A Guideline
for

Dynamic Workplans and Field Analytics:
The Keys to Cost-Effective Site Characterization and Cleanup

Prepared by

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1.0 Introduction

The ability to rapidly assess the disposition of environmental contaminants at purported or existing hazardous waste sites is an essential component of the nation's environmental restoration program. Each site, whether owned by the public or private sector, must be evaluated to determine whether risk to human health or the environment exists. If the data obtained supports the notion that no risk or an acceptable level of risk exists for the intended land usage then no further action may be required. If, on the other hand, sufficient risk has been determined to warrant a full site characterization, the site investigation effort must delineate the nature, extent, direction, concentration and rate of movement of the contamination along with the physical and chemical site attributes.

Despite the best efforts of the U.S. Environmental Protection Agency[1] (EPA) and other federal agencies including the Departments of Defense and Energy to validate field analytical technologies, field analytics has not played a significant role in either hazardous waste site assessments or cleanup. In 1995, the EPA issued a Request for Proposals in support of President Clinton's efforts to promote application of innovative environmental technologies and to address the many factors that might pose barriers toward their commercialization. The President's Environmental Technology Initiative (ETI) is focused on accelerating environmental protection, strengthening America's industrial base, and increasing exports of U.S. technologies and expertise. The Tufts project was directed at two key objectives identified in the FY95 strategic plan: namely, strengthening the capacity of technology developers and users to succeed in environmental innovation *and* strategically investing EPA funds in the development and commercialization of promising new environmental monitoring, control, and remediation technologies.

The dynamic workplan guidance document represents one aspect of these objectives. The document is aimed at helping federal and state regulators, siteowners and their consulting engineers, and remediation companies understand what is involved in constructing and carrying out a dynamic workplan. The purpose of the document is to illustrate the many factors that should be considered in incorporating field analytical instrumentation and methods into an adaptive sampling and analysis program for expediting the site investigation process. This dynamic process should result in a faster, better, and hopefully cheaper site characterization and cleanup. With this goal in mind, field analytical technologies developed by the Tufts' Center for Field Analytical Studies and Technologies and with in-kind support from several commercial companies were demonstrated in the context of a dynamic workplan/adaptive sampling and analysis strategy. The ETI project, in part, supported an ongoing soil investigation study at Hanscom Air Force Base (Bedford, MA), see Hanscom report.[2] With the assistance of EPA Region 1, the Air Force and its contractor (CH2MHill), a video tape was produced illustrating the dynamic site investigation process.

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[1] E. Koglin and L. R. Williams, Trends in Analytical Chemistry, 13, 294-299 (1994).

[2] A. Robbat, Jr., Tufts University, Case Study: Dynamic Workplans and Field Analytics: The Keys to Cost-effective Site Investigations, 1997.

1.1 Dynamic Workplans

Successful hazardous waste site investigations should be focused with goals and objectives clearly defined. This does not mean, as has been past practice, that the site investigation process should result in workplans that are "etched in stone." Figure 1 depicts a traditional sampling and analysis program. The workplan relies on pre-specified sampling locations, numbers of samples collected and the types of analysis to be performed. The traditional site investigation is static in its application. It does not provide a framework for changes in direction based on what is learned in the field. Samples are collected, packaged and typically sent off-site for analysis. Because data turnaround times range from several weeks to several months, analytical results are unavailable during the field investigation phase to address data "surprises" or concerns while the sampling team is still on site. Experience has shown that multiple field investigations within the same or subsequent seasons are required to fill data gaps. The traditional process results in several trips to the field by the sample collection and survey teams before the site investigation can be completed. This static process typically occurs during hazardous waste site cleanups as well.

Dynamic workplans, as shown in Figure 2, provide an alternative to the traditional approach. Dynamic workplans rely, in part, on an adaptive sampling and analysis strategy. Rather than dictate the details of the sample analysis to be performed and the location and number of samples to be collected, dynamic workplans specify the decision-making logic that will be used in the field to determine which chemical compounds require analysis, where to collect the samples and when to stop sampling. Adaptive sampling and analysis programs change as the conceptual model for the site is refined based on the analytical results produced in the field. A successful adaptive sampling and analysis program requires analytical methods and instrumentation that are field-practical and can produce data fast enough to support the dynamic workplan process.

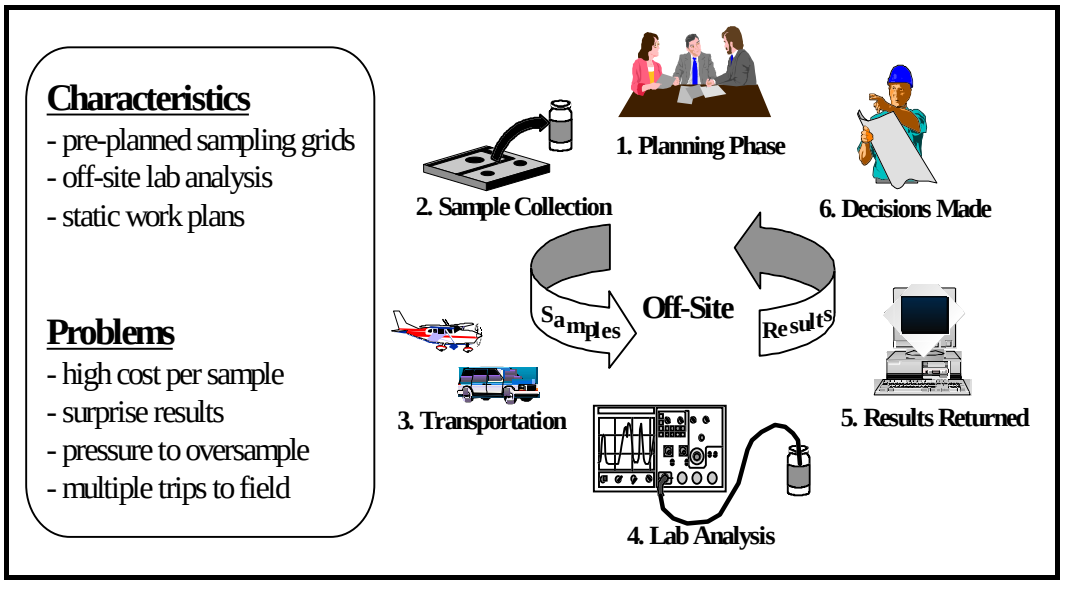

Figure 1. Traditional Site Investigation

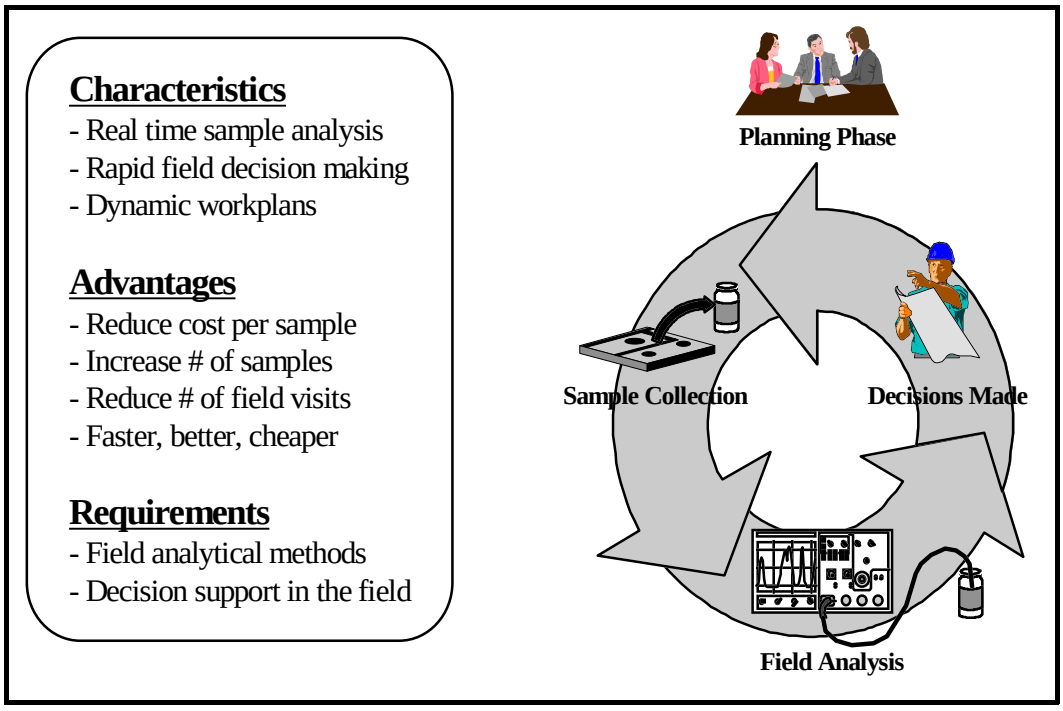

Figure 2. Dynamic Workplan Approach

1.2 Factors to be Considered

When deciding to carry out a Dynamic Workplan/Adaptive Sampling and Analysis program for projects consisting of complex chemical and physical site conditions, environmental contamination, and long duration, several factors should be considered before embarking on this approach. For example:

- Is it possible to assemble a well-rounded core technical team including analytical chemists, engineers, geologists, geochemists, geophysicists, hydrogeologists, risk assessors, and regulators?

- Will the core technical team be in the field for the duration of the field investigation? Is the decision making process well-defined and is the authority vested in an appropriate technical team member?

- Has the action level for field decisions, which rely on developing an understanding of the scientific and engineering questions under investigation, been established as part of the data quality objectives?

- Will the project objectives permit screening and semi-quantitative data or will quantitative data only be required to meet data quality objectives?

- Will more than ten percent of the samples analyzed in the field be sent off-site for laboratory confirmation analysis? Has the methodology for determining field and laboratory data comparisons been addressed?

- When selecting the field instrument or method, have measurement selectivity, sensitivity, precision, accuracy, representativeness, and action levels been addressed?

- When selecting the field instrument or method, have the measurement attributes listed above been addressed in sample throughput rates and cost? (Note that the number of sample cleanup steps and the time needed to prepare samples for analysis to meet the site-specific data quality objectives may limit throughput rates and increase sample costs.)

- Can standard operating procedures and method detection limit studies be completed before mobilization to evaluate matrix interferences that might be associated with a particular field technology?

- Will data management tools and geostatistical sampling tools be integrated into the field investigation?

- Is the site accessible for field analytic deployment including mobile laboratories, electrical power (line voltage versus a generator), and water if necessary?

- Has sufficient space been provided to house analytical instruments and staff, sample preparation, and data management in the field laboratory? Has proper ventilation been incorporated into the field laboratory?

- Does the length of the project and the potential overall cost savings warrant this approach?

2.0 Dynamic Workplan Guideline: Purpose and Objective

Dynamic workplan investigations are site dependent. They include field-based technologies and methods that produce chemical, physical, geological, and hydrogeological information about the site. The data generated must be of sufficient quality, with respect to measurement precision, accuracy, sensitivity, and completeness, to support the objectives of the site investigation or cleanup. The dynamic workplan plan guide described herein is not intended to be all inclusive. It does not address subsurface sampling tools; methods for collecting soil, water, or air samples; remote sensing and geophysical surveys; mathematical or computer modeling; nor will it discuss computer-based statistical sampling or the various site visualization tools. Depending on project objectives, a successful *dynamic* hazardous waste site investigation or cleanup will require one or more of these tools.

The guidance document is aimed at integrating field analytics into the Dynamic Workplan/Adaptive Sampling and Analysis process. It is intended to lay the foundation for incorporating an iterative process into the static but widely-used Data Quality Objectives (DQOs) framework for decision making planning. The guideline outlines field analytical instrument implementation, an adaptive sampling and analysis strategy, and site requirements.

3.0 The Dynamic Workplan Process

In the traditional approach, major decisions concerning the direction of the site investigation or cleanup are generally made by the project manager after the field work has been completed. A report is prepared presenting the findings to the appropriate regulatory body. Discussions begin about whether sufficient information has been obtained to address the scientific and engineering questions of concern. Typically, several field mobilizations occur, reports are written, with many meetings held between the siteowner and its environmental consulting company *and* the siteowner and federal and/or state regulatory agencies. In contrast, these same decisions are made in the field in an adaptive sampling and analysis program. In constructing the dynamic workplan, it is important to determine prior to mobilization what decisions will be made, how these decisions will be made, and who will make them in the field.

Step 1: Select the core technical team whose responsibility it will be to prepare the dynamic workplan. The technical team should possess expertise in analytical chemistry, geology, geochemistry, geophysics, hydrogeology, and risk analysis. The team helps with data management, QA/QC, risk assessment, fate and transport modeling, remedial action, community relations, and health and safety. The technical team will be responsible for:

1) gathering all available information for the site,

2) developing an initial "conceptual" model for the site,

3) identifying the technical objectives and goals to be accomplished,

4) supervising the field effort, making adjustments to the conceptual model based on the data produced in the field, and

5) evaluating the conceptual model and decisions made with respect to federal, state, and local regulations.

The core technical team will be responsible for making decisions in the field. One member of the team must have final decision making authority and responsibility to keep the site investigation process moving forward at a reasonable scientific and cost-effective pace. Some have proposed that the technical team be on site during the entire site investigation study[3]. This may not be practical or economically feasible for every project and is probably unnecessary given the currently available computer and telecommunication technologies. At least one member of the technical team should be on site at all times. This person must have a working knowledge of all aspects of the investigation or cleanup DQOs and be in daily communications with technical team members via electronic data transfer. Field personnel (and off-site technical team members) should be in regular communication with staff from federal and/or state regulatory agencies to ensure that decisions made in the field, typically under the pressures of time and field-resources utilization, are in conformance with the dynamic workplan framework.

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[3] ASTM Draft Provisional Standard Guide for Expedited Site Characterization of Vadose Zone and Ground Water Contamination, July, 1996.

Step 2: Develop the Initial Conceptual Model and Decision Making Framework.

Initial Conceptual Model. The initial conceptual model contains the best-available information at the start of the project. It depicts the three-dimensional site profile based on vadose zone and ground water flow systems that can exert influence on contaminant movement. Key site features such as roads, buildings, hydrography, depth to bedrock, direction of ground water flow, and potential preferential pathways for contaminant transport are mapped. Map cross sections should include water levels, high and low permeability zones, and aquifers. The conceptual site model is updated as additional data becomes available during the site investigation or cleanup process. The conceptual model is dynamic in nature and changes to reflect the increased site knowledge gained from field activities.

To assure efficient, effective decision-making the regulatory oversight organization should be included in developing the dynamic workplan. Stakeholders should 1) agree at the beginning on the most likely kinds of action(s) to be taken as a result of the field data, 2) implement the appropriate action on a daily basis as the data is generated, and 3) take new directions when the data suggests deviations from the conceptual model. It should be pointed out that site delineation is an iterative process and should be viewed as an ongoing experimental project.

The Decision Making Framework. The initial conceptual model is based on the Data Quality Objectives (DQO) for the site. The DQO process involves a series of planning steps designed to ensure that the type, quantity, and quality of environmental data used in decision making are appropriate for the intended application. It relates data needs to specific decisions to be made[4]. Briefly, the data quality objective process involves:

- Statement of the Problem. Concisely describe the overall study objectives outlining the scientific and engineering issues to be addressed. Review prior field studies and existing information to gain an understanding of the problem(s). Fuse soft information with hard data.

- Identify the Decisions to be Made that Will Address Each Problem. Independently, and then collectively, identify the types of decisions that will solve the problem(s) and the quality of sample collection and field analytical data required.

- Identify the Inputs to the Decision. Identify the information that needs to be learned in the field and the type of data quality needed to make field decisions.

- Define the Study Boundaries. Specify the range of conditions (time periods and situations) to which field decisions will apply, and within which field data will be collected.

[4] EPA QA/G-4, "Guidance for the Data Quality Objectives Process" September 1994.

- Develop Decision Rules. Integrate the decision outputs from previous steps into an "if...then..." statement that defines the conditions that would cause the decision maker in the field to choose alternative actions and/or take different directions to solve the problem(s).

- Specify Acceptable Limits on Decisions. Define the decision maker's continuation on a given pathway or alternative action based on field data produced on site: Has the direction followed gone far enough such that any further continuance provides no or marginal added value on a cost/benefit basis?

- Optimize the Conceptual Model. Evaluate information from each previous step and generate alternative sampling and analysis pathways and data quality requirements based on the initial conceptual model. Refine the model and/or pathways toward collecting additional on-site data as new information is provided.

The DQO process is used to define the quantitative and qualitative criteria for determining when, where, and how many sample measurements to collect and at what desired confidence level. Because several different data qualities may be appropriate to answer the site-specific scientific and engineering questions that must be addressed, the term sufficient or acceptable data quality is meaningful only when the intended uses for the data are known. The intended use of the data today may be different from tomorrow. Therefore, it cannot be overemphasized that cost-effective site investigations are highly dependent on anticipating data usage during the life of the characterization-to-cleanup program.

Step 3: Develop Standard Operating Procedures. The next step in developing a dynamic workplan is to establish standard operating procedures (SOPs). SOPs for sample collection and analysis should be produced along with other SOPs required to answer site-specific questions, e.g., geophysical and hydrogeological surveys, etc. The SOPs should be developed by the core technical team and approved by the appropriate regulatory body prior to initiating field activities. The field methods should be "performance based" and provide data of sufficient quality to meet the DQOs, see Section 4. The USEPA is encouraging the use of field analytical technologies and methods to expedite hazardous waste site investigations and cleanups in Superfund, RCRA, and Brownfields[5]. Because these technologies and methods may not be amenable to typical CLP or SW846 methods, QC procedures or data reporting formats, supporting data produced from the proposed field techniques should be provided to document data quality. Note that CLP and SW846 methods are not always required by the EPA to generate data.

Step 4: Develop Data Management Plan. Critical to the success of the dynamic process is the ability to manage and easily use all of the data produced in the field. Data integration (chemical, physical, geological, hydrological), sampling, and analysis protocols should be incorporated into

[5] May 1, 1996, Federal Register 61FR 19431-19463.

an overall data management plan. Protocols for sample logging, analysis, data reduction, and site mapping should be established. Several different organizations may be involved in this process. The data management plan should be established with rules and responsibilities defined prior to mobilization for the collection, assimilation, and presentation of the field generated data. As an example, computers housed in the sample receiving, organics, and metals analysis laboratories can be electronically linked through Ethernet connections to the data management trailer on site. Sampling logging information and the results of the analysis can be managed through a Laboratory Information Management System or through the use of spread sheets. The data can then be downloaded to a computer containing site visualization software for conceptual model update and review. In this manner, contaminant profiles are more easily understood facilitating the on-site decision making process.

Step 5: Develop Quality Assurance Project Plan. This document contains the sampling method, analytical procedures, and appropriate quality assurance (QA) and quality control (QC) procedures. Quality assurance/quality control (QA/QC) defines the responsibility of the technical team and regulators. It describes the procedures to be used to monitor conformance with, or documentation and justification of departure from the SOPs. The overall goal is to ensure that data of known and adequate quality have been produced to support the decision making process. Again, data of varying quality can be produced to support a range of activities from sample collection to risk assessment.

Step 6: Prepare Health and Safety Plan. Finally, a health and safety plan is produced as part of the Dynamic Workplan/Adaptive Sampling and Analysis project. DQOs should be established for the field analytical tools used to monitor worker and community safety and should be presented in the health and safety plan.

After all field organizations have mobilized and all analytical instruments have been calibrated, it is recommended that a dry run be made to ensure that all participants understand their respective roles and that the quality control (QC) systems from sample collection-to-analysis-to-site contaminant visualization are well-understood and can be easily implemented. On-site data verification may also be desirable for projects of large scope and duration.

3.1 Adaptive Sampling and Analysis Strategy

Figures 3 and 4 illustrate the adaptive sampling and analysis strategy for a hypothetical soil screening site investigation aimed at determining contaminant risk to ground water and human health. Figure 3 depicts the decision making flow chart for the investigation. Figure 4 describes the change in analysis based on what is found at the site. Once the initial sampling data (Round 1) is obtained the conceptual model is evaluated for accuracy. Typically, several sampling rounds are required before confidence in the conceptual model is obtained. The number of sampling rounds, made during the same mobilization, is dependent on the DQO specifications for confirming the absence of contaminants in areas thought to be clean (candidates for no further

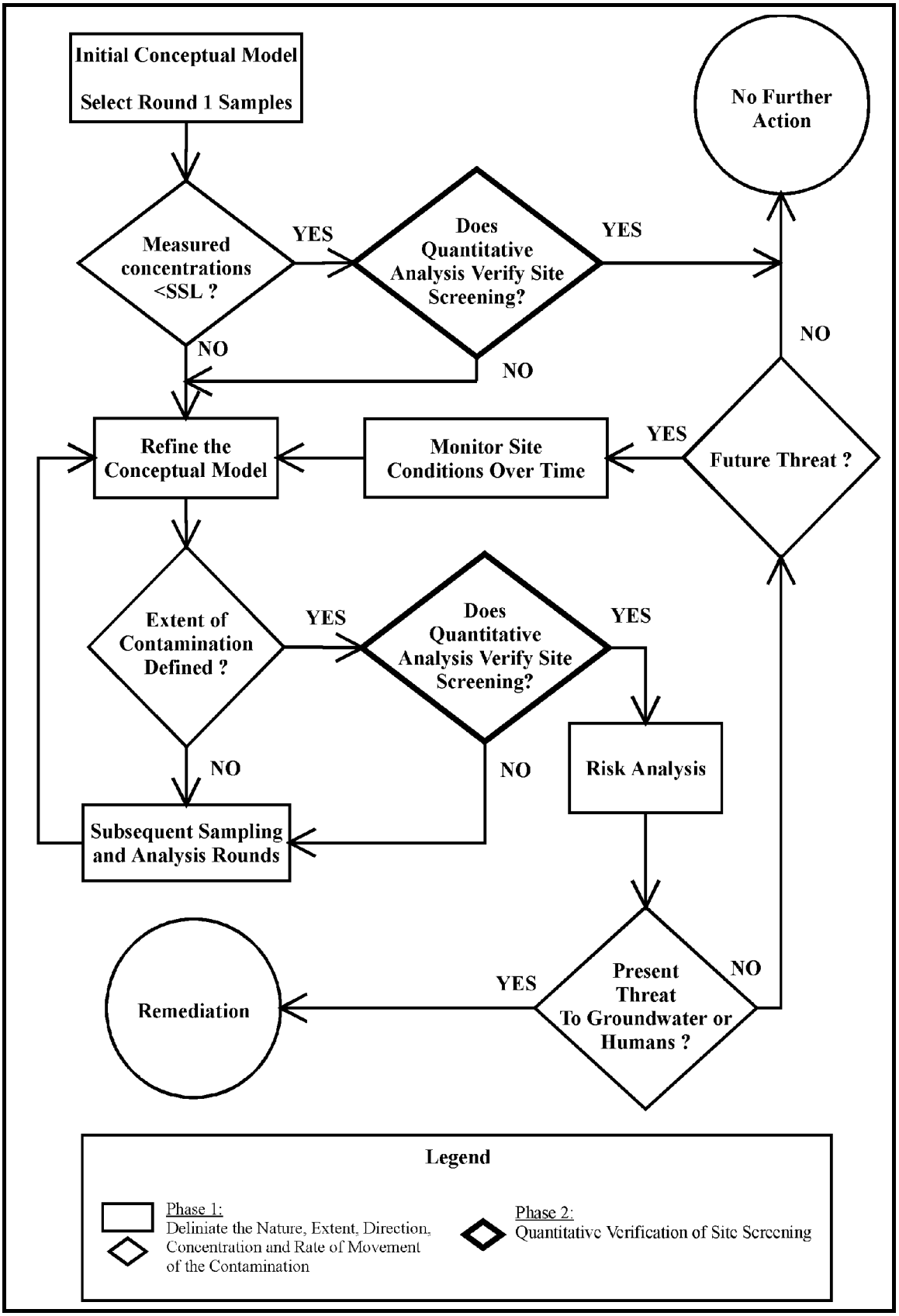

Figure 3. Adaptive Sampling and Analysis Flow Chart

action) *and* for determining the extent, direction, concentration, rate of contaminant migration, volume of contaminated soil and its risk to ground water and human health. Once the soil contamination profile objectives have been met and a verified conceptual model is produced, the data should be capable of delineating whether a particular area of investigation falls within three categories, namely:

- the site is clean or poses acceptable risk - no further action required
- the site is highly contaminated and well above action levels for acceptable risk - remedial action begins
- the site poses marginal risk - cost/benefit of an immediate cleanup not warranted, monitor for future action.

In the example provided, Round 1 samples are analyzed for the full Contract Laboratory Program (CLP) Target Compound List for volatile organic compounds (VOCs), semivolatile organic compounds (semi-VOCs), and metals if no prior field studies have been made. Target compound analysis is then performed for those contaminants found in each subsequent sampling round. As the analyte list decreases, more samples may be analyzed during the workday. Following the decision making logic through to completion, if site samples contain no detectable contaminants above the Soil Screening Levels (SSL) established for the site, site verification is made based on quantitative field analytical measurements. Several outcomes are possible. First, if the quantitative data verifies the field screening data and the data supports the conceptual model, no further action should be required at the site. Second, the comparison between field screening and quantitative measurements are within the site-specific DQOs for the data but the results do not support the conceptual model. In this case, additional sampling rounds are required to refine the model. Third, the comparison between quantitative and screening data fall outside of the acceptable DQOs, reassessment of the field screening tool is then required.

Following the alternative pathway, i.e., site screening measurements result in contaminant concentrations greater than the SSL's, sampling continues and the conceptual model is refined until the site-specific DQOs are met. The findings from the site screening effort are again verified by quantitative field analysis. Once the site data and conceptual model are verified, risk-based decision making occurs with respect to human health and the environment: that is, remediate or monitor for a future threat. At this point, new workplans must be produced to address site remediation or long-term monitoring needs. It should be pointed out that not all present or future threats will necessarily lead to a cleanup remedy. For example, the contamination may be technically impracticable to cleanup (dense non-aqueous phase liquids in bedrock) or natural attenuation may be proposed for the site.

Rather than relying on fixed grids, sampling is directed by geostatistical sampling tools that can predict where the next round of samples is collected. Because quantitative measurements are made on-site, greater confidence should be obtained in the sampling program. Phase 2 in Figure 4 illustrates one approach for verifying the site screening results. Recall that screening, semi-quantitative, or quantitative data can be generated in Phase 1 to develop the site model. If screening quality data, e.g., enzyme kits, is generated then more quantitative field, analytical data

should be produced to verify the results from the site screening phase. The number of locations within and surrounding each contaminated and non contaminated area as well as the number of depth samples at each location should be determined by the core technical team. An example is provided in the figure. The purpose of Phase 2 is to test the model and to verify the analytical results.

In an adaptive sampling and analysis program, contaminated areas are more heavily sampled than in traditional site characterization studies. Therefore, if semi-quantitative or quantitative field analytics is performed, no additional "quantitative" data may be necessary other than what is typical to verify data from one fixed-based laboratory versus another. Rapid, 5 to 15-minutes per sample, measurements should provide the majority of analyses during Phase 1, with 10% to 25% of these samples analyzed quantitatively in Phase 2. Off-site laboratory analysis should be performed only when on site quantitative analysis is not possible or cost-effective (Phase 3).

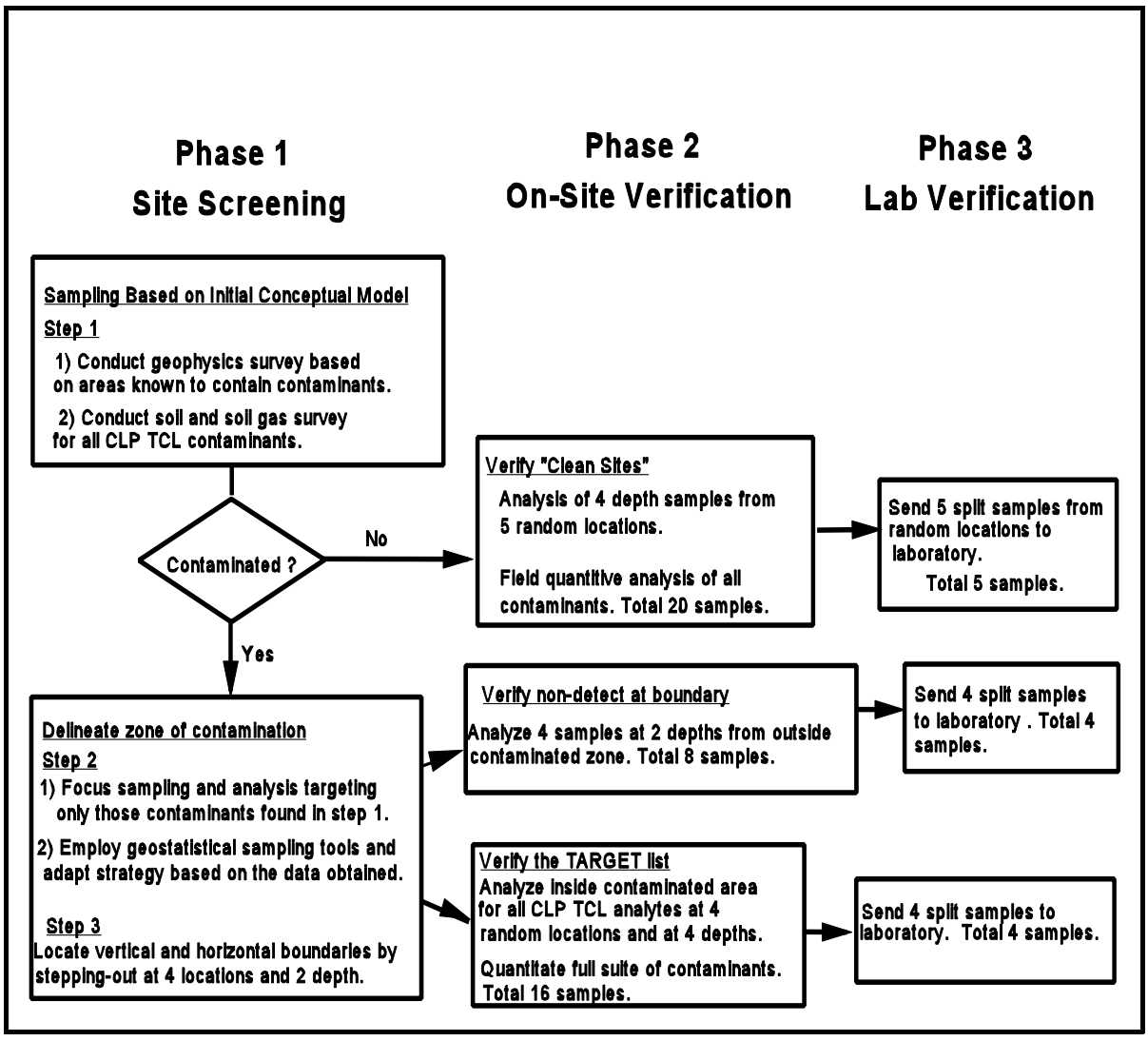

Figure 4. Example of Sampling and Analysis Flow Chart

Field results will differ from off-site laboratory results for VOC contaminated soil samples, with field measurements generally producing higher measurement concentrations because of analyte loss during off-site sample transport and storage. Care must be taken when these types of comparisons are made. Because site investigation and cleanup decisions are made based on field data, off-site laboratory analysis should be performed on no more than 10% of the samples analyzed quantitatively in the field. Field techniques that produce different data quality with the same instrumentation offer cost advantages over analytical techniques that produce either screening level or quantitative data[6]. Time and total project cost savings result when the sample load best matches the sample throughput rate of the instrumentation maximizing the effectiveness of field personnel and equipment, see Section 4.

Finally, field work begins based on the initial conceptual model. As new data are generated scientists and engineers may disagree over the direction(s) taken. Experience has shown that this will most likely occur based firstly on field discipline and secondly on stakeholder bias. One or more changes in direction should be proposed, with start/stop decisions delineated in the dynamic workplan. New results should refine the conceptual model and dictate future directions. Clearly articulated parameters with respect to sample number and DQO specifications obtained as a function of time should be identified in the workplan to set constraints on how long a particular pathway is followed before altering the investigation direction. One member of the siteowner technical team and one member of the regulatory oversight agency must have final site decision making authority. Site work stops when answers to the questions posed in the workplan meet site-specific confidence levels established as part of the DQO process. To ensure that site-specific goals have been met, the project team should statistically evaluate the results of its findings[7]. An adaptive sampling and analysis program focuses staff, equipment, and financial resources in areas where contamination exists while providing a cursory inspection in areas that pose no or little risk to human health and the environment.

4.0 Introduction to Field Analytics

The selection of field analytical methods is critically dependent on the need to make decisions in the field rapidly. Field analytical techniques should be capable of providing data from minutes to tens of minutes. They should have documented measurement sensitivity, precision, and accuracy to meet site investigation and cleanup DQOs. The simpler the technique the more likely it will be used in the field. Field instruments must be transportable, operate under adverse conditions, and provide improved cost/benefit over laboratory analysis. For projects of short duration and low sample volume, staff and equipment mobilization expenses may make field analytics a cost-prohibitive option. In addition, if quantitative measurements are required for all samples, field analytics may not provide a cost-effective means for obtaining site data. Rarely is this the case. Almost all projects will require screening or semi-quantitative data during the field

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[6] B. M. Abraham, T-Y Liu, and A. Robbat, Jr., Hazardous Waste & Management, 10, 461-473, 1993 *and* K. Jiao and A. Robbat, Jr., J. of AOAC International, 79, 1996.

[7] Guidance for Data Quality: Practical Methods for Data Analysis, EPA QA/G-9 EPA/600/R-96/084, July 1996.

screening phase of the site investigation. Even short projects of one to three days, where six to twelve samples per day may be collected, will benefit from field measurements. For example, head space gas chromatography (GC) can be simple and fast for the analysis of VOCs in soil and water samples during underground storage tank removal or well installation and monitoring. Enzyme kits can provide rapid detection of polychlorinated biphenyls (PCBs) or explosives during site characterization or remediation. Field instrumentation, such as in situ fiber optics and electrochemical sensors or portable GCs can be used to provide a security system to monitor underground subsurface contamination migration, process control, or fugitive emissions during site cleanups or long-term monitoring operations.

Field analytics can be routinely used to monitor worker and community health and safety during site investigations and cleanups. For example, the protection of workers from exposure to hazardous substances during sampling is of primary concern. In this case, sampling speed and limited sample handling is an important aspect of the measurement process. The sampling and measurement methods must be suitable to meet guidelines set forth by the National Institute for Occupational Safety and Health.

4.1 Field Measurement and Contaminants of Concern

The action level (or level of concern) defines the contaminant concentration needed to produce useful data to answer site-specific scientific and engineering questions. The selected field method must demonstrate method detection limits below the action level established for the site. The action level defines the concentration at which decisions can be made, including:

- nature and extent of contamination, i.e., field data supports the overall site investigation
- risk to human health and the environment, i.e., field data provides input into baseline risk assessment process
- achievement of cleanup objectives, i.e., field data supports site compliance with regulatory-imposed concentration levels

As an example, the EPA has compiled a list of contaminant soil screening levels for land usages based on different risk factors. These generic soil screening levels take into account the natural attenuation processes for the migration to ground water pathway(s) that can reduce contaminant concentrations in the subsurface. To insure that the field analytical instrumentation and methods selected in the workplan are amenable to a given site, site-specific method detection limit studies should be performed for each class of contaminants (e.g., VOCs, semi-VOCs, and metals) from soil obtained from the site prior to the field investigation. This will help to determine whether matrix interferents or target compounds mask (e.g., portable GC) or cross-react (e.g., enzyme/wet chemical kits) with targeted organics or metals (e.g., by electrochemical detection).

4.2 Field Analytical Techniques

Field analytics can be divided into two categories: real-time and "near" real-time measurements. Real-time measurements include those techniques that provide instantaneous analysis without the need for sample pretreatment. Examples include ion selective electrodes, fiber optic sensors, hand-held gas monitors, direct measuring GC's, and portable x-ray fluorescence (XRF) instruments. With the exception of XRF, these tools are typically used as continuous or in situ monitors for either gaseous or liquid streams.

Near real-time measurements typically include the more quantitative analytical techniques. They generally require some sample pretreatment prior to analysis of complex samples. These techniques include wet chemical and enzyme immunoassay kits; GC with a variety of non-specific detectors such as photoionization (PID) and flame ionization (FID), class-selective detectors such as electron capture (ECD for PCBs and chlorinated pesticides) or chemiluminescence (CD for nitrated explosives), and compound-specific detection by mass spectrometry (MS for identification of individual organic compounds); total petroleum hydrocarbon (TPH) analyzers; *and* inductively coupled plasma/optical emission spectroscopy (ICP/OES); XRF; and anodic stripping voltammetry for metals analysis. The size and experimental operating features dictate whether they are classified as field portable or transportable (laboratory-grade) instruments. For example, portable GCs are typically small in size, can operate off batteries but have ovens that cannot be temperature programmed (isothermal operation) or have slow temperature program ramps from ambient to 200 ^{0}C.[8] In either case, these GCs are best suited to qualitative analysis of VOCs. In contrast, GC/MS instruments require a generator or a line voltage power source, but can produce quantitative analysis of VOCs and semi-VOCs in the field.

In many instances, it is not necessary to have quantitative data for every sample during PCB, PAH, or explosives soil remediation. For example, when excavating soil, measurement accuracy can be as high as 40-70% as long as measurement precision is known. Enzyme kits and rapid screening GC with ECD, FID, or MS can provide this level of data quality. Quantitative analysis, on the other hand, is needed only for the pit closure samples to verify that the cleanup DQOs have been met. Field GC/MS can provide the necessary measurement sensitivity, precision, and accuracy to meet most site-specific cleanup DQOs. Similarly, VOC soil and water analysis by rapid screening GC with ECD/FID or MS is sufficient to determine vadose zone and ground water contamination profiles. More quantitative GC/MS data are required to determine the threat to ground water and the associated risks to human health and the environment. Performance-based methods can provide maximum flexibility to meet site-specific data needs.

A considerable amount of field analytical methods are available. Not every field method is amenable to the full range of environmental contaminants. Some are selective by design (enzyme and wet-chemical kits), while others are limited in scope (portable GC and XRF) or by media type (fiber optic, acoustic wave, and electrochemical sensors). Sample throughput rates in the field can also limit the effectiveness of field analytical measurements. Careful consideration should be given to these issues before selection of field analytical techniques or methods. The amount of sample preparation prior to analysis will determine the sample throughput rates that can be achieved. Experience has shown that field GC/MS can provide both screening and

[8] Analytical Chemistry, 69, 195A-200A, 1997.

quantitative data for the full range of organics depending on the sample introduction system and data analysis software used. Data quality and throughput rates must be determined before the decision is made as to which field analytical technologies or methods are appropriate. An initial documented statement for the end use of the data incorporated into the data decision process will ensure that inappropriate data uses do not occur.

4.3 Sample Throughput Rates and Analytical Properties

No one laboratory technique or method is universally accepted for all EPA listed organic or inorganic contaminants. The selection of field methods for site characterization and cleanup depends on the material to be examined, contaminants and action levels of concern, QC requirements, sample throughput rates, and cost. Selection of field methods also depends on the type of data quality required to answer site-specific questions. It is important to have a clear understanding of the particular analytical properties required to meet site-specific DQOs and how the economic considerations of a given analytical problem affect some properties over others.

Accuracy and Representativeness are two key attributes of data quality. Accuracy refers to the closeness of the result between the measured and actual ("true") analyte concentration in the sample. Accuracy can be calculated based on the degree of agreement between the observed value and the accepted reference value. Commercially prepared standard reference materials (SRM) or site-specific SRM's are often used to determine accuracy. Representativeness is defined as the consistency between the result and the measured sample as well as between the result and the definition of the analytical problem. Representativeness is the degree to which data accurately and precisely represents the frequency distribution of a specific variable. Measurement accuracy can be influenced by the required measurement sensitivity, selectivity, and precision whereas representativeness is affected by sampling location exactness and sample homogeneity consistency. The influence of sampling on analytical quality is, overall, crucial. For example, blood-sugar from a diabetic more than 1-hr after a hypoglycemic attack is not representative of the blood-sugar concentration at the time of the attack. Likewise, collecting soil samples two feet apart and expecting one of the samples measured by the field laboratory to be representative of the other sample analyzed by either the on-site or off-site laboratory is unreasonable. No other analytical property can be justified without representativeness. Because of subsurface soil inhomogeneities, collecting the many statistical samples necessary to gain the confidence needed to delineate the extent, direction, concentration and rate of contaminant movement is generally too costly in the traditional site investigation approach. The adaptive sampling and analysis strategy helps to focus the sampling effort in areas where contamination has been identified which, in turn, results in more data produced in the areas where it is needed. Nonetheless, the analytical measurement process is most often the bottleneck that controls the rate of the site investigation when compared to sample collection.

Assuming representative samples have been collected, measurement accuracy is directly dependent on the relationship among three key analytical parameters: precision, selectivity, and sensitivity. Accurate results cannot be obtained unless the measurement technique produces selective detection and adequate sensitivity. Selectivity refers to the instrument's or method's ability to respond to target compounds in the presence of nontarget sample constituents. For

example, if the analytical technique responds to the presence of matrix interferents or cross-reactive target compounds, measurement identity is affected and thus, accuracy. Moreover, if the analyte concentrations in the sample are at or just below the method detection limit, the measured concentrations may be inconsistent (precision). Measurement precision is the degree to which a set of analyses of the same parameter conforms to itself. To achieve unambiguous analyte identification and the desired method detection limit, extensive sample preparation procedures may be required to remove matrix constituents, dilute, or pre-concentrate the sample extract. These additional steps lengthen the overall time of the analysis (sample throughput rate).

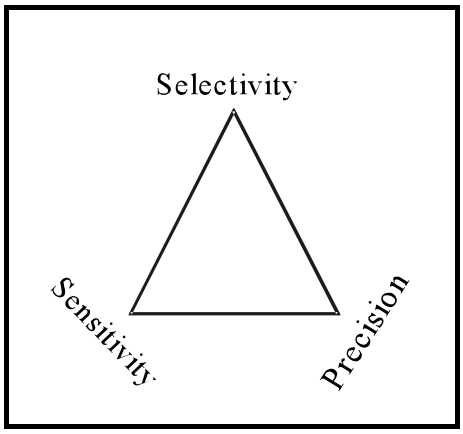

Figure 5. Data Attributes

Generally, as one property of the equilateral triangle is improved, one or both of the remaining analytical properties can become distorted. For example, increasing the number of sample preparation steps prior to the analytical measurement can result in loss of analyte, which, in turn, can influence measurement sensitivity and thus, accuracy (false negative). Another example is the detection of nitrated explosives by selective reagents such as enzymes. Field-practical enzyme immunoassay kits can significantly reduce the time of analysis over laboratory high performance liquid chromatography (HPLC) methods by eliminating the need for sample cleanup procedures. False positive detection is possible, however, due to cross-reactivity with other nitrated organic compounds that might be present in the sample. Although advancements in analytical instrumentation, sophisticated spectral deconvolution software routines, and compound-specific reagent chemistry have increased laboratory productivity, sample throughput rates and data quality are greatly influenced by the triangular interactions among selectivity, sensitivity, and precision. As increasingly more stringent measurement accuracy is specified, sample throughput rates decrease. For example, several published reports document the wide range of measurement precision and accuracy that is obtained when employing EPA method 8080 (20-min/sample) as compared to the more comprehensive congener-specific (90-min/sample) analysis for PCBs.[9,10,11]

The relationship between sample throughput rate, data quality, and field investigation costs can be viewed as follows. Assume a 10-hr workday with two hours set aside for lunch, daily meetings, instrument maintenance and lab cleanup. Also assume that each analysis requires a 5-min cycle time before the next sample can be analyzed and that any sample preparation procedures that might be necessary to remove nontarget matrix interferences occur separately from the analysis. Table 1 summarizes the relationship between number of samples that can provide information about the site and the number of QC or re-analysis samples required to

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[9] R. Eganhouse, and R. Gossett, Anal. Chem., 63, 2130-2137 (1991).

[10] D. Kimbrough, C. Rustum, and J. Wakakuwa, Analyst, 119, 1277-1281 (1994).

[11] G. Frame, J. Cochran, S. Bøwadt, JHRC., 19 657-668 (1996).

determine data quality as a function of sample throughput rate. Assume that in this hypothetical site investigation 300 soil samples are analyzed for PCBs at a soil screening level of 0.5-ppm to determine risk to ground water.

Table 1. Number of Samples Analyzed per Day

	TDGC/MS or Enzyme Kit 10-min/sample		EPA method 8080 20-min/sample	
Total Site Samples	300	300	300	300
Site Samples Analyzed Per Day	22	18	14	10
Site Samples Re-analyzed	3	5	0	2
Blanks	2	2	1	2
Replicate Analysis	2	3	1	2
Accuracy (SRM)	1	2	1	1
Initial/Final Calibration	2	2	2	2
Total Analysis/Day	32	32	19	19
Total Field Days	14	17	22	30

The number of field days needed to complete the site investigation presumes no loss of time for instrument breakdown, repair and/or re-calibration. If, for example, five samples are re-analyzed rather than three due to matrix interferents, detector overload, or frequency of field duplicates *and* three samples are analyzed to determine measurement precision and accuracy, a total of 17 site samples can be analyzed per day as compared to 22 for the 10-min analysis. Increasing the number of quality control or re-analysis samples decreases the number of site samples that can provide information about the site. A total of 18-days will be needed to complete the project as compared with 14-days when the sample throughput rate is 10-min/sample.

When analyzing soil samples by EPA method 8080 in the field, adding additional non site samples will result in the project being completed in 30-days versus 22-days. Apparent is the fact that the sample collection and field analysis rates must be matched and that the site-specific DQOs be well-understood in the context of selecting appropriate field analytical techniques, methods, and QC procedures. If, for example, PAHs must also be analyzed, then no additional analysis time is required by TDGC/MS, i.e., PCBs and PAHs are analyzed simultaneously. When standard laboratory technologies or enzyme kits are employed two separate analyses must be performed,

increasing total project costs. Note that these field laboratory costs do not represent total project costs. For TDGC/MS analyses minimal sample preparation is required. Although the extraction and cleanup of 20 samples can be accomplished in two hours for method 8080, the field laboratory must accommodate the sample preparation station and staff to achieve reasonable throughput. Expenses for the sampling crew and core technical team plus any other field services work must be added to the overall project costs.

When the principal organic contaminants and action levels are known, the selection of the field method should be straightforward. In complex mixtures, indicator compounds such as trichloroethene, carbon tetrachloride, or benzene may be used as surrogates for fast GC analysis. Although dual detector GC with ECD and either FID or PID costs less than most field or laboratory GC/MS instruments and, until recently have been easier to operate, only MS can provide unambiguous identification of VOCs. Contaminant concentrations, persistence in the environment, mobility and/or fate can be estimated from the detection of indicator compounds. If the principal contaminants at a site are unknown, field GC/MS provides the only reliable means of determining compound identity and concentration. For VOC analysis, purge and trap GC/MS can be performed as easily in the field as in the laboratory.

For semi-VOCs sample preparation is the rate-determining step when analyzing the EPA listed target compounds. Semi-VOCs must be extracted from soil or water into an organic solvent prior to analysis. Depending on the complexity of the matrix, the extract is further separated into fractions that contain compounds of similar chemical characteristics (e.g., PCB/pesticides, PAHs, explosives, acids, base/neutrals). These fractions may require additional separation before analysis by GC with ECD or MS; HPLC with UV and/or fluorescence detection; or by class-specific reagent chemistry such as the enzyme immunoassay kits. Sample cleanup, pre-concentration and/or sample dilution add extra steps to the measurement process and must be factored into field-practical sample throughput rates. Until recently, on-site analysis has only been possible for PCBs (portable GC with electron capture detection) and explosives (enzyme kits) because of time and cost constraints (sample preparation) in the field. In contrast to class-selective analysis provided by these technologies, TDGC/MS can provide rapid compound-specific analysis of most semi-VOCs.

Similarly, the same rationale applies to the analysis of soil contaminated by metals. Portable XRF provides screening level to semi-quantitative data without the need for sample preparation. Sample throughput rates exceed the data turnaround times that can be produced by field-based ICP/OES instruments. ICP/OES, however, provides more quantitative data at concentrations several orders of magnitude less than XRF can achieve. In contrast, metals analysis by electrochemical detection (anodic stripping) requires sample preparation for soil samples but not water samples and is more selective and sensitive than portable XRF instruments. As discussed above, every analytical measurement requires a trade-off among the properties precision, selectivity, and sensitivity.

4.4 Site or Facility Requirements

The physical layout of the site must have access to deploy and setup a field laboratory if the field activities extend beyond a one-week period. The site or facility should have line voltage power or a dependable source of electricity from a generator if a wide variety of field instruments and computing power are required. Power from a generator must be put through a filter to smooth out voltage fluctuations to protect analytical instruments and computers. The mobile laboratory or facility must have the proper footprint to house instruments, hoods, computers, refrigerators, and staff comfortably. The mobile laboratory should be heated in the winter and cooled in the summer. For instruments like the ICP/OES, field laboratory temperatures must be climate controlled to within ± 10 ^{0}C to achieve high quality data. Proper ventilation must be provided to protect worker safety and to separate volatile vapors produced during sample preparation procedures from cross-contaminating the organics analysis laboratory.

Access to on-site field laboratories should be limited to authorized personnel. Instrumentation, laboratory equipment, and utilities should be maintained to perform the required operations. Safety equipment should be available and readily accessible, e.g., eye wash, fire blanket, safety supplies. All instruments and equipment should be kept secured when not in use. These are customary practices of fixed-based laboratory operations.

Design and implementation of sampling programs should address situations or conditions necessary for the controlled use, storage, and disposal of sample material (e.g., soil discard, purged waters), equipment decontamination residues and remnants of samples. It should also ensure that all activities that may impact environmental data are documented and recorded in field notebooks. Field analysis will result in the production of waste materials commonly handled in off-site laboratory operations. Regulatory acceptance of these waste handling procedures should be obtained and incorporated into the workplan.

4.5 Quality Control

Sampling designs should minimize integrations between high and low concentration areas, as well as minimize common utilization of equipment, instrumentation, and facilities. A formal active contamination control program should exist that minimizes the potential spread of contamination. The collection of grab samples, e.g., individual samples collected at a specific time and location, is acceptable for TPH, semi-VOCs, VOCs, and metals. Composite samples, collected by homogenizing a sample interval or sample collection from different locations and times, are acceptable for TPH, semi-VOCs, and metals. A composite sample is not acceptable for VOCs since analyte will be lost during the homogenization process.

Prior to selecting the field analytical methods, it should be well-understood by all stakeholders as to the quality of acceptable data that will be sufficient to address site investigation or cleanup DQOs. The DQOs will dictate the limits of measurement error, selectivity, sensitivity, and resolution for the field measurement and how these attributes affect sample throughput rates, the on-site decision making process, and cost. DQOs should, therefore, dictate acceptable limits for measurement precision, accuracy, representativeness, and completeness. Once these attributes

have been defined, specific QC criteria (e.g., initial and continuing calibrations, laboratory control check sample (SRM) accuracy), frequency (e.g., every 10th or 20th predetermined, random, or positively detected sample) and, number (e.g., n = 2 or more) of repetitive sample analysis can be determined. This information must be included in the site specific-SOPs.

Goals for precision and accuracy should be established in the dynamic workplan. For example, site characterization, treatability study, or remedial action measurement precision or accuracy may differ greatly and should be based on the criteria needed to answer project-specific questions concerning the stated problem(s). A well-defined description of precision and accuracy benchmarks, instruments, field methods, chemical standards and reagents employed should be documented.

Goals for data representativeness should be addressed qualitatively since sampling locations, depths, intervals, frequency of split sampling and of QC check samples may change in the field based on new directions and requirements.

Goals for completeness and comparability of investigation are achieved when the study goals have been met. An analytical measurement value is considered complete if QC results are within acceptable ranges. There can be no assurances that the data produced by standard laboratory methods and instruments are any better than the field data. Comparability should be based on how well the field and laboratory produced data within their respective internal and external QC checks *and* through some minimum level of field versus laboratory data comparison (e.g., ≤ 100% may be an acceptable error range for some types of data usages). Federal and state regulators, siteowners, and their consulting engineers have a tendency to be risk-averse. Typically, the highest level of data quality is requested whether needed or not. As shown in Section 4.3, improper matching of sample collection, sample analysis throughput rates, and site-specific DQOs can easily lead to inefficient sampling and analysis programs and thus, cost.

5.0 Dynamic versus Traditional Investigation and Cleanup Costs

Dynamic workplans provide the framework for collecting chemical, physical, geological, and hydrological data in one or two field efforts as compared to the phased engineering approach of collecting data then evaluate, collect more data then evaluate ... until sufficient information is obtained to meet the study objectives. Fixed-based (commercial) laboratories should be able to generate data of comparable (either screening or quantitative data) quality at lower per sample costs than field/mobile laboratories. Economies of scale should be more easily achieved by fixed-based laboratories since they are designed for mass production. However, steep sample surcharges (100-200%) are generally added to the base price if samples are moved up in the queue to obtain one to three day data turnaround times. Moreover, fixed-base laboratory sample analysis costs vary greatly between regional (typically local non Contract Laboratory Program) and national laboratories.

Comparing the selection of field instruments as a function of cost is difficult. Field instruments and methods should be chosen first to meet the data quality requirements and second based on their ability to match the rate at which samples are collected. To illustrate the first

point, assume that the 16 target compound PAHs and PCBs require soil analysis to determine risk to ground water and that the action levels for PAHs are between 2-ppm (benz(a)anthracene, dibenz(a,h)anthracene) and as high as 40,000-ppm (fluoranthene and pyrene) *and* 1-ppm for total PCBs. These values are based on the 20DAF soil screening levels (SSLs, USEPA 1996), which refer to a dilution-attenuation factor (DAF) of 20. The SSLs take into account the natural attenuation process for the migration to ground water pathway that can reduce contaminant concentrations in the subsurface. Assume that the action level for the site has been established at one-half the 20DAF. For PAHs and PCBs these values are 1-ppm and 0.5-ppm, respectively. The method detection limit (sensitivity) has been determined at 0.5-ppm for GC/FID and 0.3-ppm for TDGC/MS.

Table 2 lists site-specific action levels for the hypothetical site investigation along with the data quality attributes, sample analysis, and the total number of samples analyzed per day throughput rates for field GC/ECD, TDGC/MS, and enzyme kit analyses. Tables 1 and 3 illustrate the impact of sample analysis rate and the number of site samples that can be analyzed per day. It may be necessary to make trade-offs among the data quality attributes of selectivity, sensitivity, and precision in conjunction with sample throughput rates to meet the site-specific DQO's and action levels *and* to provide a cost-effective field analytics program. This type of review should be made to insure that the selected field technology meets the site-specific DQOs established for the investigation or cleanup verification program.

The second point is not a trivial or obvious statement. If sample analysis lags behind sample collection, sample collectors and decision support staff sit idle waiting for data to be produced. On the other hand, if sample collection is operating below capacity, analytical instruments and field-laboratory personnel sit idle. In both cases, site investigation efficiency and cost is lost. Therefore, it is essential that the analytical team member play an integral role in designing the sample collection program. Moreover, combining field screening and on-site quantitative analysis into the program should increase the total number of samples analyzed while decreasing the number of samples sent off-site for traditional laboratory analysis.

Table 3 summarizes the field and laboratory sample charges and data turnaround times for the analysis of VOCs, PCBs, PAHs, explosives, and semi-VOCs. Shown in the Appendix are assumptions and costs used to determine the TDGC/MS, portable GC, and enzyme/colorimetric kit per sample charges. Commercial laboratory charges vary widely depending on the size and revenue amount of the laboratory and the number of national programs the laboratory participates in (e.g., Contract Laboratory Program, U.S. Army Corps of Engineers, HAZWRAP, and state certified programs). Field analytical technologies can provide analyses comparable in cost to regional or local laboratories employing EPA standardized methods with same or next day data turnaround times as compared with 14 to 35-days by commercial laboratories. Field analytics compete best when total project cost is considered and when it is incorporated into the Dynamic Workplan/Adaptive Sampling and Analysis Program. Cost savings can be realized when:

- sample selection and locations are optimized. Increased sampling efficiencies result in more targeted sample collection efforts minimizing the handling of samples that provide little value toward answering site-specific DQOs - <u>faster</u> site characterizations and verification of cleanup.

- the identity of the contaminants becomes known. Increased field analytical productivity is obtained when the type of analysis performed is more targeted resulting in more samples analyzed per day - faster site characterizations and verification of cleanup.

- more data are produced in less time. More informative decisions are made that improve the site delineation process, i.e., the separation of highly contaminated areas from non-contaminated areas - better site characterizations and verification of cleanup.

- a more detailed picture of the site is obtained, viz., the nature, extent, direction, concentration and rate of contaminant movement. Increased confidence in evaluating the risk to human health and the environment results - better site characterizations and verification of cleanup.

- more efficient utilization of human and financial resources is obtained. Increased project efficiencies lead to more data obtained at lower total project costs - cheaper site characterizations and verification of cleanup.

The rationale for selecting an adaptive sampling and analysis program should be based on the inherent efficiencies obtained when decisions are made in the field and the overall total project cost savings that can accrue.

Table 2. Comparison of Field Technologies for PCBs and PAHs

Polycyclic Aromatic Hydrocarbons					Polychlorinated Biphenyls		
Site-specific DQO's and Action Level	**Attributes**	**GC/FID**	**TDGC/MS**	**Enzyme Kits**	**GC/ECD**	**TDGC/MS**	**Enzyme Kits**
Yes	**Selectivity**	No	Speciate	class-specific	Yes	Speciate	class-specific
1-ppm/PAH 0.5-ppm total PCB	**Sensitivity**	0.5-ppm	0.3-ppm	MFG. and Compound Dependent	0.03-ppm	0.2-ppm	Aroclor Dependent 0.5 to 1-ppm
≤ 40%	**Precision**	≤ 40%	≤ 40%	MFG. Dependent ≤ 40%	≤ 30%	≤ 40%	MFG. Dependent ≤ 40 %
No No	**Accuracy biased toward: false positive false negative**	Yes No	No No	Yes No	Yes No	No No	Yes No
	Analysis Rate/Sample	20-min	10-min	10-min	20-min	10-min	10-min
	Total Number of Samples Analyzed per 10-hr work day	19	32	32	19	32	32

Table 3. Field and Laboratory Cost and Data Turnaround Time Comparison

Analyte	Regional Laboratory Data Turnaround: 14 Calendar Days	National Laboratory Contract Laboratory Program Data Turnaround: 35 Calendar Days	Field TDGC/MS Data Turnaround: Next Day	Field GC/PID or GC/ECD Data Turnaround: Next Day	Strategic Diagnostic Enzyme Kits Data Turnaround: Same Day
VOCs	$125/sample SW 846 method 8240/8260 25-min/sample analysis	$165/sample SW 846 method 8240/8260 25-min/sample analysis	$100/sample modified 8260 20-min/sample	$88/sample modified 8021/8015 or headspace analysis 25-min/sample	Not Applicable
PCBs	$100/sample SW 846 method 8080 20-min/sample analysis; sample preparation 2-hr/batch of 20 samples	$150/sample SW 846 method 8080 20-min/sample analysis; sample preparation 2-hr/batch of 20 samples	$100/sample modified 8270 10-min per analysis; sample preparation 1-hr/batch of 20 samples	$88/sample field method 20-min analysis; sample preparation 1-hr/batch of 20 samples	$102/kit field method 10-min analysis time; sample preparation 1-hr/batch of 20 samples
PAHs	$145/sample SW 846 method 8100/8310; 20-min/sample analysis, sample preparation 2-hr/batch of 20 samples	$255/sample SW 846 method 8100/8310 20-min/sample analysis; sample preparation 2-hr/batch of 20 samples		Not Applicable	$102/kit field method 10-min analysis time; sample preparation 2-hr/batch of 20 samples
Explosives	$180/sample SW 846 8330/USAED 30 20-min/sample analysis; sample preparation 18-hr/batch of 20 samples	$220/sample SW 846 8330/USAED 30 20-min/sample analysis; sample preparation 18-hr/batch of 20 samples	$100/sample modified 8270 10-min per analysis; sample preparation 1-hr/batch of 20 samples	Not Applicable	$102/kit field method TNT & RDX kits required 20-min per analysis; sample preparation 1-hr/batch of 20 samples
Semi-VOCs	$400/sample SW 846 method 8270 40-min/sample analysis; sample preparation 4-hr/batch of 20 samples	$450/sample SW 846 method 8270 40-min/sample analysis; sample preparation 4-hr/batch of 20 samples	$150/sample modified 8270 20-min per analysis; sample preparation 1-hr/batch of 20 samples	Not Applicable	Not Applicable

Appendix

Field Analysis Costs

Table 4 illustrates the per sample costs for field-based TDGC/MS, GC with PID or ECD, and wet chemical or enzyme kit analysis. In the cost example, a Hewlett Packard GC/MS (model GCD) was modified to introduce samples via thermal desorption (TD), with the data analysis accomplished by the Ion Fingerprint Detection™ (IFD) software. Field GC/MS instruments such as the Viking Instrument, ~ $120,000 when fully equipped, will add $5.50 to the GC/MS sample cost shown in the table. The TDGC/MS with the IFD software can provide simultaneous detection of PCBs and PAHs in complex petroleum contaminated soil samples in 10-min. The Photovac GC/PID can provide full VOC analysis in the field. As discussed in Section 4, photoionization (PID) and electron capture (ECD) detectors provide qualitative compound-specific information as compared to the MS. These GC detectors can not provide unambiguous compound identification but can provide rapid field screening analysis of VOCs. The cost of a field-based GC/ECD has also been estimated for PCB analysis. The enzyme or colorimetric kit costs shown in the table have been calculated based on an average per kit price that assumes 40 analysis per calibration for either the Ensys or Ohmicron kits. Sample analysis of less than 40 samples per calibration will result in increased sample costs.

The cost analysis is based on a one time purchase of capital equipment and includes any modifications that are required to produce high throughput field analysis; a vehicle for field transport of staff, instrument and supplies; and generator for power. Annual operating costs assume a total of 4,500 soil samples will be analyzed over a 180-day field season by two chemists. This represents an average of 25 samples analyzed per day. Since nearly 70% of the cost to provide service is in salary any additional field days will reduce the per sample cost, while booking work for less than the assumed 180-days will increase the respective sample analysis cost. Finally, the per sample cost was calculated over a five year period. The calculation takes into account the time value of money based on present value of future costs to provide the service. It ignores inflation and assumes a 4% discount rate. Details of the capital purchases and annual operating costs can be found in Tables 5 and 6. Although commercial laboratories provide volume pricing, no one project or account will dramatically affect the laboratory life-cycle per sample cost. Included in the commercial laboratory per sample charges are costs for staff, equipment, supplies, space, management, accounting, marketing and sales. An industry conservative 2.5 multiplier was used to estimate the field comparable per sample charges for each technology.

Table 4. Field Analytical Measurement Costs

	TDGC/MS	GC/PID or ECD	Enzyme Kits
Initial Capital Costs	$76,000	$47,500	$27,500
Total Annual Operating Costs	$178,828	$161,978	$283,595
Present Value of Life-Cycle Costs (assume 4% discount)	$903,890	$797,383	$595,699 (direct costs) $770,818 (kits)
Total Number of Samples Analyzed Over 5-years	22,500	22,500	22,500
Cost per sample analysis	$40	$35	$27 direct cost plus $34/kit
Total Sample Cost with 2.5 multiplier*	$100	$88	$102

* Overhead cost provided by Steve Maxwell, Technology Strategic Group, Boulder, Colorado

Table 5. Capital Equipment Costs

	Capital Equipment		**Capital Equipment**		**Capital Equipment**	
Instrument Costs	HP GC/MS full VOC and SVOC analysis 486 computer, operating/data analysis software and libraries, LaserJet printer, split/splitless inlet, diffusion/rouging pumps	$45,000	Photovac GC/PID full VOC capability oven/column & re-charge battery, start up kit, printer & cable	$26,500	SDI Enzyme Kits PAH, PCB, and Explosives Spectrometer, balance, and computer and printer	$6,500
Modifications	Thermal Desorption Unit	$10,000				
Vehicle	Van	$20,000	Van	$20,000	Van	$20,000
Power Supply	2.5 kW generator	$1,000	2.5 kW generator	$1,000	2.5 kW generator	$1,000
	Total Cost	$76,000	**Total Cost**	$47,500	**Total Cost**	$27,500

Table 6. Annual Operating Expenses

	GC/MS Operating Costs		Portable GC Operating Costs		Enzyme Kits Operating Costs	
Labor	two full time chemists	$120,000	two full time chemists	$120,000	two full time chemists	$100,000
Software	Ion Fingerprint Detection™	$10,000				
Materials and Supplies	GC columns (13), fittings, and septa	$6,500	GC columns (13), fittings, and septa	$6,500	$37/sample average kit price, PAH, PCB, explosive	$166,500
	electron multiplier &source	$3,000	detector lamp	$650	detector lamp	$550
	pump oil	$1,000				
	helium carrier gas ($4/day at 180-day)	$720	He carrier gas ($4/day at 180-day)	$720		
	calibration standards	$3,500	calibration standards	$3,500		
	reagent water ($4/day at 180-day)	$720	reagent water ($4/day at 180-day)	$720	reagent water ($4/day at 180-day)	$720
	vials ($175/case)	$10,938	vials ($175/case)	$10,938	vials ($175/case)	$10,938
	spatula	$50	spatula	$50	spatula	$50
	syringes (15)	$1,000	syringes (15)	$1,000		
	coolers (3)	$120	coolers (3)	$120	coolers (3)	$120
	solvents (40-L)	$750	solvents (40-L)	$750	solvents (10-L)	$187
Vehicle Costs	insurance	$1,500	insurance	$1,500	insurance	$1,500
	maintenance ($100/month)	$1,200	maintenance ($100/month)	$1,200	maintenance ($100/month)	$1,200
	gas (20K miles/year at $1.33/gal)	$1,330	gas (20K miles/year at $1.33/gal)	$1,330	gas (20K miles/year at $1.33/gal)	$1,330
Overhead	QA/QC 2-months	$12,000	QA/QC 2-months	$12,000	QA/QC 2-months	$12,000
	maintenance contract HP	$4,500	maintenance	$1,000		
	Total	$178,828	**Total**	$161,978	**Total labor and supplies**	$128,595
					Cost of 4,500 kits, $37 each	$166,500