type took 5 years to complete, this drill rig/borehole type would control the duration for drilling. It has been assumed that each of the various types of geologic and water quality sampling, and each of the various types of other borehole tests, will be equally divided among the various borehole types.

It is likely, however, that the number of BHG tools will be limited and shared among drill rigs, so that this part of the operation may be delayed. Moreover, the majority of this part of the program cannot start until all of the BHG tools which will be used (if any) have been adequately developed. Also, the last lab tests and the last field test analyses will remain after the above field activities have been completed.

- At the same time, various types of test rigs will mobilize on various types of existing boreholes, possibly obtain various types of water quality samples, possibly conduct various types of other borehole tests and/or BHG, and then demobilize prior to moving to the next borehole. Assuming that each test rig had all of the necessary equipment and there was no delay between holes, the total duration of this would equal the maximum (over the various types of boreholes) of: the number of boreholes of a specific type times the duration for each borehole of that type divided by the number of test rigs being used for that type of borehole, similar to new boreholes. As for new boreholes, it has been assumed that each of the various types of geologic and water quality sampling, and each of the various other borehole tests, will be equally divided among the various borehole types. However, again it is likely that the number of BHG tools will be limited and shared among test rigs and even among drill rigs (new holes), so that this part of the operation may be delayed. Moreover, the majority of this part of the program cannot start until all of the BHG tools which will be used (if any) have been adequately developed. Also, the last lab tests and the last field test analyses will remain after the above field activities have been completed.

- Also at the same time, various types of lab tests and analyses will be conducted on the various geologic and water quality samples obtained in the field, although this might be done simultaneously in different labs. Similarly, the results of other borehole tests and BHGs will be analyzed off-site, although again this might be done simultaneously in different places. Since these can all be done simultaneously, the longest of these lab/analysis programs will govern. Assuming that they all start together and that each lab/analytical facility operates at capacity (i.e., no delay between tests/analyses), the total duration of this would equal the maximum (over all types of lab tests/analyses) of: the total number of each lab test/analysis times its duration divided by the number of such test/analyses which can be done simultaneously. However, this part of the program cannot start until the first boreholes have been drilled and samples obtained or field tests conducted, which in turn may first require development of BHGs.

- Of the three cases above, the one with the longest duration constitutes the critical path.

The difference in duration for characterization between a program and the Base Case is determined simply by subtraction.

It should be noted that BHG development and application has three components in the duration of the Program:

- The majority of the drilling, sampling, and analysis activities in the program cannot start until all of the BHG tools which will be used (if any) have been adequately developed. The duration of development is a function of the number of available BHG staff, since tool development schedules are expressed in man-years, irrespective of staffing capabilities. BHG development generally falls into two categories: hardware and software. Two staff per BHG tool, equally divided between hardware and software, was assumed. It should be noted that although

increasing the staff would reduce development time, the duration of tool development is not linearly inversely proportional to the number of staff.

- After they have been developed, it is likely that the number of BHG tools will be limited and shared among boreholes, so that final completion of each borehole (i.e., well completion) may be delayed by BHG availability.

- Application of each BHG tool consists of both borehole application and subsequent data analysis. Application of a BHG tool in a borehole is not on the same critical path as subsequent data analysis, so that borehole logging and data analysis (on a different borehole) can be carried out simultaneously. The duration of borehole application is dependent on the number of available BHG tools, whereas the duration of data analysis is a function of the number of BHG staff available (which is assumed to be the same as for development). Hence increasing the number of tools and staff capabilities reduces the duration of application and analysis activities, respectively.

C.1.3 Procedure

The following inputs are required for the spreadsheet (see Figure 5-3):

- Generic
  - Definition of the various potential elements of the program, both for characterization and monitoring
  - Unit costs ($) for each element, both for characterization and monitoring
  - Unit durations for each element, for characterization only
  - Capacity of the system to conduct each element simultaneously, for characterization only
  - Cost savings associated with developing various combinations of BHGs at the same time

- Program specific (Base Case and up to 10 Alternatives)
  - Quantities of each element, both for characterization and monitoring

Different generic factors (e.g., different number of BHG tools or different level of BHG development) require the spreadsheet to be rerun, whereas different programs with the same generic factors can be considered within a single spreadsheet.

The spreadsheet output consists of (see Figure 5-3):

- Costs (Characterization, Monitoring, Total)
  - Absolute for each program
  - Savings relative to the Base Case for each program

- Duration (Characterization)
  - Absolute for each program
  - Savings relative to the Base Case for each program

It should be noted that the spreadsheet is capable of considering the uncertainties in the output as a function of the uncertainties in the input. The uncertainty in the input

would be expressed in terms of probability distributions (possibly correlated) and the uncertainty in the output would be determined by Monte Carlo simulation using the LOTUS add-on @RISK.

It should also be noted that the spreadsheet estimates the costs and durations of specific programs, assuming that they are carried out. As discussed in Section 5.2 (Figure 5-3), although one program may be intended, its use may depend on successful development of BHG. If such development is unsuccessful, a different program (e.g., the Base Case plus development) may be implemented. Hence, the "expected" cost and duration of a test program will be a function of the cost and duration of the program if BHG is successful, the cost and duration of the program if BHG development is unsuccessful (i.e., a different program) and the probability of successful BHG development. The expected cost and duration of each program is discussed further in Section C.3.

C.2 RESULTS

Four runs of the spreadsheet were performed to evaluate the results for three different base case (Program 0) conditions, five different combinations of BHG tools, and several different application levels. The Base Case elements and quantities are based on characterization of a "typical" operable unit, as discussed in Section 3. As discussed in Section 5.1, the following conditions were used:

Run 1:

- Base Case (Program 0) equal to one "typical" operable unit
- Four drill rigs, drilling four borehole types - Vadose (Rad/Non-rad) and Wells (Rad, Non-rad)
- Total of 45 boreholes/wells
- One BHG tool per tool-type developed with 1 person per type
- Substitute various percentages of specific sampling and lab testing by BHG programs, in the same number of new boreholes.
- Lab capacity to simultaneously handle 500 soil chemistry tests, 500 soil radiation tests, 500 groundwater chemistry tests, 500 groundwater radiation tests, 100 physical properties tests and 1 slug test analysis.

Run 2:

- Base Case (Program 0) equal to five "typical" operable units
- Twenty drill rigs, drilling four borehole types - Vadose (Rad, Non-Rad) and Wells (Rad, Non-rad)
- Total of 225 boreholes/wells

- Two spectral gamma tools (WHC RLS system and neutron activation without neutron source) and one of each of the other BHG tools (gamma-gamma, neutron, and neutron activation), developed with two staff per tool type

- Substitute various percentages of specific sampling and lab testing by BHG programs, in the same number of new boreholes

- Lab capacity to simultaneously handle 500 soil chemistry tests, 500 soil radiation tests, 500 groundwater chemistry tests, 500 groundwater radiation tests, 100 physical properties tests and 1 slug test analysis.

Run 3:

- Base Case (Program 0) equal to five "typical" operable units

- Twenty drill rigs, drilling four borehole types - Vadose (Rad/Non-rad) and Wells (Rad, Non-rad)

- Total of 225 boreholes/wells

- Two spectral gamma tools (WHC RLS system and neutron activation without neutron source), and one of each of the other BHG tools (gamma-gamma, neutron, and neutron activation), developed with two people per type

- Substitute various percentages of specific sampling and lab testing by BHG programs, and substitute 30% of the new boreholes with BHG in an equal number of existing boreholes.

- Lab capacity to simultaneously handle 500 soil chemistry tests, 500 soil radiation tests, 500 groundwater chemistry tests, 500 groundwater radiation tests, 100 physical properties tests and 1 slug test analysis.

Run 4:

- Base Case (Program 0) equal to fifty "typical" operable units

- Twenty drill rigs, drilling four borehole types - Vadose (Rad, Non-rad) and wells (Rad, Non-rad)

- Total of 2250 boreholes/wells

- Two spectral gamma tools (WHC RLS system and neutron activation without neutron source) and one of each of the other BHG tools (gamma-gamma, neutron, and neutron activation), developed with two people per type.

- Substitute various percentages of specific sampling and lab testing by BHG programs, in the same number of new boreholes

- Lab capacity to simultaneously handle 500 soil chemistry tests, 500 soil radiation tests, 500 groundwater chemistry tests, 500 groundwater radiation tests, 100 physical properties tests and 1 slug test analysis.

For each run, 10 alternative programs were considered, consisting of:

- Five different combinations of BHG development:

  (1) Develop spectral gamma tool (RLS) only
  (2) Develop RLS and gamma-gamma tool
  (3) Develop RLS, gamma-gamma, and neutron tool
  (4) Develop RLS, gamma-gamma, neutron and neutron activation tool
  (5) Develop RLS, and neutron activation tool

- Two different Base Case Program modifications:

  - Replace 50% (nominal, depending on tool) of appropriate sampling/lab testing activities with BHG (5 development levels), and log an additional 10 boreholes/wells per operable unit compared to base case.

  - Replace 80% (nominal, depending on tool) of appropriate sampling/lab testing activities with BHG (5 development levels), and log an additional 10 boreholes/wells per operable unit compared to base case. It should be noted that only 52% of the soil physical property sampling/testing are replaced by either the gamma-gamma or neutron activation tool by themselves.

The unit costs and unit durations of each element presented in Section 5 (Table 5-1) were used in this analysis. The various inputs and the results, in terms of output from each individual run, is included at the end of this Appendix.

C.3 EXPECTED COSTS/SCHEDULE AND PROGRAM UTILITY

The results presented in Appendix C.2 assume that the development of each BHG program will be successful. The "expected" cost and duration for each program, incorporating the probability of successful BHG development and contingencies if BHG development is unsuccessful, has been determined as follows:

$$E[X(P)] = X(P=S) * p[P=S] + X(P=F) * \{1-p[P=S]\}$$

$E[X(P)]$ = Expected value of attribute X (cost or schedule) for Program P
$X(P=S)$ = Attribute X of program P if BHG development is successful
$X(P=F)$ = Attribute X of program P if BHG development is unsuccessful
$p[P=S]$ = Probability that BHG development will be successful

This approach assumes that the contingency for unsuccessful BHG development is re-implementation of the base case. The probability of successful BHG development has been subjectively assessed based on discussions with WHC staff and other borehole geophysical experts, as discussed in Appendix B.5. It has been conservatively assumed that <u>all</u> of the BHG tools proposed for a program must be successfully developed in order to implement that program, and otherwise <u>none</u> of the BHG tools (i.e., the Base Case program) would be used <u>after</u> the unsuccessful BHG development program had been completed. The results of the probability evaluations are included at the end of this Appendix. They show the expected cost and schedule versus the probability of successful BHG development.

An overall rating is developed for each potential program by making tradeoffs among expected cost ($), expected duration (T), technologic capability (C), and regulatory acceptance (R). Whereas expected program cost and duration are determined as discussed above, technologic capability and regulatory acceptance have been based on subjective assessments, as discussed in Appendix B.5. The attributes can be translated into individual ratings, which express the degree to which each program objective has been met (e.g., on a scale of 0 to 10), through "utility functions". The individual utility functions were developed for each factor by identifying approximately equivalent ranges of "worst possible" to "ideal" for each, i.e., there is an approximately equal preference in going from worst to best in each factor. For example, the decision maker could be indifferent between two programs where one has the worst possible cost but ideal schedule and the other has the worst possible schedule but ideal cost, everything else being equal. These ranges were simply converted to a scale of 0 (for worst possible) to 10 (for ideal). Weights can then be applied to these individual ratings to emphasize the importance of one objective over another, based on the scales used. For example, for utility functions derived as discussed above, the relative weights would all be equal. Assuming that the objectives and thus individual utility functions are independent, the overall program utility function is then calculated as:

$$U[P] = \sum_{x} W_x U_x[X(P)]$$

where
$U[P]$ = total utility of Program P
W_x = relative weight of x
$U_x[X(P)]$ = utility function of x
$X = \Delta\$, \Delta T, R, C$

The results of the utility evaluations for various sets of relative weights are included at the end of this Appendix. These results are an example only, and represent arbitrary weights applied to the different factors.

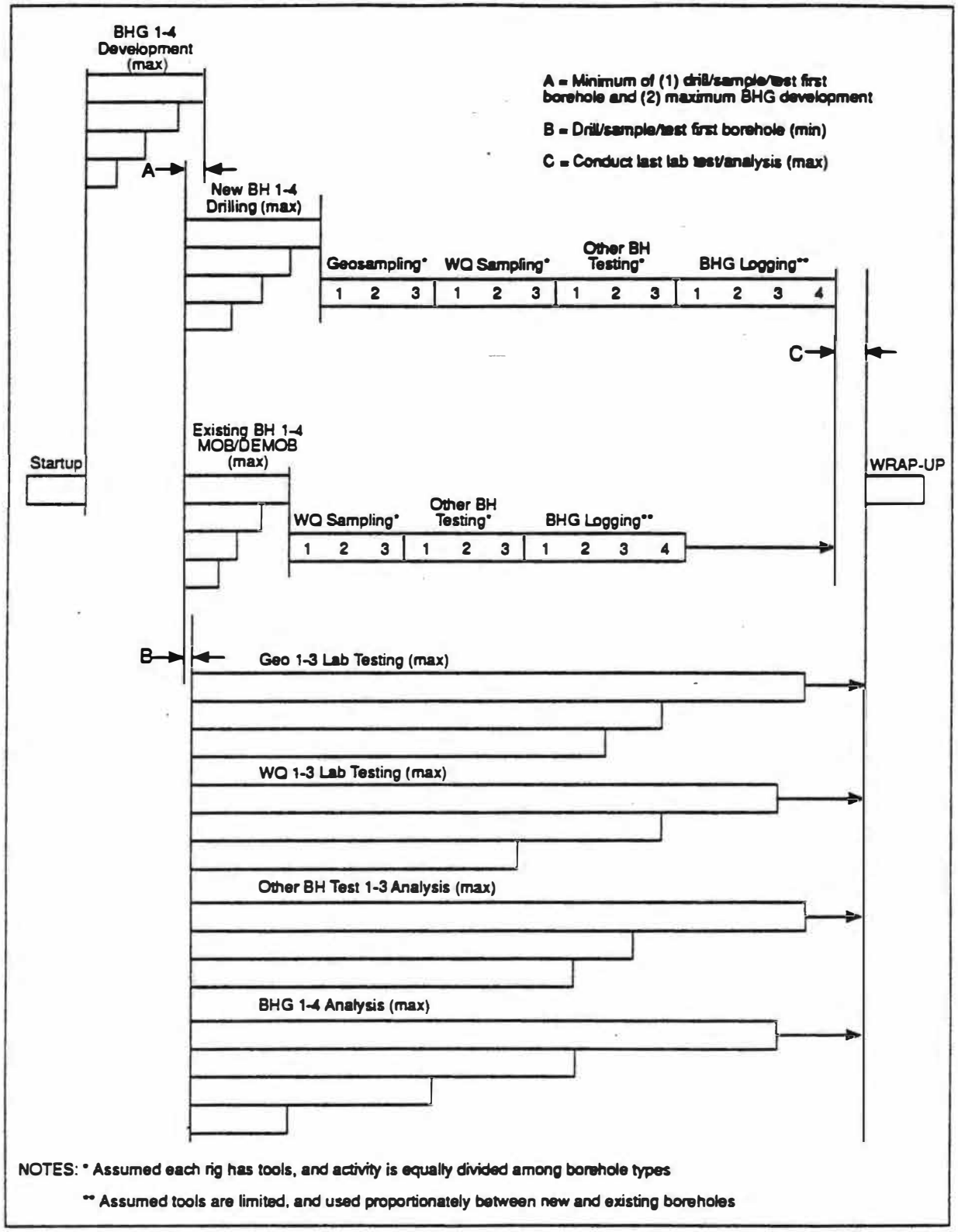

Figure C-1. Spreadsheet Critical Path Schedule Logic.

RUN 1 : BASE CASE = ONE OPERABLE UNIT

CHARACTERIZATION PROGRAMS (excluding later non-critical path monitoring)

PROGRAM ELEMENTS	COST($)	UNIT	TIME(yr)	PROGRAM:	0	1	2	3	4	5	6	7	8	9	10
				SAMPLE CHANGE	1	0.5	0.5	0.5	0.5	0.2	0.2	0.2	0.2	0.5	0.2
				BOREHOLE CHANGE	NA	1	1	1	1	1	1	1	1	1	1
Work Plan	NA	man-yr	NA	(startup)	0	0	0	0	0	0	0	0	0	0	0
Drill/Complete New BH1e	$88,500	each	0.080	N-RAD VADOSE	15	15	15	15	15	15	15	15	15	15	15
Drill/Complete New BH2e	$88,500	each	0.080	NON-RAD WELL	10	10	10	10	10	10	10	10	10	10	10
Drill/Complete New BH3e	$97,600	each	0.160	RAD VADOSE	10	10	10	10	10	10	10	10	10	10	10
Drill/Complete New BH4e	$97,600	each	0.160	RAD WELL	10	10	10	10	10	10	10	10	10	10	10
Mob/Demob Test Rig on Old BH1e	$0	each	0.000	N-RAD VADOSE	0	0	10	10	10	0	10	10	10	10	10
Mob/Demob Test Rig on Old BH2e	$0	each	0.000	NON-RAD WELL	0	0	10	10	10	0	15	10	10	10	10
Mob/Demob Test Rig on Old BH3e	$0	each	0.000	RAD VADOSE	0	10	10	10	10	10	10	10	10	10	10
Mob/Demob Test Rig on Old BH4e	$0	each	0.000	RAD WELL	0	10	10	10	10	10	10	10	10	10	10
Obtain Geo1 Samples in New BHs	$2,100	each	0.000	SOIL CHEM	126	126	126	126	63	126	126	126	26	63	26
Obtain Geo2 Samples in New BHs	$4,400	each	0.000	SOIL RAD	132	66	66	66	66	20	20	20	20	66	20
Obtain Geo3 Samples in New BHs	$400	each	0.000	SOIL PHYS	184	184	110	92	92	184	84	37	37	110	84
Conduct/Anal Lab Tests (Geo1)	$3,400	each	0.190	SOIL CHEM	126	126	126	126	63	126	126	126	26	63	26
Conduct/Anal Lab Tests (Geo2)	$1,400	each	0.410	SOIL RAD	132	66	66	66	66	20	20	20	20	66	20
Conduct/Anal Lab Tests (Geo3)	$500	each	0.080	SOIL PHYS	184	184	110	92	92	184	84	37	37	110	84
Obtain WQ1 Samples in New BHs	$2,000	each	0.003	GW CHEM	65	65	65	65	33	65	65	65	13	33	13
Obtain WQ1 Samples in Old BHs	$2,000	each	0.003	GW CHEM	64	64	64	64	32	64	64	64	13	32	13
Obtain WQ2 Samples in New BHs	$2,000	each	0.003	GW RAD	43	22	22	22	22	0	0	0	0	22	0
Obtain WQ2 Samples in Old BHs	$2,000	each	0.003	GW RAD	43	22	22	22	22	0	0	0	0	22	0
Obtain WQ3 Samples in New BHs	$0	each	0.000		0	0	0	0	0	0	0	0	0	0	0
Obtain WQ3 Samples in Old BHs	$0	each	0.000		0	0	0	0	0	0	0	0	0	0	0
Conduct/Anal Lab Tests (WQ1)	$3,400	each	0.190	GW CHEM	129	129	129	129	66	129	129	129	26	66	26
Conduct/Anal Lab Tests (WQ2)	$1,400	each	0.410	GW RAD	86	43	43	43	43	17	17	17	17	43	17
Conduct/Anal Lab Tests (WQ3)	$0	each	0.000		0	0	0	0	0	0	0	0	0	0	0
Cond Other BH1 Tests in New BHs	$2,000	per well	0.003	SLUG TEST	20	20	20	20	20	20	20	20	20	20	20
Cond Other BH1 Tests in Old BHs	$2,000	per well	0.003	SLUG TEST	10	10	10	10	10	10	10	10	10	10	10
Analyze Other BH1 Tests	$2,600	per well	0.010	SLUG TEST	30	30	30	30	30	30	30	30	30	30	30
Cond Other BH2 Tests in New BHs	$0	per well	0.000		0	0	0	0	0	0	0	0	0	0	0
Cond Other BH2 Tests in Old BHs	$0	per well	0.000		0	0	0	0	0	0	0	0	0	0	0
Analyze Other BH2 Tests	$0	per well	0.000		0	0	0	0	0	0	0	0	0	0	0
Cond Other BH3 Tests in New BHs	$0	per well	0.000		0	0	0	0	0	0	0	0	0	0	0
Cond Other BH3 Tests in Old BHs	$0	per well	0.000		0	0	0	0	0	0	0	0	0	0	0
Analyze Other BH3 Tests	$0	per well	0.000		0	0	0	0	0	0	0	0	0	0	0
Develop BHG1	$136,500	one	0.600	SPECTRAL	0	1	1	1	1	1	1	1	1	1	1
Conduct BHG1 in New BHs	$1,640	per well	0.003	SPECTRAL	0	20	20	20	20	20	20	20	20	20	20
Conduct BHG1 in Old BHs	$1,640	per well	0.003	SPECTRAL	0	20	20	20	20	20	20	20	20	20	20
Analyze BHG1	$879	per well	0.008	SPECTRAL	0	40	40	40	40	40	40	40	40	40	40
Develop BHG2	$906,000	one	3.690	AMMA-GAMMA	0	0	1	1	1	0	1	1	1	0	0
Conduct BHG2 in New BHs	$514	per well	0.001	AMMA-GAMMA	0	0	25	25	25	0	25	25	25	0	0
Conduct BHG2 in Old BHs	$514	per well	0.001	AMMA-GAMMA	0	0	20	20	20	0	20	20	20	0	0
Analyze BHG2	$586	per well	0.005	AMMA-GAMMA	0	0	45	45	45	0	45	45	45	0	0
Develop BHG3	$1,025,000	one	3.710	NEUTRON	0	0	0	1	1	0	0	1	1	0	0
Conduct BHG3 in New BHs	$514	per well	0.001	NEUTRON	0	0	0	45	45	0	0	45	45	0	0
Conduct BHG3 in Old BHs	$514	per well	0.001	NEUTRON	0	0	0	40	40	0	0	40	40	0	0
Analyze BHG3	$586	per well	0.005	NEUTRON	0	0	0	85	85	0	0	85	85	0	0
Develop BHG4	$822,600	one	1.690	ACTIVATION	0	0	0	0	1	0	0	0	1	1	1
Conduct BHG4 in New BHs	$2,650	per well	0.001	ACTIVATION	0	0	0	0	45	0	0	0	45	45	45
Conduct BHG4 in Old BHs	$2,650	per well	0.001	ACTIVATION	0	0	0	0	40	0	0	0	40	40	40
Analyze BHG4	$750	per well	0.005	ACTIVATION	0	0	0	0	85	0	0	0	85	85	85
Combine Data	NA	one	NA	(wrap-up)	0	0	0	0	0	0	0	0	0	0	0

RUN 1 : BASE CASE = ONE OPERABLE UNIT

CHARACTERIZATION PROGRAMS (excluding later non-critical path monitoring)

PROGRAM ELEMENTS	COST($)	UNIT	TIME(yr)										
				SAMPLE CHANGE	1	0.5	0.5	0.5	0.5	0.2	0.2	0.2	0.2	0.8	0.2
				BOREHOLE CHANGE	NA	1	1	1	1	1	1	1	1	1	1
				PROGRAM:	0	1	2	3	4	5	6	7	8	9	10
TOTAL CHAR PROGRAM COST (Mil $):					$6.92	$6.62	$7.51	$8.35	$8.22	$6.30	$7.17	$7.98	$7.43	$6.97	$6.22
CHANGE IN TOTAL PROGRAM COST (Mil $):						($0.30)	$0.59	$1.43	$1.30	($0.62)	$0.25	$1.06	$0.51	$0.05	($0.70)
TOTAL CHAR PROG SCHED (yrs):					2.1	2.8	6.0	6.1	6.1	2.8	5.9	6.1	6.1	4.2	4.2
CHANGE IN TOTAL PROGRAM SCHEDULE (yrs)						0.7	3.9	4.0	4.0	0.7	3.8	4.0	4.0	2.1	2.1

TOOL COMBINATIONS

PROGRAM 1, 5 Spectral Gamma Only, replaces XX% (see below) of rad analysis, add'l chem only analysis
PROGRAM 2, 6 As above (PROG 1,5), plus Gamma-gamma density tool, replacing 0.5*XX percent (see below) of physical sample analyses
PROGRAM 3, 7 As above (PROG 2,6), plus Neutron porosity tool replacing XX% (see below) of physical analyses
PROGRAM 4, 8 As above (PROG 3,7), plus neutron activation replacing XX% (see below) of chem samples
PROGRAM 9, 10 Develop spectral gamma and neutron activation only, replacing XX% of rad and chem samples (see below), and 0.5*XX percent of physical samples (porosity)

PROGRAM GROUPS

PROGRAM 0 Existing Program. No Borehole Geophysics
PROGRAMS 1,2,3,4,9 50% Reduction in sampling. Same number of boreholes/wells
PROGRAMS 5,6,7,8,10 50% Reduction in sampling. Same number of boreholes/wells

TOOL APPLICATIONS

SPECTRAL GAMMA (BHG1) Rad boreholes & wells; new or existing
GAMMA-GAMMA (BHG2) Non-rad boreholes and wells only. New only
NEUTRON-NEUTRON (BHG3) Rad & non-rad boreholes & wells; New or existing
NEUTRON ACTIVATION (BHG4) Rad & non rad boreholes and wells; new or existing

OTHER DATA

NUMBER OF SIMULT ACTS POSSIBLE

TYPE:	1	2	3	4
DRILL RIGS	1	1	1	1
TEST RIGS	1	1	1	1
GEO LABS	500	500	100	NA
WQ LABS	500	500	1	NA
OTHER ANAL	1	1	1	NA
BHG TOOLS	1	1	1	1
BHG DEVELOP/ANAL STAFF	1	1	1	1

DRILL/TEST RIG SAMPLING COMPATIBILITY (defined)

RIG:	1	2	3	4
BH	1	2	3	4
GEO	123	123	123	123
WQ	123	123	123	123
OTHER	123	123	123	123

BHG MULTI-TOOL DEVELOPMENT COS, SAVING

COMBO	14	12	123	1234
	$0	$0	$200,000	*******

RUN 1 : BASE CASE = ONE OPERABLE UNIT

CHARACTERIZATION PROGRAMS (excluding later non-critical path monitoring)

				SAMPLE CHANGE	1	0.5	0.5	0.5	0.5	0.2	0.2	0.2	0.2	0.5	0.2
				BOREHOLE CHANGE	NA	1	1	1	1	1	1	1	1	1	1
PROGRAM ELEMENTS	COST($)	UNIT	TIME(yr)	PROGRAM:	0	1	2	3	4	5	6	7	8	9	10

FACTOR	WEIGHT	PROGRAM 0	1	2	3	4	5	6	7	8	9	10
PROBABILITY OF SUCCESS		1	0.9	0.54	0.27	0.16	0.9	0.54	0.27	0.16	0.45	0.45
FAILURE COST			$7.05	$7.96	$8.72	$9.00	$7.05	$7.96	$8.72	$9.00	$9.00	$9.00
FAILURE SCHEDULE			2.706	5.706	5.816	5.816	2.706	5.706	5.816	5.816	3.006	3.006
EXPECTED COST (Mil $)		$8.92	$8.06	$7.72	$8.62	$8.87	$8.37	$7.63	$8.52	$8.75	$8.06	$7.74
EXPECTED SCHEDULE (yrs)		2.1	2.8	5.8	5.9	5.8	2.8	5.8	5.8	6.0	4.1	1.8
EXPECTED COST DIFF (Mil $)		$0.00	($0.26)	$0.90	$1.70	$1.95	($0.54)	$0.81	$1.61	$1.83	$1.17	$0.83
EXPECTED SCHEDULE DIFF (yrs)		0.0	0.7	3.8	3.8	3.8	0.7	3.8	3.8	3.8	2.0	2.0
TECHNOLOGIC CAPABILITY		1	2	3	4	5	2	3	4	5	3	3
REGULATORY ACCEPTANCE		5	4	3	3	4	4	3	3	4	4	4
	WEIGHT											
COST DIFF UTILITY	1	10.0	11.3	6.0	1.5	0.2	12.7	6.9	2.0	0.9	4.2	5.9
SCHED DIFF UTILITY	1	20.0	8.0	-55.8	-55.6	-55.3	8.2	-55.8	-55.8	-55.2	-18.5	-18.2
TECH CAP UTILITY	1	2.0	4.0	6.0	8.0	10.0	4.0	6.0	8.0	10.0	6.0	6.0
REG ACCEPT UTILITY	1	10.0	8.0	6.0	6.0	8.0	8.0	6.0	6.0	8.0	6.0	6.0
TOTAL UTILITY		42	29	-38	-40	-37	31	-37	-40	-36	-1	1

UTILITY FUNCTIONS	EQUIVALENT WORST	BEST	slope	intercept
COST DIFF UTILITY	$0.00	($2.00)	-5.0	10.0
SCHED DIFF UTILITY	0.50	0.00	-20.0	20.0
TECH CAP UTILITY	0.00	5.00	2.0	0.0
REG ACCEPT UTILITY	0.00	5.00	2.0	0.0

RUN 2 : BASE CASE = FIVE OPERABLE UNITS

CHARACTERIZATION PROGRAMS (excluding later non-critical path monitoring)

PROGRAM ELEMENTS	COST($)	UNIT	TIME(yr)	PROGRAM:	0	1	2	3	4	5	6	7	8	9	10
				SAMPLE CHANGE	5	0.5	0.5	0.5	0.5	0.2	0.2	0.2	0.2	0.5	0.2
				BOREHOLE CHANGE	NA	1	1	1	1	1	1	1	1	1	1
Work Plan	NA	man-yr	NA	(startup)	0	0	0	0	0	0	0	0	0	0	0
Drill/Complete New BH1s	$88,500	each	0.080	N-RAD VADOSE	75	75	75	75	75	75	75	75	75	75	75
Drill/Complete New BH2s	$88,500	each	0.080	NON-RAD WELL	50	50	50	50	50	50	50	50	50	50	50
Drill/Complete New BH3s	$97,600	each	0.160	RAD VADOSE	50	50	50	50	50	50	50	50	50	50	50
Drill/Complete New BH4s	$97,600	each	0.160	RAD WELL	50	50	50	50	50	50	50	50	50	50	50
Mob/Demob Test Rig on Old BH1s	$0	each	0.000	N-RAD VADOSE	0	0	50	50	50	0	50	50	50	50	50
Mob/Demob Test Rig on Old BH2s	$0	each	0.000	NON-RAD WELL	0	0	50	50	50	0	50	50	50	50	50
Mob/Demob Test Rig on Old BH3s	$0	each	0.000	RAD VADOSE	0	50	50	50	50	50	50	50	50	50	50
Mob/Demob Test Rig on Old BH4s	$0	each	0.000	RAD WELL	0	50	50	50	50	50	50	50	50	50	50
Obtain Geo1 Samples in New BHs	$2,100	each	0.000	SOIL CHEM	625	625	625	625	313	625	625	625	125	313	125
Obtain Geo2 Samples in New BHs	$4,400	each	0.000	SOIL RAD	660	330	330	330	330	132	132	132	132	330	132
Obtain Geo3 Samples in New BHs	$400	each	0.000	SOIL PHYS	920	920	552	460	460	920	442	184	184	552	442
Conduct/Anal Lab Tests (Geo1)	$3,400	each	0.190	SOIL CHEM	625	625	625	625	313	625	625	625	125	313	125
Conduct/Anal Lab Tests (Geo2)	$1,400	each	0.410	SOIL RAD	660	330	330	330	330	132	132	132	132	330	132
Conduct/Anal Lab Tests (Geo3)	$500	each	0.080	SOIL PHYS	920	920	552	460	460	920	442	184	184	552	442
Obtain WQ1 Samples in New BHs	$2,000	each	0.003	GW CHEM	325	325	325	325	163	325	325	325	65	163	65
Obtain WQ1 Samples in Old BHs	$2,000	each	0.003	GW CHEM	320	320	320	320	160	320	320	320	64	160	64
Obtain WQ2 Samples in New BHs	$2,000	each	0.003	GW RAD	215	108	108	108	108	43	43	43	43	108	43
Obtain WQ2 Samples in Old BHs	$2,000	each	0.003	GW RAD	215	108	108	108	108	43	43	43	43	108	43
Obtain WQ3 Samples in New BHs	$0	each	0.000		0	0	0	0	0	0	0	0	0	0	0
Obtain WQ3 Samples in Old BHs	$0	each	0.000		0	0	0	0	0	0	0	0	0	0	0
Conduct/Anal Lab Tests (WQ1)	$3,400	each	0.190	GW CHEM	645	645	645	645	323	645	645	645	129	323	129
Conduct/Anal Lab Tests (WQ2)	$1,400	each	0.410	GW RAD	430	215	215	215	215	86	86	86	86	215	86
Conduct/Anal Lab Tests (WQ3)	$0	each	0.000		0	0	0	0	0	0	0	0	0	0	0
Cond Other BH1 Tests in New BHs	$2,000	per well	0.003	SLUG TEST	100	100	100	100	100	100	100	100	100	100	100
Cond Other BH1 Tests in Old BHs	$2,000	per well	0.003	SLUG TEST	50	50	50	50	50	50	50	50	50	50	50
Analyze Other BH1 Tests	$2,600	per well	0.010	SLUG TEST	150	150	150	150	150	150	150	150	150	150	150
Cond Other BH2 Tests in New BHs	$0	per well	0.000		0	0	0	0	0	0	0	0	0	0	0
Cond Other BH2 Tests in Old BHs	$0	per well	0.000		0	0	0	0	0	0	0	0	0	0	0
Analyze Other BH2 Tests	$0	per well	0.000		0	0	0	0	0	0	0	0	0	0	0
Cond Other BH3 Tests in New BHs	$0	per well	0.000		0	0	0	0	0	0	0	0	0	0	0
Cond Other BH3 Tests in Old BHs	$0	per well	0.000		0	0	0	0	0	0	0	0	0	0	0
Analyze Other BH3 Tests	$0	per well	0.000		0	0	0	0	0	0	0	0	0	0	0
Develop BHG1	$135,500	one	0.600	SPECTRAL	0	1	1	1	1	1	1	1	1	1	1
Conduct BHG1 in New BHs	$1,540	per well	0.003	SPECTRAL	0	100	100	100	100	100	100	100	100	100	100
Conduct BHG1 in Old BHs	$1,540	per well	0.003	SPECTRAL	0	100	100	100	100	100	100	100	100	100	100
Analyze BHG1	$879	per well	0.008	SPECTRAL	0	200	200	200	200	200	200	200	200	200	200
Develop BHG2	$906,000	one	3.690	AMMA-GAMMA	0	0	1	1	1	0	1	1	1	0	0
Conduct BHG2 in New BHs	$514	per well	0.001	AMMA-GAMMA	0	0	125	125	125	0	125	125	125	0	0
Conduct BHG2 in Old BHs	$514	per well	0.001	AMMA-GAMMA	0	0	100	100	100	0	100	100	100	0	0
Analyze BHG2	$586	per well	0.005	AMMA-GAMMA	0	0	225	225	225	0	225	225	225	0	0
Develop BHG3	$1,025,000	one	3.710	NEUTRON	0	0	0	1	1	0	0	1	1	0	0
Conduct BHG3 in New BHs	$514	per well	0.001	NEUTRON	0	0	0	225	225	0	0	225	225	0	0
Conduct BHG3 in Old BHs	$514	per well	0.001	NEUTRON	0	0	0	200	200	0	0	200	200	0	0
Analyze BHG3	$586	per well	0.005	NEUTRON	0	0	0	425	425	0	0	425	425	0	0
Develop BHG4	$822,600	one	1.890	ACTIVATION	0	0	0	0	1	0	0	0	1	1	1
Conduct BHG4 in New BHs	$2,650	per well	0.001	ACTIVATION	0	0	0	0	225	0	0	0	225	225	225
Conduct BHG4 in Old BHs	$2,650	per well	0.001	ACTIVATION	0	0	0	0	200	0	0	0	200	200	200
Analyze BHG4	$750	per well	0.005	ACTIVATION	0	0	0	0	425	0	0	0	425	425	425
Combine Data	NA	one	NA	(wrap-up)	0	0	0	0	0	0	0	0	0	0	0

RUN 2 : BASE CASE = FIVE OPERABLE UNITS

CHARACTERIZATION PROGRAMS (excluding later non-critical path monitoring)

			SAMPLE CHANGE	5	0.5	0.5	0.5	0.5	0.2	0.2	0.2	0.2	0.5	0.2
			BOREHOLE CHANGE	NA	1	1	1	1	1	1	1	1	1	1
PROGRAM ELEMENTS	COST($)	UNIT	TIME(yr)	PROGRAM:	0	1	2	3	4	5	6	7	8	9	10
TOTAL CHAR PROGRAM COST (Mil $):					$34.59	$32.55	$33.37	$34.52	$32.77	$30.95	$31.67	$32.67	$26.85	$31.02	$27.25
CHANGE IN TOTAL PROGRAM COST (Mil $):						($2.05)	($1.22)	($0.07)	($1.82)	($3.64)	($2.92)	($1.92)	($5.74)	($3.57)	($7.34)
TOTAL CHAR PROG SCHED (yrs):					2.9	3.2	4.7	5.0	5.5	3.2	4.7	5.0	5.5	3.8	3.8
CHANGE IN TOTAL PROGRAM SCHEDULE (yrs)						0.2	1.8	2.1	2.5	0.2	1.8	2.1	2.5	0.9	0.9

TOOL COMBINATIONS

PROGRAM 1, 5 Spectral Gamma Only, replaces XX% (see below) of rad analysis, add'l chem only analysis
PROGRAM 2, 6 As above (PROG 1,5), plus Gamma-gamma density tool, replacing 0.5*XX percent (see below) of physical sample analyses
PROGRAM 3, 7 As above (PROG 2,6), plus Neutron porosity tool replacing XX% (see below) of physical analyses
PROGRAM 4, 8 As above (PROG 3,7), plus neutron activation replacing XX% (see below) of chem samples
PROGRAM 9, 10 Develop spectral gamma and neutron activation only, replacing XX% of rad and chem samples (see below), and 0.5*XX percent of physical samples (porosity)

PROGRAM GROUPS

PROGRAM 0 Existing Program. No Borehole Geophysics
PROGRAMS 1,2,3,4,9 50% Reduction in sampling. Same number of boreholes/wells
PROGRAMS 5,6,7,8,10 80% Reduction in sampling. Same number of boreholes/wells

TOOL APPLICATIONS

SPECTRAL GAMMA (BHG1) Rad boreholes & wells; new or existing
GAMMA-GAMMA (BHG2) Non-rad boreholes and wells only. New only
NEUTRON-NEUTRON (BHG3) Rad & non-rad boreholes & wells; New or existing
NEUTRON ACTIVATION (BHG4) Rad & non rad boreholes and wells; new or existing

OTHER DATA

	NUMBER OF SIMULT ACTS POSSIBLE						DRILL/TEST RIG SAMPLING COMPATIBILITY (defined)			
TYPE:	1	2	3	4	RIG:		1	2	3	4
DRILL RIGS	5	5	5	5	BH		1	2	3	4
TEST RIGS	1	1	1	1	GEO		123	123	123	123
GEO LABS	500	500	100	NA	WQ		123	123	123	123
WQ LABS	500	500	1	NA	OTHER		123	123	123	123
OTHER ANAL	1	1	1	NA	BHG MULTI-TOOL DEVELOPMENT COST SAVING					
BHG TOOLS	2	1	1	1	COMBO		14	12	123	1234
BHG DEVELOP/ANAL STAFF	2	2	2	2			$0	$0	$260,000	*******

RUN 2 : BASE CASE = FIVE OPERABLE UNITS

CHARACTERIZATION PROGRAMS (excluding later non-critical path monitoring)

				SAMPLE CHANGE	5	0.5	0.5	0.5	0.5	0.2	0.2	0.2	0.2	0.5	0.2
				BOREHOLE CHANGE	NA	1	1	1	1	1	1	1	1	1	1
PROGRAM ELEMENTS	COST($)	UNIT	TIME(yr)	PROGRAM:	0	1	2	3	4	5	6	7	8	9	10

		PROGRAM										
FACTOR		0	1	2	3	4	5	6	7	8	9	10
PROBABILITY OF SUCCESS		1	0.9	0.54	0.27	0.16	0.9	0.54	0.27	0.16	0.45	0.45
FAILURE COST			$34.73	$35.63	$36.40	$36.67	$34.73	$36.63	$36.40	$36.67	$36.67	$36.67
FAILURE SCHEDULE			3.089	3.8615	3.8665	3.8665	3.089	3.8615	3.8665	3.8665	3.4115	3.4115
EXPECTED COST (Mil $)		$34.69	$32.76	$34.41	$35.69	$36.04	$31.32	$33.49	$36.39	$35.42	$34.13	$32.43
EXPECTED SCHEDULE (yrs)		2.9	3.1	4.3	4.2	4.1	3.1	4.3	4.2	4.1	3.8	1.7
EXPECTED COST DIFF (Mil $)		$0.00	($1.93)	($0.18)	$1.30	$1.45	($3.27)	($1.10)	$0.90	$0.83	($0.46)	($2.16)
EXPECTED SCHEDULE DIFF (yrs)		0.0	0.2	1.4	1.2	1.2	0.2	1.4	1.2	1.2	0.7	0.8
TECHNOLOGIC CAPABILITY		1	2	3	4	5	2	3	4	5	3	3
REGULATORY ACCEPTANCE		5	4	3	3	4	4	3	3	4	4	4
	WEIGHT											
COST DIFF UTILITY	3	30.0	57.4	32.7	10.5	8.2	79.0	46.5	18.0	17.0	37.0	62.4
SCHED DIFF UTILITY	1	20.0	16.0	-7.8	-4.8	-3.7	18.0	-7.8	-4.7	-3.0	0.8	7.0
TECH CAP UTILITY	1	2.0	4.0	6.0	8.0	10.0	4.0	6.0	8.0	10.0	6.0	6.0
REG ACCEPT UTILITY	1	10.0	8.0	6.0	6.0	8.0	8.0	6.0	6.0	8.0	8.0	8.0
TOTAL UTILITY		62	85	37	20	22	107	51	27	32	58	83

UTILITY FUNCTIONS	EQUIVALENT WORST	BEST	slope	intercept
COST DIFF UTILITY	$0.00	($2.00)	-5.0	10.0
SCHED DIFF UTILITY	0.50	0.00	-20.0	20.0
TECH CAP UTILITY	0.00	5.00	2.0	0.0
REG ACCEPT UTILITY	0.00	5.00	2.0	0.0

RUN 2 : BASE CASE = FIVE OPERABLE UNITS

CHARACTERIZATION PROGRAMS (excluding later non-critical path monitoring)

SAMPLE CHANGE			5	0.5	0.5	0.5	0.5	0.2	0.2	0.2	0.2	0.5	0.2
BOREHOLE CHANGE			NA	1	1	1	1	1	1	1	1	1	1
PROGRAM ELEMENTS	COST($)	UNIT	TIME(yr)	PROGRAM:	0	1	2	3	4	5	6	7	8	9	10

FACTOR	WEIGHT	PROGRAM 0	1	2	3	4	5	6	7	8	9	10
PROBABILITY OF SUCCESS		1	0.9	0.54	0.27	0.18	0.9	0.54	0.27	0.18	0.45	0.45
FAILURE COST			$34.73	$35.63	$36.40	$36.67	$34.73	$35.63	$36.40	$36.67	$36.67	$36.67
FAILURE SCHEDULE			3.069	3.8615	3.8665	3.8665	3.069	3.8615	3.8665	3.8665	3.4115	3.4115
EXPECTED COST (Mil $)		$34.59	$32.76	$34.41	$35.89	$36.04	$31.32	$33.49	$35.39	$35.42	$34.13	$32.43
EXPECTED SCHEDULE (yrs)		2.8	3.1	4.3	4.2	4.1	3.1	4.3	4.2	4.1	3.8	1.7
EXPECTED COST DIFF (Mil $)		$0.00	($1.83)	($0.18)	$1.30	$1.45	($3.27)	($1.10)	$0.80	$0.83	($0.46)	($2.16)
EXPECTED SCHEDULE DIFF (yrs)		0.0	0.2	1.4	1.2	1.2	0.2	1.4	1.2	1.2	0.7	0.8
TECHNOLOGIC CAPABILITY		1	2	3	4	5	2	3	4	5	3	3
REGULATORY ACCEPTANCE		5	4	3	3	4	4	3	3	4	4	4
	WEIGHT											
COST DIFF UTILITY	1	10.0	19.1	10.8	3.5	2.7	26.3	15.5	6.0	5.8	12.3	20.6
SCHED DIFF UTILITY	1	20.0	16.0	-7.5	-4.8	-3.7	16.0	-7.5	-4.7	-3.0	0.8	7.0
TECH CAP UTILITY	1	2.0	4.0	0.0	8.0	10.0	4.0	0.0	0.0	10.0	0.0	0.0
REG ACCEPT UTILITY	1	10.0	8.0	0.0	0.0	8.0	0.0	0.0	0.0	0.0	8.0	0.0
TOTAL UTILITY		42	47	16	13	17	54	20	16	20	33	42

UTILITY FUNCTIONS	EQUIVALENT WORST	BEST	slope	intercept
COST DIFF UTILITY	$0.00	($2.00)	-5.0	10.0
SCHED DIFF UTILITY	0.50	0.00	-20.0	20.0
TECH CAP UTILITY	0.00	5.00	2.0	0.0
REG ACCEPT UTILITY	0.00	5.00	2.0	0.0

RUN 3 : BASE CASE = FIVE OPERABLE UNITS (BHG SUB FOR NEW BHs)

CHARACTERIZATION PROGRAMS (excluding later non-critical path monitoring)

PROGRAM ELEMENTS	COST($)	UNIT	TIME(yr)	PROGRAM:	0	1	2	3	4	5	6	7	8	9	10
				SAMPLE CHANGE	0	0.5	0.5	0.5	0.5	0.2	0.2	0.2	0.2	0.0	0.2
				BOREHOLE CHANGE	NA	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
Work Plan	NA	man-yr	NA	(startup)	0	0	0	0	0	0	0	0	0	0	0
Drill/Complete New BH1s	$88,500	each	0.080	N-RAD VADOSE	75	75	61	53	53	75	61	53	53	53	53
Drill/Complete New BH2s	$88,500	each	0.080	NON-RAD WELL	50	50	34	35	35	50	34	35	35	35	35
Drill/Complete New BH3s	$97,600	each	0.160	RAD VADOSE	50	35	35	35	35	35	35	35	35	35	35
Drill/Complete New BH4s	$97,600	each	0.160	RAD WELL	50	35	35	35	35	35	35	35	35	35	35
Mob/Demob Test Rig on Old BH1s	$0	each	0.000	N-RAD VADOSE	0	0	74	72.5	72.5	0	74	72.5	72.5	72.5	72.5
Mob/Demob Test Rig on Old BH2s	$0	each	0.000	NON-RAD WELL	0	0	66	65	65	0	66	65	65	65	65
Mob/Demob Test Rig on Old BH3s	$0	each	0.000	RAD VADOSE	0	65	65	65	65	65	65	65	65	65	65
Mob/Demob Test Rig on Old BH4s	$0	each	0.000	RAD WELL	0	65	65	65	65	65	65	65	65	65	65
Obtain Geo1 Samples in New BHs	$2,100	each	0.000	SOIL CHEM	625	438	438	438	219	438	438	438	68	219	68
Obtain Geo2 Samples in New BHs	$4,460	each	0.000	SOIL RAD	660	231	231	231	231	92	92	92	92	231	92
Obtain Geo3 Samples in New BHs	$400	each	0.000	SOIL PHYS	920	644	368	322	322	644	309	129	129	368	309
Conduct/Anal Lab Tests (Geo1)	$3,400	each	0.190	SOIL CHEM	625	438	438	438	219	438	438	438	68	219	68
Conduct/Anal Lab Tests (Geo2)	$1,400	each	0.410	SOIL RAD	660	231	231	231	231	92	92	92	92	231	92
Conduct/Anal Lab Tests (Geo3)	$500	each	0.080	SOIL PHYS	920	644	368	322	322	644	309	129	129	368	309
Obtain WQ1 Samples in New BHs	$2,000	each	0.003	GW CHEM	328	227	227	227	114	227	227	227	46	114	46
Obtain WQ1 Samples in Old BHs	$2,000	each	0.003	GW CHEM	320	320	320	320	160	320	320	320	64	160	64
Obtain WQ2 Samples in New BHs	$2,000	each	0.003	GW RAD	215	75	75	75	75	30	30	30	30	75	30
Obtain WQ2 Samples in Old BHs	$2,000	each	0.003	GW RAD	215	108	108	108	108	43	43	43	43	108	43
Obtain WQ3 Samples in New BHs	$0	each	0.000		0	0	0	0	0	0	0	0	0	0	0
Obtain WQ3 Samples in Old BHs	$0	each	0.000		0	0	0	0	0	0	0	0	0	0	0
Conduct/Anal Lab Tests (WQ1)	$3,400	each	0.190	GW CHEM	548	548	548	548	274	548	548	548	110	274	110
Conduct/Anal Lab Tests (WQ2)	$1,400	each	0.410	GW RAD	430	183	183	183	183	73	73	73	73	183	73
Conduct/Anal Lab Tests (WQ3)	$0	each	0.000		0	0	0	0	0	0	0	0	0	0	0
Cond Other BH1 Tests in New BHs	$2,000	per well	0.003	SLUG TEST	100	100	100	100	100	100	100	100	100	100	100
Cond Other BH1 Tests in Old BHs	$2,000	per well	0.003	SLUG TEST	50	50	50	50	50	50	50	50	50	50	50
Analyze Other BH1 Tests	$2,600	per well	0.010	SLUG TEST	150	150	150	150	150	150	150	150	150	150	150
Cond Other BH2 Tests in New BHs	$0	per well	0.000		0	0	0	0	0	0	0	0	0	0	0
Cond Other BH2 Tests in Old BHs	$0	per well	0.000		0	0	0	0	0	0	0	0	0	0	0
Analyze Other BH2 Tests	$0	per well	0.000		0	0	0	0	0	0	0	0	0	0	0
Cond Other BH3 Tests in New BHs	$0	per well	0.000		0	0	0	0	0	0	0	0	0	0	0
Cond Other BH3 Tests in Old BHs	$0	per well	0.000		0	0	0	0	0	0	0	0	0	0	0
Analyze Other BH3 Tests	$0	per well	0.000		0	0	0	0	0	0	0	0	0	0	0
Develop BHG1	$135,500	one	0.600	SPECTRAL	0	1	1	1	1	1	1	1	1	1	1
Conduct BHG1 in New BHs	$1,640	per well	0.003	SPECTRAL	0	70	70	70	70	70	70	70	70	70	70
Conduct BHG1 in Old BHs	$1,640	per well	0.003	SPECTRAL	0	130	130	130	130	130	130	130	130	130	130
Analyze BHG1	$879	per well	0.006	SPECTRAL	0	200	200	200	200	200	200	200	200	200	200
Develop BHG2	$906,000	one	3.690	AMMA-GAMMA	0	0	1	1	1	0	1	1	1	0	0
Conduct BHG2 in New BHs	$514	per well	0.001	AMMA-GAMMA	0	0	86	86	86	0	86	86	86	0	0
Conduct BHG2 in Old BHs	$514	per well	0.001	AMMA-GAMMA	0	0	140	138	138	0	140	138	138	0	0
Analyze BHG2	$586	per well	0.005	AMMA-GAMMA	0	0	225	225	225	0	225	225	225	0	0
Develop BHG3	$1,025,000	one	3.710	NEUTRON	0	0	0	1	1	0	0	1	1	0	0
Conduct BHG3 in New BHs	$514	per well	0.001	NEUTRON	0	0	0	158	158	0	0	158	158	0	0
Conduct BHG3 in Old BHs	$514	per well	0.001	NEUTRON	0	0	0	268	268	0	0	268	268	0	0
Analyze BHG3	$586	per well	0.005	NEUTRON	0	0	0	425	425	0	0	425	425	0	0
Develop BHG4	$822,600	one	1.890	ACTIVATION	0	0	0	0	1	0	0	0	1	1	1
Conduct BHG4 in New BHs	$2,650	per well	0.001	ACTIVATION	0	0	0	0	158	0	0	0	158	158	158
Conduct BHG4 in Old BHs	$2,650	per well	0.001	ACTIVATION	0	0	0	0	268	0	0	0	268	268	268
Analyze BHG4	$750	per well	0.005	ACTIVATION	0	0	0	0	425	0	0	0	425	425	425
Combine Data	NA	one	NA	(wrap-up)	0	0	0	0	0	0	0	0	0	0	0

RUN 3 : BASE CASE = FIVE OPERABLE UNITS (BHG SUB FOR NEW BHs)

CHARACTERIZATION PROGRAMS (excluding later non-critical path monitoring)

PROGRAM ELEMENTS	COST($)	UNIT	TIME(yr)	PROGRAM:	0	1	2	3	4	5	6	7	8	9	10
SAMPLE CHANGE					5	0.5	0.5	0.5	0.5	0.2	0.2	0.2	0.2	0.5	0.2
BOREHOLE CHANGE					NA	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
TOTAL CHAR PROGRAM COST (Mil $):					$34.59	$27.12	$24.50	$25.90	$24.93	$25.94	$23.25	$24.54	$21.97	$23.16	$20.29
CHANGE IN TOTAL PROGRAM COST (Mil $):						($7.47)	($10.09)	($8.69)	($9.66)	($8.65)	($11.34)	($10.05)	($12.63)	($11.43)	($14.30)
TOTAL CHAR PROG SCHED (yrs):					2.9	3.2	4.7	4.7	5.0	3.2	4.7	4.7	5.0	3.8	3.8
CHANGE IN TOTAL PROGRAM SCHEDULE (yrs)						0.2	1.8	1.8	2.0	0.2	1.8	1.8	2.0	0.9	0.9

TOOL COMBINATIONS

- PROGRAM 1, 5 — Spectral Gamma Only, replaces XX% (see below) of rad analysis, add'l chem only analysis
- PROGRAM 2, 6 — As above (PROG 1,5), plus Gamma-gamma density tool, replacing 0.5*XX percent (see below) of physical sample analyses
- PROGRAM 3, 7 — As above (PROG 2,6), plus Neutron porosity tool replacing XX% (see below) of physical analyses
- PROGRAM 4, 8 — As above (PROG 3,7), plus neutron activation replacing XX% (see below) of chem samples
- PROGRAM 9, 10 — Develop spectral gamma and neutron activation only, replacing XX% of rad and chem samples (see below), and 0.5*XX percent of physical samples (porosity)

PROGRAM GROUPS

- PROGRAM 0 — Existing Program. No Borehole Geophysics
- PROGRAMS 1,2,3,4,6 — 50% Reduction in sampling. Same number of boreholes/wells
- PROGRAMS 5,6,7,8,10 — 80% Reduction in sampling. Same number of boreholes/wells

TOOL APPLICATIONS

- SPECTRAL GAMMA (BHG1) — Rad boreholes & wells; new or existing
- GAMMA-GAMMA (BHG2) — Non-rad boreholes and wells only. New only
- NEUTRON-NEUTRON (BHG3) — Rad & non-rad boreholes & wells; New or existing
- NEUTRON ACTIVATION (BHG4) — Rad & non rad boreholes and wells; new or existing

OTHER DATA

NUMBER OF SIMULT ACTS POSSIBLE

TYPE:	1	2	3	4
DRILL RIGS	5	5	5	5
TEST RIGS	1	1	1	1
GEO LABS	500	500	100	NA
WQ LABS	500	500	1	NA
OTHER ANAL	1	1	1	NA
BHG TOOLS	2	1	1	1
BHG DEVELOP/ANAL STAFF	2	2	2	2

DRILL/TEST RIG SAMPLING COMPATIBILITY (defined)

RIG:	1	2	3	4
BH	1	2	3	4
GEO	123	123	123	123
WQ	123	123	123	123
OTHER	123	123	123	123

BHG MULTI-TOOL DEVELOPMENT COST SAVING

COMBO	14	12	123	1234
	$0	$0	$260,000	*******

RUN 3 : BASE CASE = FIVE OPERABLE UNITS (BHG SUB FOR NEW BHs)

CHARACTERIZATION PROGRAMS (excluding later non-critical path monitoring)

SAMPLE CHANGE			5	0.5	0.5	0.5	0.5	0.2	0.2	0.2	0.2	0.5	0.2
BOREHOLE CHANGE			NA	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
PROGRAM ELEMENTS	COST($)	UNIT	TIME(yr)	PROGRAM:	0	1	2	3	4	5	6	7	8	9	10

FACTOR	PROGRAM 0	1	2	3	4	5	6	7	8	9	10
PROBABILITY OF SUCCESS	1	0.9	0.54	0.27	0.16	0.9	0.54	0.27	0.16	0.45	0.45
FAILURE COST		$34.73	$35.63	$36.40	$36.67	$34.73	$35.63	$36.40	$36.67	$36.67	$36.67
FAILURE SCHEDULE		3.060	3.8615	3.8665	3.8665	3.060	3.8615	3.8665	3.8665	3.4115	3.4115
EXPECTED COST (Mil $)	$34.56	$27.88	$29.62	$33.56	$34.79	$26.82	$28.94	$33.20	$34.32	$30.60	$29.30
EXPECTED SCHEDULE (yrs)	2.9	3.1	4.3	4.1	4.0	3.1	4.3	4.1	4.0	3.6	1.7
EXPECTED COST DIFF (Mil $)	$0.00	($6.71)	($4.97)	($1.03)	$0.20	($7.76)	($5.66)	($1.36)	($0.26)	($4.00)	($5.29)
EXPECTED SCHEDULE DIFF (yrs)	0.0	0.2	1.4	1.2	1.1	0.2	1.4	1.2	1.1	0.6	0.6
TECHNOLOGIC CAPABILITY	1	2	3	4	5	2	3	4	5	3	3
REGULATORY ACCEPTANCE	5	4	3	3	4	4	3	3	4	4	4
WEIGHT											
COST DIFF UTILITY 1	10.0	43.5	34.8	15.1	9.0	48.9	36.2	17.6	11.4	30.6	36.6
SCHED DIFF UTILITY 1	20.0	15.9	-7.6	-3.1	-2.1	16.9	-7.6	-3.1	-2.1	7.1	7.1
TECH CAP UTILITY 1	2.0	4.0	6.0	8.0	10.0	4.0	6.0	8.0	10.0	6.0	6.0
REG ACCEPT UTILITY 1	10.0	8.0	6.0	6.0	8.0	8.0	6.0	6.0	8.0	6.0	6.0
TOTAL UTILITY	42	71	39	26	25	77	43	26	27	51	58

UTILITY FUNCTIONS	EQUIVALENT WORST	BEST	slope	intercept
COST DIFF UTILITY	$0.00	($2.00)	-5.0	10.0
SCHED DIFF UTILITY	0.50	0.00	-20.0	20.0
TECH CAP UTILITY	0.00	5.00	2.0	0.0
REG ACCEPT UTILITY	0.00	5.00	2.0	0.0

RUN 4 : BASE CASE = FIFTY OPERABLE UNITS

CHARACTERIZATION PROGRAMS (excluding later non-critical path monitoring)

PROGRAM ELEMENTS	COST($)	UNIT	TIME(yr)												
				SAMPLE CHANGE	50	0.5	0.5	0.5	0.5	0.2	0.2	0.2	0.2	0.5	0.2
				BOREHOLE CHANGE	NA	1	1	1	1	1	1	1	1	1	1
				PROGRAM:	0	1	2	3	4	5	6	7	8	9	10
Work Plan	NA	man-yr	NA	(startup)	0	0	0	0	0	0	0	0	0	0	0
Drill/Complete New BH1e	$88,500	each	0.080	N-RAD VADOSE	750	750	750	750	750	750	750	750	750	750	750
Drill/Complete New BH2e	$88,500	each	0.080	NON-RAD WELL	500	500	500	500	500	500	500	500	500	500	500
Drill/Complete New BH3e	$97,600	each	0.160	RAD VADOSE	500	500	500	500	500	500	500	500	500	500	500
Drill/Complete New BH4e	$97,600	each	0.160	RAD WELL	500	500	500	500	500	500	500	500	500	500	500
Mob/Demob Test Rig on Old BH1e	$0	each	0.000	N-RAD VADOSE	0	0	500	500	500	0	500	500	500	500	500
Mob/Demob Test Rig on Old BH2e	$0	each	0.000	NON-RAD WELL	0	0	500	500	500	0	500	500	500	500	500
Mob/Demob Test Rig on Old BH3e	$0	each	0.000	RAD VADOSE	0	500	500	500	500	500	500	500	500	500	500
Mob/Demob Test Rig on Old BH4e	$0	each	0.000	RAD WELL	0	500	500	500	500	500	500	500	500	500	500
Obtain Geo1 Samples in New BHs	$2,100	each	0.000	SOIL CHEM	6250	6250	6250	6250	3125	6250	6250	6250	1250	3125	1250
Obtain Geo2 Samples in New BHs	$4,460	each	0.000	SOIL RAD	6600	3300	3300	3300	3300	1320	1320	1320	1320	3300	1320
Obtain Geo3 Samples in New BHs	$400	each	0.000	SOIL PHYS	9200	9200	5520	4600	4600	9200	4410	1840	1840	5520	4410
Conduct/Anal Lab Tests (Geo1)	$3,400	each	0.190	SOIL CHEM	6250	6250	6250	6250	3125	6250	6250	6250	1250	3125	1250
Conduct/Anal Lab Tests (Geo2)	$1,400	each	0.410	SOIL RAD	6600	3300	3300	3300	3300	1320	1320	1320	1320	3300	1320
Conduct/Anal Lab Tests (Geo3)	$500	each	0.080	SOIL PHYS	9200	9200	5520	4600	4600	9200	4410	1840	1840	5520	4410
Obtain WQ1 Samples in New BHs	$2,000	each	0.003	GW CHEM	3250	3250	3250	3250	1625	3250	3250	3250	650	1625	650
Obtain WQ1 Samples in Old BHs	$2,000	each	0.003	GW CHEM	3200	3200	3200	3200	1600	3200	3200	3200	640	1600	640
Obtain WQ2 Samples in New BHs	$2,000	each	0.003	GW RAD	2150	1075	1075	1075	1075	430	430	430	430	1075	430
Obtain WQ2 Samples in Old BHs	$2,000	each	0.003	GW RAD	2150	1075	1075	1075	1075	430	430	430	430	1075	430
Obtain WQ3 Samples in New BHs	$0	each	0.000		0	0	0	0	0	0	0	0	0	0	0
Obtain WQ3 Samples in Old BHs	$0	each	0.000		0	0	0	0	0	0	0	0	0	0	0
Conduct/Anal Lab Tests (WQ1)	$3,400	each	0.190	GW CHEM	6450	6450	6450	6450	3225	6450	6450	6450	1290	3225	1290
Conduct/Anal Lab Tests (WQ2)	$1,400	each	0.410	GW RAD	4300	2150	2150	2150	2150	860	860	860	860	2150	860
Conduct/Anal Lab Tests (WQ3)	$0	each	0.000		0	0	0	0	0	0	0	0	0	0	0
Cond Other BH1 Tests in New BHs	$2,000	per well	0.003	SLUG TEST	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
Cond Other BH1 Tests in Old BHs	$2,000	per well	0.003	SLUG TEST	500	500	500	500	500	500	500	500	500	500	500
Analyze Other BH1 Tests	$2,600	per well	0.010	SLUG TEST	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500
Cond Other BH2 Tests in New BHs	$0	per well	0.000		0	0	0	0	0	0	0	0	0	0	0
Cond Other BH2 Tests in Old BHs	$0	per well	0.000		0	0	0	0	0	0	0	0	0	0	0
Analyze Other BH2 Tests	$0	per well	0.000		0	0	0	0	0	0	0	0	0	0	0
Cond Other BH3 Tests in New BHs	$0	per well	0.000		0	0	0	0	0	0	0	0	0	0	0
Cond Other BH3 Tests in Old BHs	$0	per well	0.000		0	0	0	0	0	0	0	0	0	0	0
Analyze Other BH3 Tests	$0	per well	0.000		0	0	0	0	0	0	0	0	0	0	0
Develop BHG1	$136,500	one	0.600	SPECTRAL	0	1	1	1	1	1	1	1	1	1	1
Conduct BHG1 in New BHs	$1,540	per well	0.003	SPECTRAL	0	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
Conduct BHG1 in Old BHs	$1,540	per well	0.003	SPECTRAL	0	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
Analyze BHG1	$879	per well	0.008	SPECTRAL	0	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000
Develop BHG2	$908,000	one	3.690	AMMA-GAMMA	0	0	1	1	1	0	1	1	1	0	0
Conduct BHG2 in New BHs	$514	per well	0.001	AMMA-GAMMA	0	0	1250	1250	1250	0	1250	1250	1250	0	0
Conduct BHG2 in Old BHs	$514	per well	0.001	AMMA-GAMMA	0	0	1000	1000	1000	0	1000	1000	1000	0	0
Analyze BHG2	$566	per well	0.005	AMMA-GAMMA	0	0	2250	2250	2250	0	2250	2250	2250	0	0
Develop BHG3	$1,025,000	one	3.710	NEUTRON	0	0	0	1	1	0	0	1	1	0	0
Conduct BHG3 in New BHs	$514	per well	0.001	NEUTRON	0	0	0	2250	2250	0	0	2250	2250	0	0
Conduct BHG3 in Old BHs	$514	per well	0.001	NEUTRON	0	0	0	2000	2000	0	0	2000	2000	0	0
Analyze BHG3	$566	per well	0.005	NEUTRON	0	0	0	4250	4250	0	0	4250	4250	0	0
Develop BHG4	$822,600	one	1.890	ACTIVATION	0	0	0	0	1	0	0	0	1	1	1
Conduct BHG4 in New BHs	$2,650	per well	0.001	ACTIVATION	0	0	0	0	2250	0	0	0	2250	2250	2250
Conduct BHG4 in Old BHs	$2,650	per well	0.001	ACTIVATION	0	0	0	0	2000	0	0	0	2000	2000	2000
Analyze BHG4	$750	per well	0.005	ACTIVATION	0	0	0	0	4250	0	0	0	4250	4250	4250
Combine Data	NA	one	NA	(wrap-up)	0	0	0	0	0	0	0	0	0	0	0

RUN 4 : BASE CASE = FIFTY OPERABLE UNITS

CHARACTERIZATION PROGRAMS (excluding later non-critical path monitoring)

PROGRAM ELEMENTS	COST($)	UNIT	TIME(yr)	PROGRAM:	0	1	2	3	4	5	6	7	8	9	10
SAMPLE CHANGE					50	0.5	0.5	0.5	0.5	0.2	0.2	0.2	0.2	0.5	0.2
BOREHOLE CHANGE					NA	1	1	1	1	1	1	1	1	1	1
TOTAL CHAR PROGRAM COST (Mil $):					$345.91	$324.23	$324.30	$328.91	$309.03	$308.24	$307.32	$310.44	$269.80	$301.59	$263.65
CHANGE IN TOTAL PROGRAM COST (Mil $):						($21.67)	($21.60)	($16.99)	($36.87)	($37.66)	($38.58)	($35.47)	($76.11)	($44.32)	($82.06)
TOTAL CHAR PROG SCHED (yrs):					28.6	28.8	30.3	30.4	34.5	28.8	30.3	30.4	34.3	29.4	29.4
CHANGE IN TOTAL PROGRAM SCHEDULE (yrs)						0.2	1.8	1.8	5.9	0.2	1.8	1.8	5.7	0.9	0.9

TOOL COMBINATIONS

PROGRAM 1, 5 Spectral Gamma Only, replaces XX% (see below) of rad analysis, add'l chem only analysis
PROGRAM 2, 6 As above (PROG 1,5), plus Gamma-gamma density tool, replacing 0.5*XX percent (see below) of physical sample analyses
PROGRAM 3, 7 As above (PROG 2,6), plus Neutron porosity tool replacing XX% (see below) of physical analyses
PROGRAM 4, 8 As above (PROG 3,7), plus neutron activation replacing XX% (see below) of chem samples
PROGRAM 9, 10 Develop spectral gamma and neutron activation only, replacing XX% of rad and chem samples (see below), and 0.5*XX percent of physical samples (porosity)

PROGRAM GROUPS

PROGRAM 0 Existing Program. No Borehole Geophysics
PROGRAMS 1,2,3,4,9 50% Reduction in sampling. Same number of boreholes/wells
PROGRAMS 5,6,7,8,10 50% Reduction in sampling. Same number of boreholes/wells

TOOL APPLICATIONS

SPECTRAL GAMMA (BHG1) Rad boreholes & wells; new or existing
GAMMA-GAMMA (BHG2) Non-rad boreholes and wells only. New only
NEUTRON-NEUTRON (BHG3) Rad & non-rad boreholes & wells; New or existing
NEUTRON ACTIVATION (BHG4) Rad & non rad boreholes and wells; new or existing

OTHER DATA

NUMBER OF SIMULT ACTS POSSIBLE

TYPE:	1	2	3	4	5
DRILL RIGS	5	5	5	5	1
TEST RIGS	1	1	1	1	
GEO LABS	500	500	100	NA	
WQ LABS	500	500	1	NA	
OTHER ANAL	1	1	1	NA	
BHG TOOLS	2	1	1	1	
BHG DEVELOP/ANAL STAFF	2	2	2	2	

DRILL/TEST RIG SAMPLING COMPATIBILITY (defined)

RIG:	1	2	3	4
BH	1	2	3	4
GEO	123	123	123	123
WQ	123	123	123	123
OTHER	123	123	123	123

BHG MULTI-TOOL DEVELOPMENT COST SAVING

COMBO	14	12	123	1234
	$0	$0	$260,000	*******

RUN 4 : BASE CASE = FIFTY OPERABLE UNITS

CHARACTERIZATION PROGRAMS (excluding later non-critical path monitoring)

SAMPLE CHANGE				50	0.5	0.5	0.5	0.5	0.2	0.2	0.2	0.2	0.5	0.2
BOREHOLE CHANGE				NA	1	1	1	1	1	1	1	1	1	1
PROGRAM ELEMENTS	COST($)	UNIT	TIME(yr)	PROGRAM:	0	1	2	3	4	5	6	7	8	9	10

FACTOR		PROGRAM 0	1	2	3	4	5	6	7	8	9	10
PROBABILITY OF SUCCESS		1	0.9	0.54	0.27	0.18	0.9	0.54	0.27	0.18	0.45	0.45
FAILURE COST			$346.04	$346.95	$347.71	$347.96	$346.04	$346.95	$347.71	$347.96	$347.96	$347.96
FAILURE SCHEDULE			28.730	29.5115	29.5165	29.5165	28.730	29.5115	29.5165	29.5165	29.0615	29.0615
EXPECTED COST (Mil $)		$345.91	$326.41	$334.72	$342.64	$341.75	$312.02	$325.55	$337.66	$336.47	$327.11	$310.12
EXPECTED SCHEDULE (yrs)		28.6	28.8	30.0	29.7	30.3	28.8	30.6	29.7	30.3	29.2	13.8
EXPECTED COST DIFF (Mil $)		$0.00	($19.49)	($11.19)	($3.27)	($4.16)	($33.88)	($20.36)	($8.26)	($10.43)	($18.80)	($35.79)
EXPECTED SCHEDULE DIFF (yrs)		0.0	0.2	1.4	1.2	1.7	0.2	1.4	1.2	1.7	0.6	0.6
TECHNOLOGIC CAPABILITY		1	2	3	4	5	2	3	4	5	3	3
REGULATORY ACCEPTANCE		5	4	3	3	4	4	3	3	4	4	4
	WEIGHT											
COST DIFF UTILITY	1	10.0	107.5	65.9	26.3	30.8	179.4	111.6	51.3	62.2	104.0	188.9
SCHED DIFF UTILITY	1	20.0	15.9	-7.5	-3.1	-14.6	15.9	-7.5	-3.1	-13.7	7.1	7.1
TECH CAP UTILITY	1	2.0	4.0	6.0	6.0	10.0	4.0	6.0	6.0	10.0	6.0	6.0
REG ACCEPT UTILITY	1	10.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0
TOTAL UTILITY		42	135	70	37	34	207	116	62	66	126	210

UTILITY FUNCTIONS	EQUIVALENT WORST	BEST	slope	intercept
COST DIFF UTILITY	$0.00	($2.00)	-5.0	10.0
SCHED DIFF UTILITY	0.50	0.00	-20.0	20.0
TECH CAP UTILITY	0.00	5.00	2.0	0.0
REG ACCEPT UTILITY	0.00	5.00	2.0	0.0

RUN 2 : BASE CASE = FIVE OPERABLE UNITS

CHARACTERIZATION PROGRAMS (excluding later non-critical path monitoring)

			SAMPLE CHANGE	5	0.5	0.5	0.5	0.5	0.2	0.2	0.2	0.2	0.5	0.2
			BOREHOLE CHANGE	NA	1	1	1	1	1	1	1	1	1	1
PROGRAM ELEMENTS	COST($)	UNIT	TIME(yr)	PROGRAM:	0	1	2	3	4	5	6	7	8	9	10

FACTOR		PROGRAM 0	1	2	3	4	5	6	7	8	9	10
PROBABILITY OF SUCCESS		1	0.9	0.54	0.27	0.18	0.9	0.54	0.27	0.18	0.45	0.45
FAILURE COST			$34.73	$35.63	$36.40	$36.67	$34.73	$35.63	$36.40	$36.67	$36.67	$36.67
FAILURE SCHEDULE			3.089	3.5616	3.8665	3.8665	3.089	3.5616	3.8665	3.8665	3.4116	3.4116
EXPECTED COST (Mil $)		$34.59	$32.76	$34.41	$35.69	$36.04	$31.32	$33.49	$35.39	$35.42	$34.13	$32.43
EXPECTED SCHEDULE (yrs)		2.9	3.1	4.3	4.2	4.1	3.1	4.3	4.2	4.1	3.6	1.7
EXPECTED COST DIFF (Mil $)		$0.00	($1.83)	($0.18)	$1.30	$1.45	($3.27)	($1.10)	$0.80	$0.83	($0.46)	($2.16)
EXPECTED SCHEDULE DIFF (yrs)		0.0	0.2	1.4	1.2	1.2	0.2	1.4	1.2	1.2	0.7	0.8
TECHNOLOGIC CAPABILITY		1	2	3	4	5	2	3	4	5	3	3
REGULATORY ACCEPTANCE		5	4	3	3	4	4	3	3	4	4	4
	WEIGHT											
COST DIFF UTILITY	1	10.0	19.1	10.0	3.5	2.7	26.3	15.5	8.0	5.0	12.3	20.5
SCHED DIFF UTILITY	3	60.0	47.7	-22.4	-14.3	-11.2	47.7	-22.4	-14.2	-10.6	20.4	21.0
TECH CAP UTILITY	1	2.0	4.0	6.0	8.0	10.0	4.0	6.0	8.0	10.0	6.0	6.0
REG ACCEPT UTILITY	1	10.0	8.0	6.0	6.0	8.0	8.0	6.0	6.0	8.0	8.0	8.0
TOTAL UTILITY		82	79	1	3	10	88	5	8	13	47	56

UTILITY FUNCTIONS	EQUIVALENT WORST	BEST	slope	intercept
COST DIFF UTILITY	$0.00	($2.00)	-5.0	10.0
SCHED DIFF UTILITY	0.50	0.00	-20.0	20.0
TECH CAP UTILITY	0.00	5.00	2.0	0.0
REG ACCEPT UTILITY	0.00	5.00	2.0	0.0

RUN 2 : BASE CASE = FIVE OPERABLE UNITS

CHARACTERIZATION PROGRAMS (excluding later non-critical path monitoring)

SAMPLE CHANGE			5	0.5	0.5	0.5	0.5	0.2	0.2	0.2	0.2	0.5	0.2
BOREHOLE CHANGE			NA	1	1	1	1	1	1	1	1	1	1
PROGRAM ELEMENTS	COST($)	UNIT	TIME(yr)	PROGRAM;	0	1	2	3	4	5	6	7	8	9	10

FACTOR	WEIGHT	PROGRAM 0	1	2	3	4	5	6	7	8	9	10
PROBABILITY OF SUCCESS		1	0.9	0.54	0.27	0.16	0.9	0.54	0.27	0.16	0.45	0.45
FAILURE COST			$34.73	$35.63	$36.40	$36.67	$34.73	$35.63	$36.40	$36.67	$36.67	$36.67
FAILURE SCHEDULE			3.089	3.8615	3.8665	3.8665	3.089	3.8615	3.8665	3.8665	3.4115	3.4115
EXPECTED COST (Mil $)		$34.59	$32.76	$34.41	$35.89	$36.04	$31.32	$33.49	$35.39	$35.42	$34.13	$32.43
EXPECTED SCHEDULE (yrs)		2.9	3.1	4.3	4.2	4.1	3.1	4.3	4.2	4.1	3.9	1.7
EXPECTED COST DIFF (Mil $)		$0.00	($1.83)	($0.18)	$1.30	$1.45	($3.27)	($1.10)	$0.80	$0.83	($0.46)	($2.16)
EXPECTED SCHEDULE DIFF (yrs)		0.0	0.2	1.4	1.2	1.2	0.2	1.4	1.2	1.2	0.7	0.8
TECHNOLOGIC CAPABILITY		1	2	3	4	5	2	3	4	5	3	3
REGULATORY ACCEPTANCE		5	4	3	3	4	4	3	3	4	4	4
	WEIGHT											
COST DIFF UTILITY	1	10.0	19.1	10.9	3.5	2.7	20.3	15.5	6.0	5.9	12.3	20.6
SCHED DIFF UTILITY	1	20.0	15.9	-7.5	-4.8	-3.7	15.9	-7.5	-4.7	-3.8	6.8	7.0
TECH CAP UTILITY	3	6.0	12.0	18.0	24.0	30.0	12.0	18.0	24.0	30.0	18.0	18.0
REG ACCEPT UTILITY	1	10.0	8.0	6.0	6.0	8.0	6.0	6.0	6.0	8.0	6.0	8.0
TOTAL UTILITY		46	55	27	29	37	62	32	31	40	45	54

UTILITY FUNCTIONS	EQUIVALENT WORST	BEST	slope	intercept
COST DIFF UTILITY	$0.00	($2.00)	-5.0	10.0
SCHED DIFF UTILITY	0.50	0.00	-20.0	20.0
TECH CAP UTILITY	0.00	5.00	2.0	0.0
REG ACCEPT UTILITY	0.00	5.00	2.0	0.0

RUN 2 : BASE CASE = FIVE OPERABLE UNITS

CHARACTERIZATION PROGRAMS (excluding later non-critical path monitoring)

				SAMPLE CHANGE	5	0.5	0.5	0.5	0.5	0.2	0.2	0.2	0.2	0.5	0.2
				BOREHOLE CHANGE	NA	1	1	1	1	1	1	1	1	1	1
PROGRAM ELEMENTS	COST($)	UNIT	TIME(yr)	PROGRAM:	0	1	2	3	4	5	6	7	8	9	10

FACTOR		PROGRAM 0	1	2	3	4	5	6	7	8	9	10
PROBABILITY OF SUCCESS		1	0.9	0.54	0.27	0.16	0.9	0.54	0.27	0.16	0.45	0.45
FAILURE COST			$34.73	$35.63	$36.40	$36.67	$34.73	$35.63	$36.40	$36.67	$36.67	$36.67
FAILURE SCHEDULE			3.089	3.8615	3.8665	3.8665	3.089	3.8615	3.8665	3.8665	3.4115	3.4115
EXPECTED COST (Mil $)		$34.69	$32.76	$34.41	$35.89	$36.04	$31.32	$33.49	$36.30	$36.42	$34.13	$32.43
EXPECTED SCHEDULE (yrs)		2.8	3.1	4.3	4.2	4.1	3.1	4.3	4.2	4.1	3.6	1.7
EXPECTED COST DIFF (Mil $)		$0.00	($1.93)	($0.18)	$1.30	$1.45	($3.27)	($1.10)	$0.80	$0.83	($0.46)	($2.16)
EXPECTED SCHEDULE DIFF (yrs)		0.0	0.2	1.4	1.2	1.2	0.2	1.4	1.2	1.2	0.7	0.8
TECHNOLOGIC CAPABILITY		1	2	3	4	5	2	3	4	5	3	3
REGULATORY ACCEPTANCE		5	4	3	3	4	4	3	3	4	4	4
	WEIGHT											
COST DIFF UTILITY	1	10.0	19.1	10.9	3.5	2.7	20.3	15.5	6.0	5.9	12.3	20.8
SCHED DIFF UTILITY	1	20.0	15.0	-7.5	-4.8	-3.7	15.0	-7.5	-4.7	-3.0	6.5	7.0
TECH CAP UTILITY	1	2.0	4.0	6.0	8.0	10.0	4.0	6.0	8.0	10.0	6.0	6.0
REG ACCEPT UTILITY	3	30.0	24.0	18.0	18.0	24.0	24.0	18.0	18.0	24.0	24.0	24.0
TOTAL UTILITY		62	63	27	25	33	70	32	27	36	49	58

UTILITY FUNCTIONS	EQUIVALENT WORST	BEST	slope	intercept
COST DIFF UTILITY	$0.00	($2.00)	-5.0	10.0
SCHED DIFF UTILITY	0.50	0.00	-20.0	20.0
TECH CAP UTILITY	0.00	5.00	2.0	0.0
REG ACCEPT UTILITY	0.00	5.00	2.0	0.0

RUN 2 : BASE CASE - FIVE OPERABLE UNITS

CHARACTERIZATION PROGRAMS (excluding later non-critical path monitoring)

				SAMPLE CHANGE	5	0.5	0.5	0.5	0.5	0.2	0.2	0.2	0.2	0.5	0.2
				BOREHOLE CHANGE	NA	1	1	1	1	1	1	1	1	1	1
PROGRAM ELEMENTS	COST($)	UNIT	TIME(yr)	PROGRAM:	0	1	2	3	4	5	6	7	8	9	10

		PROGRAM										
FACTOR		0	1	2	3	4	5	6	7	8	9	10
PROBABILITY OF SUCCESS		1	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
FAILURE COST			$34.73	$35.63	$36.40	$36.67	$34.73	$35.63	$36.40	$36.67	$36.67	$36.67
FAILURE SCHEDULE			3.069	3.8615	3.8665	3.8665	3.069	3.8615	3.8665	3.8665	3.4115	3.4115
EXPECTED COST (Mil $)		$34.59	$32.76	$33.59	$34.71	$33.16	$31.32	$32.07	$33.04	$29.63	$31.69	$28.16
EXPECTED SCHEDULE (yrs)		2.8	3.1	4.6	4.8	5.3	3.1	4.8	4.9	5.3	3.8	3.4
EXPECTED COST DIFF (Mil $)		$0.00	($1.83)	($1.00)	$0.11	($1.43)	($3.27)	($2.53)	($1.55)	($4.96)	($3.00)	($6.40)
EXPECTED SCHEDULE DIFF (yrs)		0.0	0.2	1.7	2.0	2.4	0.2	1.7	2.0	2.4	0.8	0.8
TECHNOLOGIC CAPABILITY		1	2	3	4	5	2	3	4	5	3	3
REGULATORY ACCEPTANCE		5	4	3	3	4	4	3	3	4	4	4
	WEIGHT											
COST DIFF UTILITY	1	10.0	19.1	15.0	9.4	17.1	26.3	22.6	17.7	34.8	25.0	42.0
SCHED DIFF UTILITY	1	20.0	15.0	-13.5	-10.3	-27.0	15.0	-13.5	-10.1	-27.2	3.0	3.5
TECH CAP UTILITY	1	2.0	4.0	6.0	6.0	10.0	4.0	6.0	6.0	10.0	6.0	6.0
REG ACCEPT UTILITY	1	10.0	8.0	6.0	6.0	8.0	8.0	6.0	6.0	8.0	8.0	8.0
TOTAL UTILITY		42	47	14	4	8	54	21	13	26	42	59

UTILITY FUNCTIONS	EQUIVALENT WORST	BEST	slope	intercept
COST DIFF UTILITY	$0.00	($2.00)	-5.0	10.0
SCHED DIFF UTILITY	0.50	0.00	-20.0	20.0
TECH CAP UTILITY	0.00	5.00	2.0	0.0
REG ACCEPT UTILITY	0.00	5.00	2.0	0.0

RUN 2 : BASE CASE = FIVE OPERABLE UNITS

CHARACTERIZATION PROGRAMS (excluding later non-critical path monitoring)

PROGRAM ELEMENTS	COST($)	UNIT	TIME(yr)	PROGRAM:	0	1	2	3	4	5	6	7	8	9	10
				SAMPLE CHANGE	5	0.5	0.5	0.5	0.5	0.2	0.2	0.2	0.2	0.5	0.2
				BOREHOLE CHANGE	NA	1	1	1	1	1	1	1	1	1	1

FACTOR	WEIGHT	PROGRAM 0	1	2	3	4	5	6	7	8	9	10
PROBABILITY OF SUCCESS		1	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
FAILURE COST			$34.73	$35.63	$36.40	$36.67	$34.73	$35.63	$36.40	$36.67	$36.67	$36.67
FAILURE SCHEDULE			3.080	3.8615	3.8665	3.8665	3.080	3.8615	3.8665	3.8665	3.4115	3.4115
EXPECTED COST (Mil $)		$34.60	$33.20	$34.05	$35.06	$33.94	$32.06	$32.88	$33.70	$31.10	$32.72	$30.07
EXPECTED SCHEDULE (yrs)		2.8	3.1	4.4	4.7	5.0	3.1	4.4	4.7	5.0	3.7	2.7
EXPECTED COST DIFF (Mil $)		$0.00	($1.39)	($0.54)	$0.46	($0.66)	($2.51)	($1.73)	($0.90)	($3.40)	($1.88)	($4.52)
EXPECTED SCHEDULE DIFF (yrs)		0.0	0.2	1.5	1.7	2.1	0.2	1.5	1.7	2.0	0.0	0.7
TECHNOLOGIC CAPABILITY		1	2	3	4	5	2	3	4	5	3	3
REGULATORY ACCEPTANCE		5	4	3	3	4	4	3	3	4	4	4
	WEIGHT											
COST DIFF UTILITY	1	10.0	17.0	12.7	7.5	13.2	22.0	16.7	14.0	27.0	18.4	32.6
SCHED DIFF UTILITY	1	20.0	16.1	-10.1	-14.7	-21.2	16.1	-10.1	-14.0	-20.0	4.7	5.0
TECH CAP UTILITY	1	2.0	4.0	6.0	8.0	10.0	4.0	6.0	8.0	10.0	6.0	6.0
REG ACCEPT UTILITY	1	10.0	8.0	6.0	6.0	8.0	8.0	6.0	6.0	8.0	8.0	8.0
TOTAL UTILITY		42	45	15	7	10	51	21	13	24	36	52

UTILITY FUNCTIONS	EQUIVALENT WORST	BEST	slope	intercept
COST DIFF UTILITY	$0.00	($2.00)	-5.0	10.0
SCHED DIFF UTILITY	0.50	0.00	-20.0	20.0
TECH CAP UTILITY	0.00	5.00	2.0	0.0
REG ACCEPT UTILITY	0.00	5.00	2.0	0.0

RUN 2 : BASE CASE = FIVE OPERABLE UNITS

CHARACTERIZATION PROGRAMS (excluding later non-critical path monitoring)

SAMPLE CHANGE			5	0.5	0.5	0.5	0.5	0.2	0.2	0.2	0.2	0.5	0.2
BOREHOLE CHANGE			NA	1	1	1	1	1	1	1	1	1	1
PROGRAM ELEMENTS	COST($)	UNIT	TIME(yr)	PROGRAM:	0	1	2	3	4	5	6	7	8	9	10

		PROGRAM										
FACTOR		0	1	2	3	4	5	6	7	8	9	10
PROBABILITY OF SUCCESS		1	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
FAILURE COST			$34.73	$35.63	$36.40	$36.67	$34.73	$35.63	$36.40	$36.67	$36.67	$36.67
FAILURE SCHEDULE			3.089	3.8615	3.8665	3.8665	3.089	3.8615	3.8665	3.8665	3.4115	3.4115
EXPECTED COST (Mil $)		$34.59	$33.64	$34.50	$35.46	$34.72	$32.84	$33.66	$34.53	$32.79	$33.84	$31.96
EXPECTED SCHEDULE (yrs)		2.9	3.1	4.3	4.4	4.7	3.1	4.3	4.4	4.7	3.8	1.8
EXPECTED COST DIFF (Mil $)		$0.00	($0.95)	($0.09)	$0.87	$0.13	($1.75)	($0.94)	($0.06)	($1.83)	($0.75)	($2.63)
EXPECTED SCHEDULE DIFF (yrs)		0.0	0.2	1.3	1.5	1.7	0.2	1.3	1.5	1.7	0.7	0.7
TECHNOLOGIC CAPABILITY		1	2	3	4	5	2	3	4	5	3	3
REGULATORY ACCEPTANCE		5	4	3	3	4	4	3	3	4	4	4
	WEIGHT											
COST DIFF UTILITY	1	10.0	14.8	10.5	5.7	9.4	15.8	14.7	10.3	19.2	13.7	23.2
SCHED DIFF UTILITY	1	20.0	16.4	-8.8	-10.1	-14.7	16.4	-8.8	-16.0	-14.5	8.4	8.0
TECH CAP UTILITY	1	2.0	4.0	6.0	8.0	10.0	4.0	6.0	8.0	10.0	6.0	6.0
REG ACCEPT UTILITY	1	10.0	8.0	6.0	6.0	8.0	8.0	6.0	6.0	8.0	8.0	8.0
TOTAL UTILITY		42	43	16	10	13	47	20	14	23	34	44

UTILITY FUNCTIONS	EQUIVALENT WORST	BEST	slope	intercept
COST DIFF UTILITY	$0.00	($2.00)	-5.0	10.0
SCHED DIFF UTILITY	0.50	0.00	-20.0	20.0
TECH CAP UTILITY	0.00	5.00	2.0	0.0
REG ACCEPT UTILITY	0.00	5.00	2.0	0.0

RUN 2 : BASE CASE - FIVE OPERABLE UNITS

CHARACTERIZATION PROGRAMS (excluding later non-critical path monitoring)

			SAMPLE CHANGE	5	0.5	0.5	0.5	0.5	0.2	0.2	0.2	0.2	0.5	0.2
			BOREHOLE CHANGE	NA	1	1	1	1	1	1	1	1	1	1
PROGRAM ELEMENTS	COST($)	UNIT	TIME(yr)	PROGRAM:	0	1	2	3	4	5	6	7	8	9	10

FACTOR	WEIGHT	PROGRAM 0	1	2	3	4	5	6	7	8	9	10
PROBABILITY OF SUCCESS		1	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
FAILURE COST			$34.73	$35.63	$36.40	$36.67	$34.73	$35.63	$36.40	$36.67	$36.67	$36.67
FAILURE SCHEDULE			3.089	3.8615	3.8665	3.8665	3.089	3.8615	3.8665	3.8665	3.4115	3.4115
EXPECTED COST (Mil $)		$34.50	$34.07	$34.95	$35.83	$35.50	$33.50	$34.44	$36.28	$34.32	$34.97	$33.84
EXPECTED SCHEDULE (yrs)		2.9	3.1	4.1	4.2	4.4	3.1	4.1	4.2	4.3	3.8	1.1
EXPECTED COST DIFF (Mil $)		$0.00	($0.52)	$0.39	$1.24	$0.91	($1.00)	($0.16)	$0.68	($0.27)	$0.36	($0.75)
EXPECTED SCHEDULE DIFF (yrs)		0.0	0.2	1.2	1.3	1.4	0.2	1.2	1.3	1.4	0.9	0.9
TECHNOLOGIC CAPABILITY		1	2	3	4	5	2	3	4	5	3	3
REGULATORY ACCEPTANCE		5	4	3	3	4	4	3	3	4	4	4
	WEIGHT											
COST DIFF UTILITY	1	10.0	12.6	9.2	3.8	5.5	15.0	10.7	6.8	11.3	8.1	13.7
SCHED DIFF UTILITY	1	20.0	16.6	-3.5	-6.5	-6.2	16.0	-3.5	-6.4	-6.1	8.0	8.2
TECH CAP UTILITY	1	2.0	4.0	6.0	8.0	10.0	4.0	6.0	8.0	10.0	6.0	6.0
REG ACCEPT UTILITY	1	10.0	8.0	6.0	6.0	8.0	8.0	6.0	6.0	8.0	6.0	6.0
TOTAL UTILITY		42	41	17	12	15	44	19	16	21	30	36

UTILITY FUNCTIONS	EQUIVALENT WORST	BEST	slope	intercept
COST DIFF UTILITY	$0.00	($2.00)	-5.0	10.0
SCHED DIFF UTILITY	0.50	0.00	-20.0	20.0
TECH CAP UTILITY	0.00	5.00	2.0	0.0
REG ACCEPT UTILITY	0.00	5.00	2.0	0.0

RUN 2 : BASE CASE = FIVE OPERABLE UNITS

CHARACTERIZATION PROGRAMS (excluding later non-critical path monitoring)

				SAMPLE CHANGE	5	0.5	0.5	0.5	0.5	0.2	0.2	0.2	0.2	0.5	0.2
				BOREHOLE CHANGE	NA	1	1	1	1	1	1	1	1	1	1
PROGRAM ELEMENTS	COST($)	UNIT	TIME(yr)	PROGRAM:	0	1	2	3	4	5	6	7	8	9	10

FACTOR	WEIGHT	PROGRAM 0	1	2	3	4	5	6	7	8	9	10
PROBABILITY OF SUCCESS		1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
FAILURE COST			$34.73	$35.63	$36.40	$36.67	$34.73	$36.63	$36.40	$36.67	$36.67	$36.67
FAILURE SCHEDULE			3.089	3.8615	3.8665	3.8665	3.089	3.8615	3.8665	3.8665	3.4115	3.4115
EXPECTED COST (Mil $)		$34.59	$34.61	$35.41	$36.21	$36.28	$34.36	$35.24	$36.02	$35.69	$36.10	$36.73
EXPECTED SCHEDULE (yrs)		2.9	3.1	3.9	4.0	4.0	3.1	3.9	4.0	4.0	3.5	0.4
EXPECTED COST DIFF (Mil $)		$0.00	($0.08)	$0.82	$1.62	$1.69	($0.24)	$0.65	$1.43	$1.30	$1.51	$1.14
EXPECTED SCHEDULE DIFF (yrs)		0.0	0.2	1.0	1.0	1.1	0.2	1.0	1.0	1.1	0.5	0.5
TECHNOLOGIC CAPABILITY		1	2	3	4	5	2	3	4	5	3	3
REGULATORY ACCEPTANCE		5	4	3	3	4	4	3	3	4	4	4
	WEIGHT											
COST DIFF UTILITY	1	10.0	10.4	5.9	1.9	1.6	11.2	6.5	2.5	3.5	2.4	4.3
SCHED DIFF UTILITY	1	20.0	19.9	-0.1	-0.0	-1.5	19.9	-0.1	-0.0	-1.7	0.7	0.5
TECH CAP UTILITY	1	2.0	4.0	6.0	8.0	10.0	4.0	6.0	8.0	10.0	6.0	6.0
REG ACCEPT UTILITY	1	10.0	8.0	6.0	6.0	8.0	8.0	6.0	6.0	8.0	6.0	6.0
TOTAL UTILITY		42	39	18	15	18	40	19	19	20	20	28

UTILITY FUNCTIONS	EQUIVALENT WORST	BEST	slope	Intercept
COST DIFF UTILITY	$0.00	($2.00)	-5.0	10.0
SCHED DIFF UTILITY	0.50	0.00	-20.0	20.0
TECH CAP UTILITY	0.00	5.00	2.0	0.0
REG ACCEPT UTILITY	0.00	5.00	2.0	0.0