ABSTRACT

DEVELOPMENT OF A COMPUTER MODEL AND EXPERT SYSTEM FOR PNEUMATIC FRACTURING OF GEOLOGIC FORMATIONS

by
Brian Michael Sielski

The objective of this study was the development of a new computer program called PF-Model to analyze pneumatic fracturing of geologic formations. Pneumatic fracturing is an *in situ* remediation process that involves injecting high pressure gas into soil or rock matrices to enhance permeability, as well as to introduce liquid and solid amendments. PF-Model has two principal components: (1) Site Screening, which heuristically evaluates sites with regard to process applicability; and (2) System Design, which uses the numerical solution of a coupled algorithm to generate preliminary design parameters.

Designed as an expert system, the Site Screening component is a high performance computer program capable of simulating human expertise within a narrow domain. The reasoning process is controlled by the inference engine, which uses subjective probability theory (based on Bayes' theorem) to handle uncertainty. The expert system also contains an extensive knowledge base of geotechnical data related to field performance of pneumatic fracturing. The hierarchical order of importance established for the geotechnical properties was formation type, depth, consistency/relative density, plasticity, fracture frequency, weathering, and depth of water table.

The expert system was validated by a panel of five experts who rated selected sites on the applicability of the three main variants of pneumatic fracturing. Overall, PF-Model demonstrated better than an 80% agreement with the expert panel.

The System Design component was programmed with structured algorithms to accomplish two main functions: (1) to estimate fracture aperture and radius (Fracture Prediction Mode); and (2) to calibrate post-fracture Young's modulus and pneumatic conductivity (Calibration Mode). The Fracture Prediction Mode uses numerical analysis to converge on a solution by considering the three coupled physical processes that affect fracture propagation: pressure distribution, leakoff, and deflection. The Calibration Mode regresses modulus using a modified deflection equation, and then converges on the conductivity in a method similar to the Fracture Prediction Mode.

The System Design component was validated and calibrated for each of the 14 different geologic formation types supported by the program. Validation was done by comparing the results of PF-Model to the original mathematical model. For the calibration process, default values for flow rate, density, Poisson's ratio, modulus, and pneumatic conductivity were established by regression until the model simulated, in general, actual site behavior.

PF-Model was programmed in Visual Basic 5.0 and features a menu driven GUI. Three extensive default libraries are provided: probabilistic knowledge base, flownet shape factors, and geotechnical defaults. Users can conveniently access and modify the default libraries to reflect evolving trends and knowledge.

Recommendations for future study are included in the work.

DEVELOPMENT OF A COMPUTER MODEL AND EXPERT SYSTEM FOR PNEUMATIC FRACTURING OF GEOLOGIC FORMATIONS

by
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To My Loving Parents

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I am greatly indebted to my family and friends for reminding me why it all matters, making me feel useful, sheltering me from the travails of the real world, and surrounding me with so much love, support, and hope.

Finally, I'd like to thank all my maternal and paternal ancestors for providing me with the correct DNA sequence to be here today.

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LIST OF SYMBOLS

b	=	aperture width
b_w	=	ground heave at well
C	=	cohesion
C_{norm}	=	idealized C for normal consolidation
cm	=	centimeter(s)
©	=	copyright
E	=	Young's modulus
e.g.	=	for example (from the Latin *exempli gratia*)
et al.	=	and others (from the Latin *et alii*)
etc.	=	and other things (from the Latin *et cetera*)
ft	=	feet
g	=	acceleration due to gravity
GUI	=	graphical user interface
H	=	total head
i.e.	=	that is (from the Latin *id est*)
in	=	inches
K	=	conductivity
K_{ic}	=	fracture toughness
K_{gas}	=	effective pneumatic conductivity
$K_{h\text{-}gas}$	=	horizontal pneumatic conductivity
$K_{v\text{-}gas}$	=	vertical pneumatic conductivity

LIST OF SYMBOLS
(Continued)

lb	=	pound(s)
l_{grad}	=	flowpath length
LL	=	liquid limit
m	=	meter(s)
mm	=	millimeter
N	=	number of blow counts
N_d	=	number of potential drops
N_f	=	number of flow tubes
p	=	pressure
p_d	=	driving pressure
PF	=	pneumatic fracturing
p_k	=	pressure required to overcome fracture toughness
p_m	=	maintenance pressure
p_{prop}	=	propagation pressure
p_w	=	pressure in well
pcf	=	pounds per cubic foot
psf	=	pounds per square foot
PL	=	plastic limit
$\overline{p}_o$	=	effective overburden pressure

LIST OF SYMBOLS
(Continued)

Q = injection flow rate

Q_{leak} = air flow lost into formation

Q_{res} = residual flow in fracture

q_u = unconfined compressive strength

R = final fracture radius

r = radius

r_n = segmented radius

r_w = well radius

r_{incr} = incremental radius

scfm = standard cubic feet per minute

sec = second(s)

t = time

TM = trademark

u = velocity of fluid

w = moisture content

z = depth

z_w = depth to water table or depth below surface

γ_{eff} = effective unit weight

γ_t = dry unit weight

LIST OF SYMBOLS
(Continued)

γ_w = unit weight of water

λ = a coefficient

μ = dynamic viscosity of fluid

π = ratio of a circle's circumference to its diameter, silly

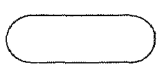
ρ = density of fluid

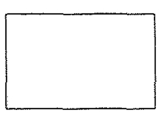
υ = Poisson's ratio

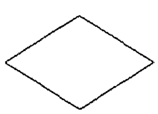
φ = potential function

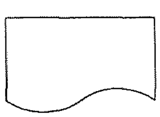
Ω = sample space

$\forall$ = universal quantifier

 = the start or end of a program flow

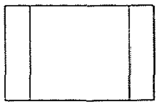
 = represents any kind of processing function

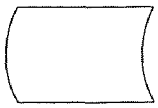
 = a decision or switching type function

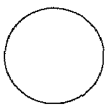
 = represents human readable data, such as printed output

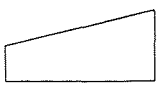
 = data

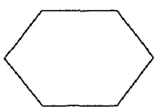
LIST OF SYMBOLS
(Continued)

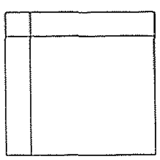
 = represents a named process, such as a subroutine, or a module

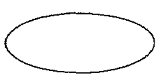
 = stored data

 = identifier, or connector

 = data input by manual means, such as with a keyboard

 = represents modifications, preparations, or initializing a routine

 = internal storage

 = Bayesian Network belief node

CHAPTER 1

INTRODUCTION AND OBJECTIVES

1.1 Introduction

Over the past 25 years, industry, government, and the general public have become increasingly aware of the need to respond to the hazardous waste problem, which has grown steadily over the past 50 years. In 1980, Congress enacted the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) - the Superfund Law - to provide for "liability, compensation, cleanup, and emergency response for hazardous substances released into the environment and the cleanup of inactive waste disposal sites."

A major difficulty in cleaning up some hazardous waste sites is the relative low permeability of the formation (*i.e.*, fine-grained soils and dense bedrock). Current remediation technologies such as pump and treat, air sparging, bioremediation, vapor extraction, thermal treatment, and soil washing work best in formations of relatively high permeability. In response to this problem of low permeability formations, a research effort was begun in 1987 at the Hazardous Substance Management Research Center (HSMRC) at New Jersey Institute of Technology (NJIT). It culminated with the development of a new remediation enhancement technology known as "pneumatic fracturing" (U.S. Patent # 5,032,042) in 1991.

Pneumatic fracturing enhances the permeability of contaminated geologic formations by injecting high pressure air creating fractures or fissures in the soil or rock matrix. The fractures or fissures occur if the injection is performed at a pressure which exceeds the natural *in situ* stresses, and at a flow rate which exceeds the permeability of the formation. In soil formations, pneumatic fracturing enhances the permeability of the formation by creating fracture networks, while in rock formations, the effect is the dilation and extension of existing discontinuities which improves the interconnection between existing fractures. The immediate benefit is improved access to the subsurface contaminants so that liquids and vapors can be transported and extracted more rapidly.

Pneumatic fracturing is similar in concept to the hydraulic fracturing techniques used in the petroleum industry (Gidley *et al.*, 1989). The principal difference is that hydraulic fracturing uses water to create the fractures, while pneumatic fracturing uses a gas (usually air). This is a significant and advantageous difference. In using air as an injection fluid, fracture propagation is more rapid due to the lower viscosity of air over water. In addition, air is less likely to remobilize and spread contaminants than water.

Pneumatic fracturing has been successfully demonstrated in the field at a number of contaminated sites. Among these are U.S. EPA SITE Demonstrations at contaminated sites in Hillsborough, New Jersey, to enhance soil vapor extraction (U.S. EPA, 1993) and in Marcus Hook, Pennsylvania, to enhance *in situ* bioremediation (U.S. EPA, 1995). Pneumatic fracturing is now available commercially for enhancement of pump and treat, vapor extraction, air sparging, and bioremediation. Other innovative approaches using the pneumatic fracturing process are also under investigation, and include *in situ* vitrification, *in situ* ultrasonic enhancement, and reactive media injection.

1.2 Objectives and Scope

The objective of this study is to develop a comprehensive pneumatic fracturing computer model (called PF-Model) with two principal functions. First, the model will assist in deciding whether or not a site is a potential candidate for the technology. Second, it will generate preliminary design parameters for applying the pneumatic fracturing process at the site. Each of these model functions will now be briefly introduced.

An essential step in the successful remediation of a site is the selection of appropriate technologies. In the past, the decision when and if to use pneumatic fracturing was made by informal quantitative comparisons with empirical data from past projects by an expert familiar with the capabilities of the technology. Now, the computer model will make the same judgment by functioning, in part, as an "expert system."

An expert system is a high performance problem-solving computer program capable of simulating human expertise within a narrow domain. An expert system either performs the function of a human being, or it fulfills the role as an assistant to the human decision maker. Expert systems are best suited for conditions in which there are no efficient algorithmic solutions (Biondo, 1990), such as the decision of whether a site is a potential candidate for pneumatic fracturing.

Once PF-Model has determined that pneumatic fracturing is an appropriate technology for the site, the program will then make preliminary estimations of design parameters such as well spacing, injection pressures, and fracture intervals. This part of the program incorporates current mathematical models developed at the Center for Environmental Engineering and Science (CEES) (Puppala, 1998, and King, 1993). The coding of this part of the computer model uses conventional programming techniques, since mathematical models and algorithmic solutions require rigid control structures.

The computer model is designed in a Windows™ format that is interactive with the user. The program makes extensive use of graphics and objects, thus providing a friendly user interface. The computer program also includes a User's Guide for design applications.

A data base library of probabilities representing geologic evidence necessary for site screening is also included in PF-Model. This part of the program allows the data base to be updated with new probabilities as desired, allowing "expert" potential users to customize their own proprietary version of the program. The library provides the expert system with the needed information (*i.e.*, probabilities) to assess pneumatic fracturing applicability, dry media injections, and liquid media injections based on the geologic evidence that is known and subsequently entered as data.

The final phase of the study involves validation of the predictive aspects of the computer model, especially those parts coded as an expert system. Since 1989, a considerable amount of field data has been collected and was available to calibrate the propagation model. Likewise, for site screening, calibration is based on actual past field demonstrations combined with heuristic reasoning. In addition, the model is run for hypothetical sites to "push the envelope" of the pneumatic fracturing technology in consultation with current experts in the field.

In summary, the objectives of this research study are to:

1. Investigate various probabilistic options available for an expert system.

2. Design and code an expert system to make technology recommendations.
3. Convert available analytical and numerical component models to computer code in order to make preliminary estimates of design parameters used in the technology.
4. Establish an overall design and logic implementing a Windows™ format program.
5. Include a User's Guide for design applications.
6. Develop an interactive knowledge base containing the probabilities for pneumatic fracturing applications for previous and future site data and technology information.
7. Develop a library of system and geotechnical defaults for PF-Model to support the System Design component for estimating fracture radius and aperture.

This dissertation will begin with a summary of expert systems, site screening, and propagation model backgrounds (Chapter 2). This will be followed by a discussion of the approach for the different model components and how they are coded and/or theorized (Chapter 3). Next, the model will be field validated and calibrated with data from previous sites and discussion with experts (Chapter 4). Finally, conclusions and recommendations for future study are presented (Chapter 5). The User's Guide for PF-Model is included in Appendix H.

CHAPTER 2

BACKGROUND INFORMATION

This chapter will provide the reader with appropriate background information used in programming the computer model. First, since some components of the computer model are in part based on expert systems, an introduction to expert systems is presented. Second, the parameters, or geologic evidence, required for successful application of the site screening model will be described. Finally, the analytical model used in solving fracture propagation and associated research will be discussed.

2.1 Expert Systems

The overall objective of the study is to "capture" the available knowledge of the pneumatic fracturing process, thus allowing distribution of this expertise on a wider scale. PF-Model encompasses both a heuristic model (*i.e.*, the Site Screening component) and an analytical model (*i.e.*, the System Design component). The Site Screening component is based on the development of an expert system which generates technology recommendations. This section provides an overview of current expert system technology and theory, as well as the advantages and disadvantages.

2.1.1 Introduction to Expert Systems

Expert systems, or knowledge-based expert systems, are computer programs that represent and use the knowledge of some human expert in order to solve problems or give advice within a narrowly defined field or domain (Durkin, 1994). This definition does not distinguish the difference between expert systems and conventional programs and techniques, however. Conventional programs can be interactive and contain rules of selection/decision, yet still not be an expert system. Table 2.1 shows the important differences between expert systems and conventional programs.

Table 2.1 Differences Between Conventional Programs and Expert Systems (Maher, 1987).

Conventional programs	Expert systems
Representation and use of data	Representation and use of knowledge
Knowledge and control integrated	Knowledge and control separated
Algorithmic (repetitive) process	Heuristic (inferential) process
Effective manipulation of data bases	Effective manipulation of knowledge bases
Oriented toward numerical processing	Orientated toward symbolic processing

2.1.1.1 Origins of Expert Systems: Early computers were originally high speed data processors. Programs were written based on a prescribed algorithm to perform a series of specific actions, or tasks. The programs solved equations, processed data, and scanned data bases for information. They were able to do this exceptionally well, but they were still not able to reason about the information they were processing. Any problem that required human reasoning was performed by a human expert (Shapiro, 1987).

Eventually, programmers began coding knowledge about a problem into the computer. The knowledge consisted of facts, rules, and structures of the problem which was coded in "symbolic" form. The problem knowledge was represented as symbols, which is simply alphanumeric characters. In order to encode and search through the symbolic information, symbolic processing languages were developed. Some early examples of symbolic languages include LISP and PROLOG (Michie, 1979).

As advances in symbolic programming languages and symbolic knowledge representation were made in the late 1950s, programmers began efforts to create programs that displayed intelligent behavior. This created a new field of study called Artificial Intelligence, or AI (Shapiro, 1987).

AI strives to simulate human intelligence in a computer. Early AI research centered around the belief that a few laws of reasoning paired with computers would be able to simulate human intelligence. After years of research in developing AI programs, it was found that the general problem-solving strategies were too weak to solve most complex problems (Newell and Simon, 1972). This is because solution of a specific problem required quality knowledge within some narrow domain to successfully search for a solution. Eventually, the technology known as "expert systems" grew out of the AI branch of computer science (Patterson, 1990). In essence, an expert system is an AI program with specialized problem-solving expertise.

2.1.1.2 Characteristics of Expert Systems: The best way to introduce the concept of an expert system is to describe characteristics which are common to all expert systems. These are listed and briefly discussed below.

Limited to Solvable Problems. It may seem surprising, but before the development of an expert system begins, it must be determined if the problem is solvable. An expert system will not work if there is no human expert available to obtain knowledge from. New or novel research issues are therefore not candidates for expert systems programming (Prerau, 1985).

Possesses Expert Knowledge. An expert system must capture and encode the knowledge of a human expert, including the expert's problem-solving skills and his domain knowledge. These skills or knowledge are not necessarily unique or brilliant, rather they are known only by a few others.

Focuses Expertise. Focusing the expertise should seem obvious, but in fact, programmers who have designed expert systems to encompass broad topics have achieved little success and failed (Ham, 1984, and Prerau, 1985). Expert systems do not perform well when tasked with problems outside their area of expertise, just like humans. An expert system can be successfully developed only when the scope of the problem is well defined.

Reasons Symbolically. The knowledge used by an expert system can be expressed in symbolic terms rather than numerical terms. Symbols can represent facts, concepts, and rules. Problems are solved by manipulating symbols rather than by numeric processing (*i.e.*, conventional programs).

Reasons Heuristically. Heuristics is the study or practice of procedures that are valuable but are incapable of proof (Lenat, 1982). A human expert possesses more than just public knowledge, *i.e.*, knowledge which is available in published literature. A human expert uses not only facts and theories to solve a problem, but also considers past experiences. Such knowledge gives the expert a practical understanding of the problem and allows the development of "rules-of-thumb," or heuristics, to solve the problem.

To illustrate the difference between conventional programs that use algorithms and expert systems that often use heuristic techniques, consider the example of a bicycle chain which keeps coming off while riding, an indication of a stretched chain. The conventional algorithm is a series of orders or calculations that are well structured:

1. Measure the length of chain.
2. Count the number of chain links.
3. Compute link to length ratio.
4. If ratio > 1.1, then chain is stretched.

The algorithm performs this same sequence of operations each and every time. It is this repetitiveness that makes it attractive for conventional programming techniques.

Heuristic reasoning does not follow a rigid structure of steps (Georgeff, 1983). Rather, it draws a conclusion based on the available information. The heuristic approach to determine if the chain is stretched would be as follows:

IF	Chain comes off bike
AND	Chain is old
THEN	Suspect stretched chain.

Notice that heuristic reasoning does not guarantee that the chain is actually stretched, but it is a good starting point to begin analysis of the problem. The problem may actually have been a faulty rear derailleur or worn chainrings.

Makes Mistakes. It must be recognized that since expert systems are programmed with the knowledge of a human expert, they are therefore capable of making the same mistakes. That is not to say conventional programs with structured algorithms have a significant advantage over expert systems. Both types of programs address different types of problems. Conventional programs work well where information or data is readily available or certain. But if the data is wrong or incomplete, a conventional program will return a wrong result, or nothing at all. Expert systems are designed to work with less information. The result may not be exact, but it can be reasonable.

Other Characteristics. Expert systems usually exhibit some other common characteristics. First, expert systems must perform at a competence level which is equal to or better than an expert in the field. It should also reach decisions within a reasonable amount of time. Finally, the system should have a stable platform and not be subject to crashing or freezing up.

2.1.2 Expert Systems Architecture

There are three major traits of an expert that are modeled in an expert system: (1) the expert's knowledge in the specific domain; (2) the reasoning used to reach a conclusion or provide an answer; and (3) knowledge about the problem being solved. To accomplish this, the expert system must be designed with a number of interactive working components. They have three principal components: a knowledge base, the working memory, and an inference engine. Other components that can enhance the model are a user interface, explanation facility, and knowledge acquisition facility (Durkin, 1994). Figure 2.1 shows an idealized representation of the architecture of an expert system and the relationship between its components.

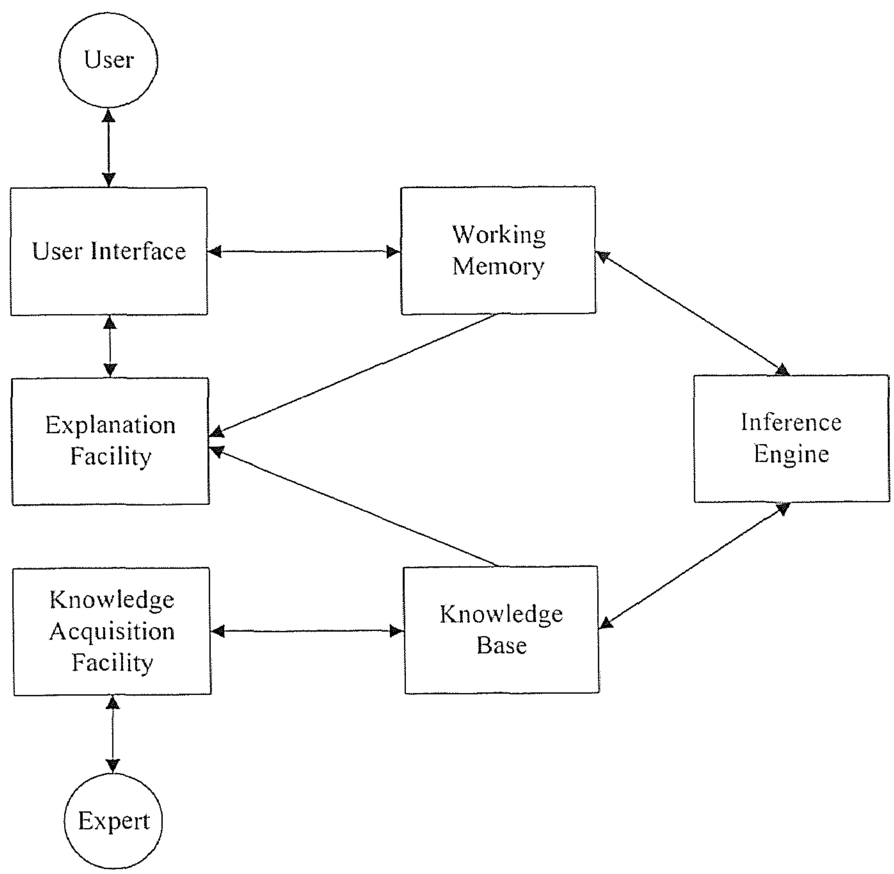


Figure 2.1 Relationship of Expert System Components.

The remainder of this section will discuss each of these components, all of which are needed to build an expert system.

Knowledge Base. The knowledge base is the part of the expert system that contains the domain knowledge and heuristics of the expert. In general, it is the collection of knowledge in the form of rules, procedures, and facts. The most typical way to represent the heuristics of the expert is to apply an IF/THEN decision structure (Georgeff, 1983). The knowledge base also contains a high level of competence in the general knowledge about the behavior and interactions in the problem domain. The scheme of the knowledge base is one of the most critical decisions in that it impacts the design of the inference engine, the knowledge acquisition facility, and overall efficiency of the system (Stefik *et al.*, 1982).

Working Memory. The working memory is the component of the expert system that models the human's short term memory. It contains the global data base used by the rules of the system, facts both entered and inferred, and the intermediate results that make up the current state of the problem (Hunt, 1986). Eventually, the working memory expands as the expert system reasons about the current problem. Information and data subsequently generated by the expert system in order to solve the problem are also stored. When the problem is solved, the working memory not only contains the solution, but all the intermediate results as well.

Inference Engine. Also known as the control structure or rule interpreter, the inference engine is the part of the program that performs the reasoning. It locates the required knowledge and infers new knowledge from the base knowledge. Armed with the control information, it uses the knowledge base to match facts in the working memory. When the inference engine finds a match, it will add the rule's condition to the working memory and continue to scan for other possible matches. The inference engine must also have the capability to modify and expand the knowledge base to draw conclusions about the problem.

The search strategy used by the inference engine to develop the required knowledge, or inference paradigm, can be one of three fundamental types (Bielawski and Lewand, 1988): (1) forward chaining, which starts with known conditions and works toward a desired goal; (2) backward chaining, which starts from the desired goal and works backward toward supporting conditions; or (3) mixed chaining, which is a combination of both forward and backward chaining. These search strategies for the inference engine will be further discussed in Section 2.1.3, "Problem Solving Strategies Using Expert Systems."

Since the inference engine is detached from the knowledge base, changes can be made to either component without necessarily having to alter the other. For example, one may be able to add information to the knowledge base, or increase the performance of the inference engine, without having to modify code elsewhere (Clancey, 1983). That is not to say that the inference engine is totally independent of the knowledge base. On the contrary, they are intimately related. Should the inference engine control the reasoning process at a very low level (*i.e.*, providing solution strategy flexibility), the knowledge base must contain concise and specific data. On the other hand, if the inference engine has a high-level reasoning process, the knowledge base does not need to be extensive.

The interaction between the knowledge base and inference engine constitutes the major source of uncertainty in the expert system due to unreliable information, incomplete information, or a poor combination of knowledge from different experts. Therefore, the expert system must be capable of handling this uncertainty. Three popular methods are subjective probability theory, the Dempster-Shafer theory, and more recently Bayesian networks, all of which will be described later in Section 2.1.3, "Problem Solving Strategies Using Expert Systems."

User Interface. This is how the user and the expert system communicate. The user interface should interact in a natural language style and should be as close as possible to humans in conversation in order to gather as much information as is possible. It may also be designed to allow the interface to change information in the working memory should this be desirable for the user.

The actual interface design can take on many variations. Today, most interfaces are interactive and make extensive use of menus, graphics, and specifically designed screens. Overall, the interface design should be as accommodating as possible.

Explanation Facility. An expert system should not just reach a conclusion when faced with a complex problem, but be capable of explaining to some extent, some of the reasoning that led to that conclusion. Since an expert system works on a problem that lacks a rigid control structure, this capability takes on some importance in an expert system due to the fact that the validity of the system's findings may come into question. Why a particular question is asked allows the user to feel more comfortable with the line of questioning, and understand what line of reasoning the system is pursuing.

Knowledge Acquisition Facility. In expert systems knowledge and data are constantly changing and expanding, and the knowledge base must be modified accordingly. The knowledge acquisition facility is an automatic way for the user to enter knowledge in the system rather than by having the knowledge engineer explicitly code the knowledge (Giarratano and Riley, 1989). The knowledge acquisition facility acts as an editor, allowing new knowledge to be entered, or modifying existing knowledge.

2.1.3 Problem Solving Strategies Using Expert Systems

The search to solve a problem with an expert system begins with known facts or data, and ends at a final conclusion or solution. This section discusses the various problem-solving strategies including general approaches, control strategies, and handling uncertainty.

2.1.3.1 General Approaches: In expert systems there are two main approaches to solve problems: the derivation approach and the formation approach (Maher, 1987). The derivation approach starts at a known state and uses deductive logic to arrive at a known solution. This approach is desirable if there are predefined solutions available in the knowledge base of the expert system. This means that the expert system will provide a solution based on the specifications of the given problem. If an inference network between the predefined solutions and the input data can be achieved, the derivation approach can be implemented.

The other general approach is the formation approach which uses information about the known state to generate more information to form higher level solutions. Information from the knowledge base is used in order to form a solution. This method is used when it is either impractical or impossible to store all the predefined solutions in the knowledge base. The formation approach is implemented by identifying parts of the solution and then heuristics to combine them.

2.1.3.2 Control Strategies: Many strategies for solving problems guided by the knowledge contained in the knowledge base exist. The three most common control strategies for choosing the next action, given many alternative problem-solving steps, are presented next.

Forward Chaining. An expert system uses a forward chaining strategy if it works from known facts to a conclusion. Forward chaining is advantageous since most problems begin with the gathering of information and then seeing what conclusions or goals can be reached from it. It can also provide information from only a small amount of input data.

Forward chaining operates by collecting all the initial information into the working memory. The information can be obtained from either the data base or inputted from the user. The system then scans the rules searching for a match. When a rule match is found, it is executed, or fired, placing its conclusion in the working memory. The scanning process is repeated again until no additional rules are fired.

It is possible that during a scan of the rules, several rules may be applicable. Usually though, only one of these rules needs to be fired before the system cycles through the rules again. This is called a recognize-resolve-act cycle (Durkin, 1994). There is also the process called conflict resolution in which several rules compete, but only one is to be fired. In this method, the rules are given a priority value in which the rule with the highest priority fires.

Some disadvantages exist with a forward chaining system, however. There may be no means for the system to recognize that some data might be more important than others. The system will also ask all possible questions, or require all possible input data for all possible conditions, which may not be known or relevant. Only a few questions may have been needed to arrive at a conclusion.

Backward Chaining. Backward chaining involves reasoning from a conclusion or hypothesis, backing through the rules in search of the facts which support or discount that hypothesis. This type of control strategy can be advantageous since some problems begin naturally by forming a hypothesis and then seeing if it can be proven: "I believe the chain just fell off my bike." This strategy also focuses on the given goal, asking questions that relate only to its solution. It searches the knowledge base that is relevant only to the current problem, as opposed to forward chaining which attempts to infer everything possible from all available information. The primary disadvantage of backward chaining is that it will follow a given line of reasoning even if the goal is dropped and switches to a different one (Durkin, 1994).

Backward chaining operates by collecting the set of rules that contain the solution in the THEN part. These rules are called goal rules: rules that can be proven if one of these goal rules fires. The goal rule will only fire if its premises are satisfied. These premises are in turn supported by other rules, which requires the inference engine to prove them as well. These are termed subgoals. The system then searches its rules recursively to validate both the subgoals and the original goal. Eventually a premise is reached that is not supported by any of the system's rules, *i.e.*, a primitive. The system may then ask the user other questions which will cause possible firing of other rules. These conclusions are then added to the working memory.

The entire process repeats until all subgoals and goals have been searched. The information provided by the user and inferred by the system are stored in working memory. With an understanding of the original goal, this information determines if it is true or false.

Mixed Chaining. The mixed chaining control strategy is when the system uses both forward chaining and backward chaining strategies. The advantage of mixed chaining is that the user supplies only the relevant information needed to solve the problem. If the initial hypothesis is wrong, the system moves to the next assumption based on the current information.

This strategy operates with known facts and assigns a probability to the potential solutions or conclusions. It then attempts to support the highest priority solution by creating subgoals and requesting additional information from the user if necessary. If the conclusion is false, the system takes the next highest priority solution and then attempts again to determine if the solution is true or false. This process is repeated until the solution is true.

2.1.3.3 Handling Uncertainty: An expert system is required to reason with uncertain information, so selecting an uncertainty theory to model the expert system becomes important. A discussion of the more popular theories for handling uncertainty is presented in the following.

Subjective Probability Theory. Subjective (or Bayesian) probability is used by most expert systems since it is favored by system developers (Levitt, 1988 and Tzvieli, 1992). This is because a knowledge base stores human knowledge and facts, and when representing an expert's knowledge, it is usually viewed as subjective by the programmer.

Subjective probability is developed from the theory of partial belief, called Bayesian theory after the English clergyman Thomas Bayes (1702-1761). The basic premise is that all degrees of belief should obey certain rules. By attributing A as the degree of belief p, given evidence B, the famous formula of Bayes can be stated (Pearl, 1988):

$$p(A|B) = \frac{p(B|A) \times p(A)}{p(B)} \qquad \textbf{(2-1)}$$

For Bayes' rule to handle the uncertainty found in expert systems, it must be developed into a different form. The mathematical extension of Bayes' theorem, which is detailed in Appendix A, yields the following basic equation for applying probability theory to expert systems,

$$p(A|B) = \frac{p(B|A) \times p(A)}{p(B|A) \times p(A) + p(B|-A) \times p(-A)} \qquad \textbf{(2-2)}$$

This states that the conditional probability of A given B can be obtained from the conditional probability of B given A. For example, consider an expert system where the rules are in the form: "If <*A* is true> Then <*B* will be observed with probability *p*>." Clearly, if A is observed, then the probability of event B is p. But Equation 2-2 is also applicable in the case when A is unknown and B is observed. Equation 2-2 can then be used to compute the probability that A is true as well.

Dempster-Shafer Theory. The Dempster-Shafer theory was originally developed in the 1960s by Arthur Dempster (Dempster, 1967) and later extended by Glen Shafer (Shafer, 1976) in the 1970s. The development of the theory was driven by the two difficulties Dempster and Shafer had with subjective probability theory. These were the representation of ignorance, and the idea that the subjective beliefs assigned to an event and its negation must sum to one (Ng and Abramson, 1990).

In probability theory, ignorance is represented by indifference or by uniform probabilities. The problem believed here is that uniform probabilities seem to represent more information than is known. Therefore, you can attribute equal prior beliefs to either complete ignorance or equal belief in all hypotheses (or events). Also, when new data or information does become available, the original ignorance expressed in the prior belief may no longer be valid.

The mathematical development of the Dempster-Shafer theory is outlined in Appendix B. Shafer believed that evidence which partially favors a hypothesis should not be construed as also supporting its negation. This contrasts with subjective probability theory, which states that once the probability of the occurrence is known, the probability of the hypothesis' negation is fixed, *i.e.*, $p(H) + p(-H) = 1$ (Shafer, 1976).

Bayesian Networks. One of the more promising belief networks that plays a central role in handling uncertainty are Bayesian networks (Pearl, 1988). Bayesian networks handle this uncertainty using probability theory and the formal use of diagrams. The diagrams show important conceptual information about the network.

Bayesian networks are represented by directed acyclic graphs (a directed graph is acyclic if there is no directed path $A_1 \rightarrow \ldots \rightarrow A_n$ such that $A_1 = A_n$) where each node represents an uncertainty. The use of arrows in the directed graphs allow for distinguishing dependencies between nodes by inspection. The probabilities assigned in the network are conditional and quantify conceptual relationships in one's own mind, *i.e.*, cause and effect. These are psychologically meaningful and can be obtained by direct measurement or data analysis. Appendix C details Bayesian networks and discusses its possible use as a model for the Site Screening component of PF-Model.

The greatest advantage of using directed graphs, such as Bayesian networks, is that it is easier to quantify the directed links with local nodes, turning the network into a globally consistent knowledge base (Pearl, 1988). The disadvantage of using a Bayesian network when applied to the Site Screening component, as detailed in Appendix C, is the subsequent scaling of posterior probabilities and assignment of priori probabilities to geologic evidence.

Other Theories. Two other theories for dealing with uncertainty in expert systems are possibility theory and the certainty factor approach. Possibility theory was developed by Zadeh (1978) due to the difficulties he had with using probability theory's representation of inexact or vague information. It is based on his theory of fuzzy sets. Possibility theory expresses vague terms such as "very likely" or "probably" with precision and accuracy. If these terms were coded with probability, their imprecision or "fuzziness" would be lost, *i.e.*, either the event occurred or it did not.

The advantage of possibility theory then is that events may be represented with shades of gray since human knowledge of facts is very rarely precise. There are disadvantages with fuzziness, however, that are identified in Cheeseman (1986), Stallings (1977), Wise and Henrion (1986), and Giles (1982). The disadvantages include the difficulty of interpreting fuzzy quantifiers and the necessity of fuzzy theories altogether.

In the 1970s, Shortliffe developed the certainty factor approach which he used in the later development of MYCIN, a medical expert system for the diagnosis of infectious blood diseases (Shortliffe and Buchanan, 1984). Shortliffe felt that probability theory would not be appropriate (Shortliffe *et al.*, 1979) for medical diagnosis, since decisions can vary over a wide spectrum, from categorical reasoning on one extreme to probabilistic at the other (Szolovits and Pauker, 1978). The certainty factor approach is designed to handle these difficulties. Obviously, there were disadvantages with this method, the most obvious brought out by Adams. He found, for example, that some unstated assumptions made by certainty factors may not be valid (Adams, 1976).

2.2 Site Screening Model Background

An essential step in successful site remediation is selection of appropriate technologies. Geotechnical properties play a major role in the decision process for *in situ* technologies like pneumatic fracturing. This section discusses the various geotechnical properties which are considered in the Site Screening component of PF-Model.

2.2.1 Geotechnical Properties

Years of experience and research with the pneumatic fracturing process have demonstrated that the success of the technology (or its failure) is dependent on a number of different geotechnical properties. This has led to a hierarchical ranking of the geological properties. After careful consideration and discussion with experts, it has been determined that seven different factors can significantly affect the pneumatic fracturing process (Sielski, 1998). They are presented below in the order of perceived importance.

- Formation type
- Depth
- Plasticity (soils)
- Relative Density/Consistency (soils)
- Fracture frequency (rocks)
- Weathering (rocks)
- Water table

Each of these will now be discussed in the context of their importance to pneumatic fracturing.

Formation Type. For soils, texture is the most fundamental descriptor of the geomaterial. The sizes of particles that make up soil vary over a wide range from clay size (< 0.075 mm) all the way up to boulders (> 9 in.) (Burmister, 1970). A number of different classification systems have been developed to describe particle size within an engineering context. Table 2.2 shows the more common classification systems including those developed by the U.S. Department of Agriculture (USDA), the American Association of State Highway and Transportation Officials (AASHTO), and the Unified Soil Classification System, (USCS) developed by the U.S. Army Corps of Engineers. In the United States, the USCS is the most used.

Table 2.2 Particle Size Classifications (Das, 1994).

	Grain size (mm)			
Name	**Gravel**	**Sand**	**Silt**	**Clay**
USDA	>2	2 to 0.05	0.05 to 0.002	< 0.002
AASHTO	76.2 to 2	2 to 0.075	0.075 to 0.002	<0.002
USCS	76.2 to 4.75	4.75 to 0.075	Fines (*i.e.*, silts and clays) <0.075	

The principal effect of soil texture on pneumatic fracturing is that it largely controls the permeability and porosity of the soil. This is related to the basic principle that a pneumatic fracture will continue to propagate only as long the fluid injection rate exceeds the ability of the soil pores to accept the fluid, *i.e.*, the permeability. For example, when air is injected into clay soils, the natural permeability of the formation can not accept the air quick enough, and discrete fractures are created in the formation.

Conversely, in a coarse soil formation such as sand which has a relatively high permeability, the effect of pneumatic fracturing is very different. Although there may be some local fracturing around the borehole, for the most part the sand is able to accept the injected air. In this instance, the main effect is rapid aeration as air passes through interstitial pore spaces.

In cases where soils have a marginal permeability, it becomes difficult to predict the effect pneumatic fracturing will have. In this instance, more evidence about the soil formation is required.

In rocks, the lithology acts as the fundamental descriptor (type, color, mineral composition, and grain size are all lithologic characteristics) (Boggs, 1987). The principal effect of rock lithology on pneumatic fracturing is that it largely controls discontinuities and interconnectivity.

For example, consider a sedimentary rock such as shale or sandstone. Sedimentary rocks are formed by particle deposition and are characterized by their distinctive layers. This layering, also known as stratification, imparts numerous and regular discontinuities which dilate during pneumatic fracturing. A certain amount of dilation is permanent, leading to substantial increases in permeability and interconnectivity.

On the other hand, igneous and metamorphic rocks are not formed by particle deposition and their existing discontinuities are mostly formed by thermal strain during cooling or tectonic movements. Discontinuity patterns are less regular, and it is likely that permeability and interconnectivity are more difficult to enhance. It is noted that, unlike sedimentary rocks, experience with pneumatic fracturing of igneous and metamorphic rocks is very limited.

Overall, when pneumatic fracturing is applied to a formation, there are expected trends and predictable behaviors. Fine-grained soils and sedimentary rocks respond well to permeability enhancement by pneumatic fracturing. In contrast, coarse-grained soils (*e.g.*, sand) already have substantial permeability and pneumatic fracturing is not appropriate for permeability enhancement. However, media injection by the pneumatic fracturing process might still be recommended as an alternative technology variant for coarse-grained soils. In summary, then, it is texture and lithology that largely determine whether or not fractures will be formed, and also how fluids will move through the formation. Thus, these are clearly the most important parameters in determining the applicability of pneumatic fracturing, and they will be the dominant pieces of evidence in the probabilistic model.

Depth. The depth of a formation is the second most important parameter in determining whether or not pneumatic fracturing will be successful. Pneumatic fracturing projects to date have reached depths of 50 ft, but there is no theoretical maximum depth limit. As long as sufficient back pressure and flow can be delivered into the formation with higher capacity equipment, fracturing can be propagated at greater depths.

The minimum depth of injection is based on the ability of the formation to act as a "seal" during injection. For example, formations which are made of fill materials will tend to exhibit "daylighting" which means that the fractures will intersect the ground surface. However, formations such as rock will allow injections closer to the surface, *i.e.*, 3 ft, with minimal amounts of daylighting.

Plasticity. Another important property is plasticity. A soil that can be remolded in the presence of some moisture without crumbling is said to be plastic. Plasticity applies only to fine-grained soils when clay minerals are present (*i.e.*, clay, clayey silt, clayey sand, and silty clay). Soil plasticity is measured using the Atterberg Limits Test (ASTM D4318-93) which correlates soil moisture content with plastic behavior. Descriptions of soil consistency in relationship to Atterberg Limits are presented in Table 2.3.

Table 2.3 Description of Atterberg Limit Range.

Atterberg Limit Range	Description
$w < PL$	brittle
$PL < w < LL$	plastic
$w > LL$	liquid

Note: PL = plastic limit, LL = liquid limit, and w = moisture content

It has generally been found that brittle soils ($w < PL$) respond well to pneumatic fracturing (Pisciotta *et al.*, 1991, and Schuring *et al.*, 1991). Experience has shown that soils which are in the plastic range ($PL < w < LL$) can also be successfully fractured.

However, post-fracture air flows in plastic soils may be retarded by moisture in the pores and fractures.

As the moisture content of a clay soil increases above the liquid limit ($w > LL$), the soil exhibits a tendency to flow. Although there has been little field experience with fracturing soils above the liquid limit, laboratory studies have shown that fracture healing could be a problem (Hall, 1995).

Relative Density/Consistency. This geotechnical property is only used to describe soil formations. Relative density is applied to cohesionless soils, *e.g.*, sand, while consistency is applied to cohesive soils, *e.g.*, clay. The relative density/consistency is usually obtained by the widely used standard penetration test or SPT (ASTM D1586-84), which consists of driving a split spoon sampler into the ground by dropping a 140 lb. weight from a height of 30 in. The sum of the blows required to drive the spoon is recorded and is used to compute the standard penetration resistance, or *N-value* (Sowers and Sowers, 1970).

Table 2.4 on the following page shows a correlation between penetration resistance and relative density for cohesionless soils, and a correlation between penetration resistance and consistency for cohesive soils.

Relative density/consistency has two important influences on the propagation of pneumatically induced fractures. First, it is an indication of the elastic modulus or stiffness of soil formations. Loose or soft soil formations will usually exhibit localized deformation around the injection point resulting in modest propagation radii. In contrast, firm or stiff formations will deform less but influence radii will be larger.

Table 2.4 Standard Penetration Test.

Relative Density of Cohesionless Soils		Consistency of Cohesive Soils	
Penetration Resistance, *N* (blows/ft)	Relative Density	Penetration Resistance, *N* (blows/ft)	Consistency
0-4	Very loose	< 2	Very soft
4-10	Loose	2-4	Soft
10-30	Medium dense	4-8	Medium
30-50	Dense	8-15	Stiff
> 50	Very dense	15-30	Very Stiff
		> 30	Hard

The second influence of relative density/consistency on pneumatic fracturing is it may affect the direction of fracture propagation. It is well known that in the hydraulic fracturing industry that fractures tend to propagate perpendicular to the direction of least principal stress (Hubbert and Willis, 1957). Therefore, in formations where the least principal stress is vertical, most pneumatically induced fractures occur in the horizontal plane. Such behavior may be expected in soils that are at least of firm density or medium consistency. Since most formations tend to be overconsolidated due to past geologic events (and therefore more likely to be of firm density or medium consistency), horizontal fractures are most often expected when the pneumatic fracturing process is applied. It follows that in formations of loose density or soft consistency, fractures will tend to propagate in the vertical plane.

Although the standard penetration test is a valuable method of soil investigation, it should only be used as a guide for relative density/consistency since results are always approximate (Lambe and Whitman, 1969). Therefore, caution must be applied when applying this piece of evidence in the probabilistic model. In general, the standard penetration test is considered more reliable for cohesionless soils than cohesive soils.

Fracture Frequency. Discontinuities, or fractures, occur naturally in rock formations, originating from thermal and tectonic stresses, as well as unloading of overburden materials. Various types of discontinuities are encountered including cracks, joints, faults, and shear zones (Bates and Jackson, 1984). In general, rock formations of the same lithology develop a somewhat similar discontinuity geometry. For example, basalt commonly exhibits vertical columnar joints, while shale exhibits bedding joints.

Research over the last 10 years has shown that the principal effect that pneumatic fracturing has on rock formations is that it dilates existing discontinuities. Thus, rocks with fairly frequent fractures will respond best. Conversely, formations with only a few widely spaced fractures are not good candidates for the pneumatic fracturing technology since process pressures are not sufficient to break intact rock. It is further noted that pneumatic fracturing may also have reduced effectiveness in intensely fractured rock formations due to high leakoff rates. The standard scale for fracture frequency for field classification of rocks is given in Table 2.5 on the following page.

Weathering. The breakdown of rocks by weathering involves three processes: chemical, physical, and biological. The most important of these as it applies to pneumatic fracturing is by far the chemical process. In the chemical process secondary minerals are

Table 2.5 Standard Scale for Fracture Frequency for Field Classification of Rocks.

Fracture Frequency	Spacing	Description for Structural Features: Bedding, Foliation, or Banding
Widely jointed	> 2 ft	Thickly to very thickly
Medium jointed	8 - 24 in.	Medium
Closely jointed	< 8 in.	Thinly to very thinly

formed *in situ* by chemical recombination and crystallization. Secondary minerals continue to accumulate as weathering progresses, eventually forming a residual soil of various grain sizes from clay to gravel (Boggs, 1987).

It is obvious then that rock formations that are highly weathered will respond to pneumatic fracturing like soil formations, and thus can develop new fractures. Partially weathered rock formations will exhibit an intermediate behavior. However, a rock formation that is relatively unweathered will contain only discrete discontinuities like those described in the previous section, so enhancement results from dilation.

Water Table. The last geotechnical property of concern is water table depth. For permeability enhancement, there does not appear to be any significant difference in the effectiveness of the pneumatic fracturing process in either the vadose or saturated zone (U.S. EPA, 1993). Saturation may have some effect on propagation radius, however, due to increased unit weight and improved pressure sealing. Also, if performing a dry media or liquid media injection, the vadose zone may be preferred since media transport in the saturated zone is retarded by the pore water.

2.3 System Design Model Background

Fracture propagation radius is one of the most critical and frequently asked questions on pneumatic fracturing projects. The design of a project, and even the applicability of the pneumatic fracturing technology, is based largely on the extent to which fractures will propagate. Figure 2.2 provides a schematic of the pneumatic fracturing process showing a typical subsurface fracture pattern.

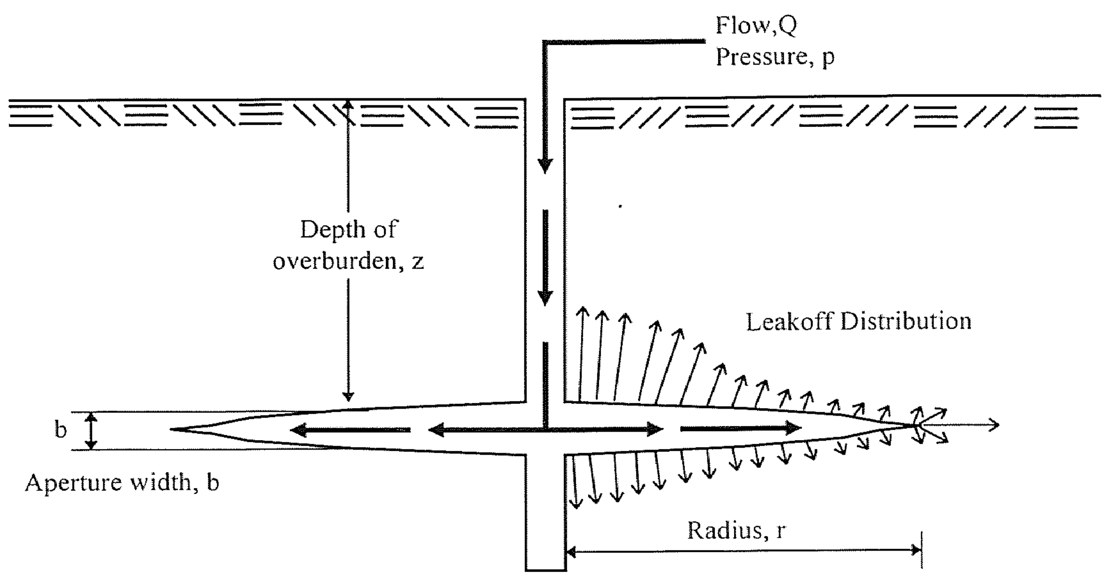


Figure 2.2 Pneumatic Fracturing Process.

Fracture propagation has been studied for various types of soil and rock media in relation to several different mechanisms including magma intrusion, hydraulic fracturing, and explosive fracturing. Magma intrusion is a natural phenomena in which molten rock penetrates geologic formations at a relatively low velocity of 0.5 m/sec (Pollard, 1973; Spence and Turcotte, 1985). Propagation velocities for hydraulic fracturing are similar to those for magma intrusion. Numerous studies of hydraulic fracture propagation have been conducted due to its importance in the petroleum industry (Perkins and Kern, 1961; Geertsma and de Klerk, 1969). Explosive fracturing, which causes much higher propagation velocities (approximately 330 m/sec and greater), has been applied to enhance the permeabilities of oil, gas, and geothermal wells (Nilson *et al.*, 1985).

Pneumatically induced fractures propagate at velocities which are intermediate between the previously cited mechanisms. A unique aspect of pneumatic fracture propagation is the profound influence of formation leakoff owing to the lower viscosity of the fracturing fluid. The effects of leakoff have been modeled during a recent study at CEES (Puppala, 1998). This model serves as the basis for the algorithmic logic used in the System Design component of PF-Model. The approach is developed around the coupling of three physical processes controlling propagation:

- pressure loss due to frictional effects,
- leakoff into the surrounding formation, and
- deflection of the overburden.

Pressure loss is modeled based on Poiseuille's law, leakoff is modeled using two-dimensional Darcian flow, while deflection is modeled as a circular plate clamped at its edges and subjected to a logarithmically varying load. These processes and their coupling are discussed in detail in Section 3.3, "System Design Approach."

CHAPTER 3

PROGRAM AND MODEL APPROACH

3.1 Overview of Concept and Model Components

In order for technologies to advance from the research arena into the industrial sector, they must undergo the process of technology transfer. The "leap" of technology transfer is an important, yet difficult link to accomplish. Pneumatic fracturing is receiving considerable industrial attention since it addresses a problem which has plagued environmental clean-up efforts to date, *i.e.*, remediation of low permeability geologic formations. It is clear, then, that the computer model greatly enhances the technology transfer of pneumatic fracturing by linking together the results of numerous laboratory studies, pilot field demonstrations, and analytical modeling studies. Figure 3.1 on the following page illustrates the conceptual role of the computer model in the technology transfer of pneumatic fracturing.

PF-Model is a Windows™ format program which is interactive with the user. The program contains a data library (*i.e.*, the knowledge base) of geotechnical probabilities related to pneumatic fracturing based on previous experience and expert knowledge. It also contains an extensive default library which is calibrated to previous site data. PF-Model allows potential users to add proprietary data generated by future projects into the knowledge base and default library. A nominal amount of format detailing is incorporated for user convenience. The program has two principal

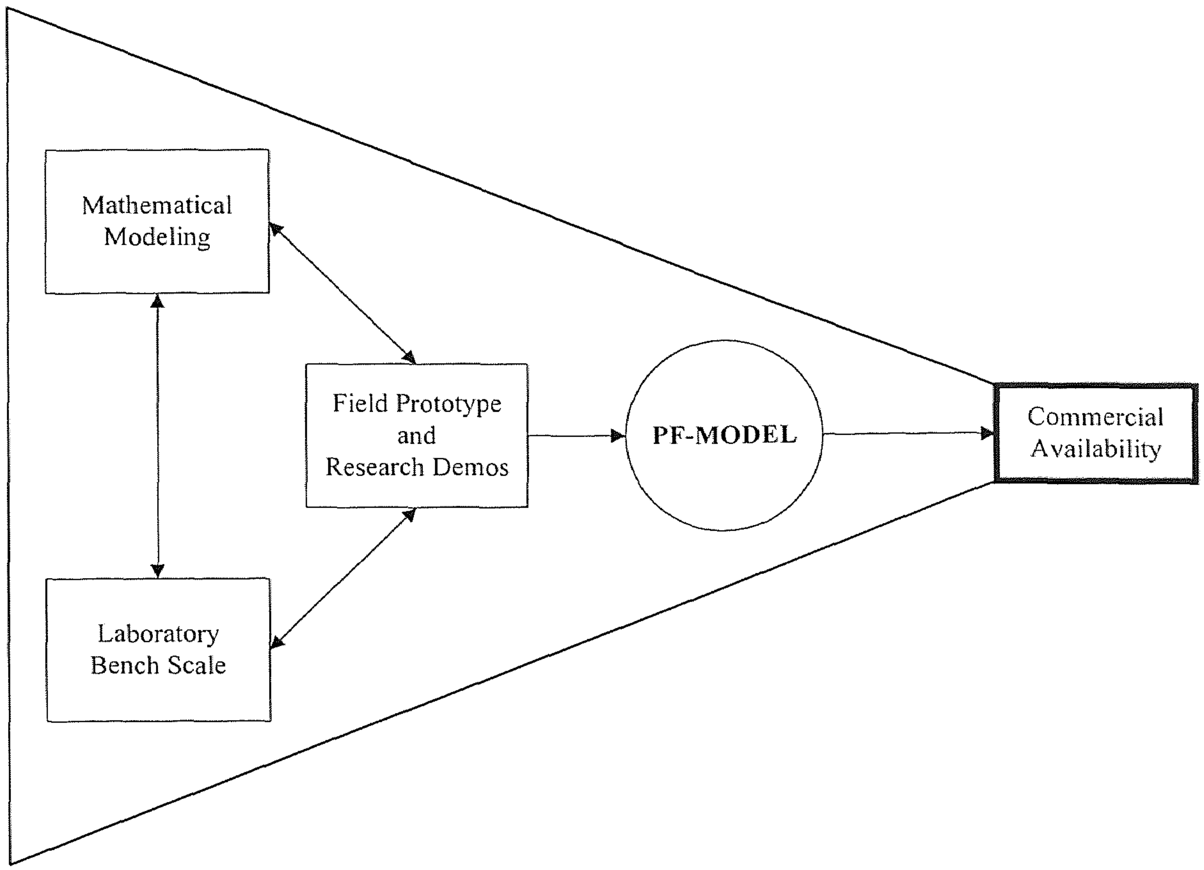


Figure 3.1 Conceptualization of the Technology Transfer Process.

components: Site Screening and System Design. Figure 3.2 on the following page is a "top level" flow chart showing the model component's interactions and outputs. The dashed lines in Figure 3.2 represent areas of future research.

This section will introduce these model components. Discussion of the design approach for Site Screening and System Design are detailed in Sections 3.2 and 3.3, respectively. The Calibration Mode (Section 3.4) follows. The chapter will conclude with a description of the program language and structure (Section 3.5).

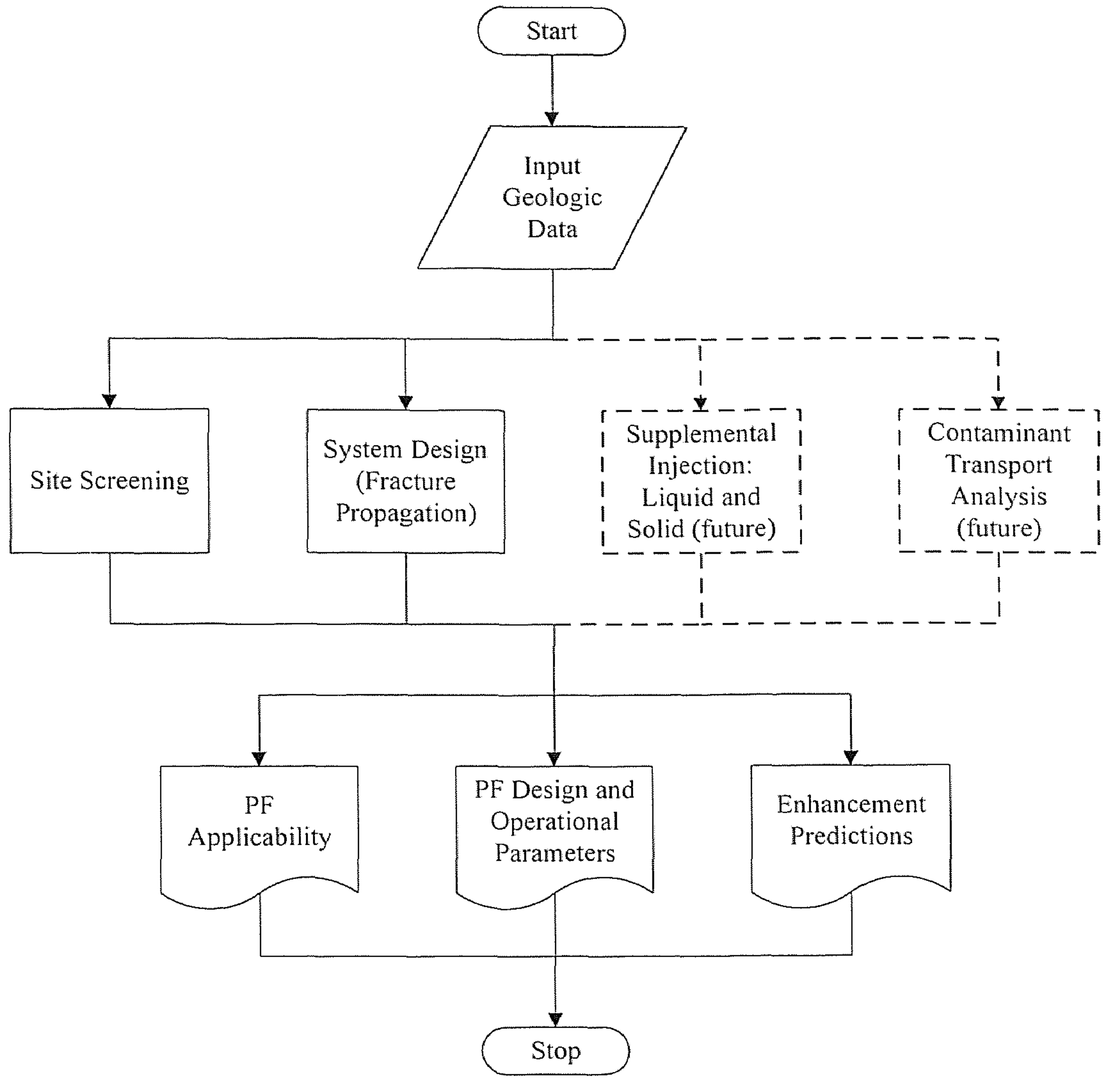


Figure 3.2 Top Level Flow Chart Showing the Model Components.

3.1.1 Site Screening

This component incorporates data collected from pneumatic fracturing projects to date, and new data can be added as it becomes available. The needed input data for a site screening analysis was previously discussed in Section 2.2.1, "Geotechnical Properties." They include formation type, depth, relative density, consistency, plasticity, fracture frequency, weathering, and water table depth. These data are modeled as expert heuristic knowledge, *i.e.*, knowledge that cannot be quantified, in PF-Model's knowledge base.

To activate this model component, the user must first enter any known or estimated geologic properties for a prospective site. The program then compares the inputted information with the knowledge base. Based upon the results of these comparisons, a semi-quantitative applicability rating will be assigned for the prospective site. The programming methods to reach this decision will be based largely on expert systems.

3.1.2 System Design

The ability to initiate and propagate pneumatic fractures is a function of the geomechancial properties of the formation, as well as the depth of overburden. A model for predicting pneumatic fracture initiation and maintenance pressure has been developed at HSMRC by considering the geologic medium to be brittle, elastic, and overconsolidated (King, 1993). A model study describing fracture propagation behavior is also available (Puppala, 1998). These two studies form the basis of the fracture propagation component of PF-Model.

Most often the System Design component will be used in a "Fracture Prediction Mode" which is activated when the user enters the system parameters and site geological properties. The system parameters which influence fracture propagation are the injection flow rate and well radius. The key geologic properties which must be input into PF-Model to analyze fracture propagation are modulus of elasticity, cohesion, soil/rock density, and depth of overburden. If the user is unable to determine these key parameters, or if they are unavailable, the computer program provides default values. For the system parameters the program defaults for flow rate and well radius are 1500 scfm and 0.25 in., respectively (although some flow rates may vary based on formation type, *i.e.*, typically 100-200 scfm higher in rock). For the geotechnical properties, the default values are based largely on a general textural description of the geologic materials at the site, *e.g.* silty sand, clayey silt, shale, etc. For example, if the site formation is sandstone, but no tests were performed to determine the rock density, the user could allow the computer program to use the default value, in this instance 140 lb/ft^3. Default values for the 14 geologic formation types supported by the program are given in Appendix D.

3.1.2.1 Calibration Mode: Another important function of PF-Model's System Design component is the "Calibration Mode." In this mode, the post-fracture Young's modulus and pneumatic conductivity can be estimated if a pilot test has been performed at a site. Evidence and system data are entered just as in the Fracture Prediction Mode, and after a series of calculations, the estimated modulus and conductivity can be updated as known evidence for the Fracture Prediction Mode. This allows for a more accurate estimate of fracture extent. This mode is detailed further in Section 3.4, "Calibration Mode."

3.1.2.2 Consistency and Strength of Clay Soils: As discussed in Section 2.2.1, the consistency of fine-grained soils is used as a piece of evidence in the expert system. However, consistency also plays a major role in the System Design component. The pneumatic conductivity and modulus of fine-grained formations vary according to consistency. Therefore, PF-Model will select different default values based on formation type and consistency, thereby greatly affecting the final estimated aperture and radius.

It is advantageous, then, to expand this system utility (*i.e.*, Relative Density/Consistency) to include other descriptors. At times, field data may be available in the form of SPT penetration, visual description, or unconfined compressive strength, q_u. The relationship of these descriptors to consistency is shown in Table 3.1. In PF-Model, this table functions as an interactive system utility, where the user selects the appropriate descriptor and then PF-Model uses the corresponding consistency.

Table 3.1 Guide to Consistency and Strength of Clay Soils.

Consistency	SPT Penetration (blows/ft)	Field Identification Guide	Estimated Unconfined Compressive Strength, q_u (tons/ft^2)
Very soft	< 2	Extruded between fingers when squeezed	< 0.25
Soft	2 - 4	Molded by slight finger pressure	0.25 - 0.5
Medium	4 - 8	Molded by strong finger pressure	0.5 - 1.0
Stiff	8 - 15	Readily indented by thumb, but penetrated only with great effort	1.0 - 2.0
Very stiff	15 - 30	Readily indented by thumbnail	2.0 - 4.0
Hard	> 30	Indented with difficulty by thumbnail	> 4.0

Another descriptor related to consistency, but not as definitive, is the overconsolidation ratio (OCR). Some users may prefer to describe soil by OCR in lieu of the descriptors mentioned above. Therefore, the guide shown in Table 3.2 which related consistency to OCR is also incorporated into PF-Model, but as a subsequent interactive utility to Table 3.1.

Table 3.2 Approximate Relationship Between Consistency, Consolidation, and OCR.

Consistency	Typical Consolidation Description	Typical Value of OCR
Very soft to soft	Normally consolidated	OCR < 1
Medium to stiff	Slightly overconsolidated	1 < OCR < 5
Very stiff to hard	Heavily overconsolidated	OCR > 5

3.1.3 Future Components

The components of PF-Model can be considered "modules" that can be added or removed from the main program at any time. Therefore, future model components can be added at a later date as research progresses. Two components which are currently planned include Supplemental Media Injection and Contaminant and Transport Analysis, and these are discussed briefly below.

Supplemental Media Injection. In some pneumatic fracturing applications, liquid or solid supplements are injected into the formation during the fracturing process to enhance *in situ* treatments (*e.g.*, bioremediation, reactive media injection), or for the purposes of mechanical propping. For example, during a recent U.S. EPA SITE Emerging Technology Project by HSMRC (U.S. EPA, 1995), liquid nutrients and buffer solutions were injected into fine-grained soils at a refinery site to enhance bioremediation of gasoline contamination. Thus, there is a clear need for development of a mathematical model to predict the distribution of supplemental media for various flow rates and injection times into the subsurface. Once developed, it can be added into the computer model.

Contaminant Transport Analysis. After a geologic formation has been pneumatically fractured, the ability to treat and/or remove contaminants depends on the flow and transport characteristics of the fractured medium. Once a fracture network is established in a formation, contaminants are more easily accessed since the diffusive distances are shortened. A one-dimensional solution for a single discrete fracture is currently available (Ding, 1995). Work is underway to extend this to multiple fractures, and this component can be added at a later date.

3.2 Site Screening Approach

The general approach to the site screening model was to implement an expert system that establishes the applicability of pneumatic fracturing for a particular site. Figure 3.3 depicts a flow chart of the site screening model component in which the dotted box represents the tasks and actions performed by the expert system.

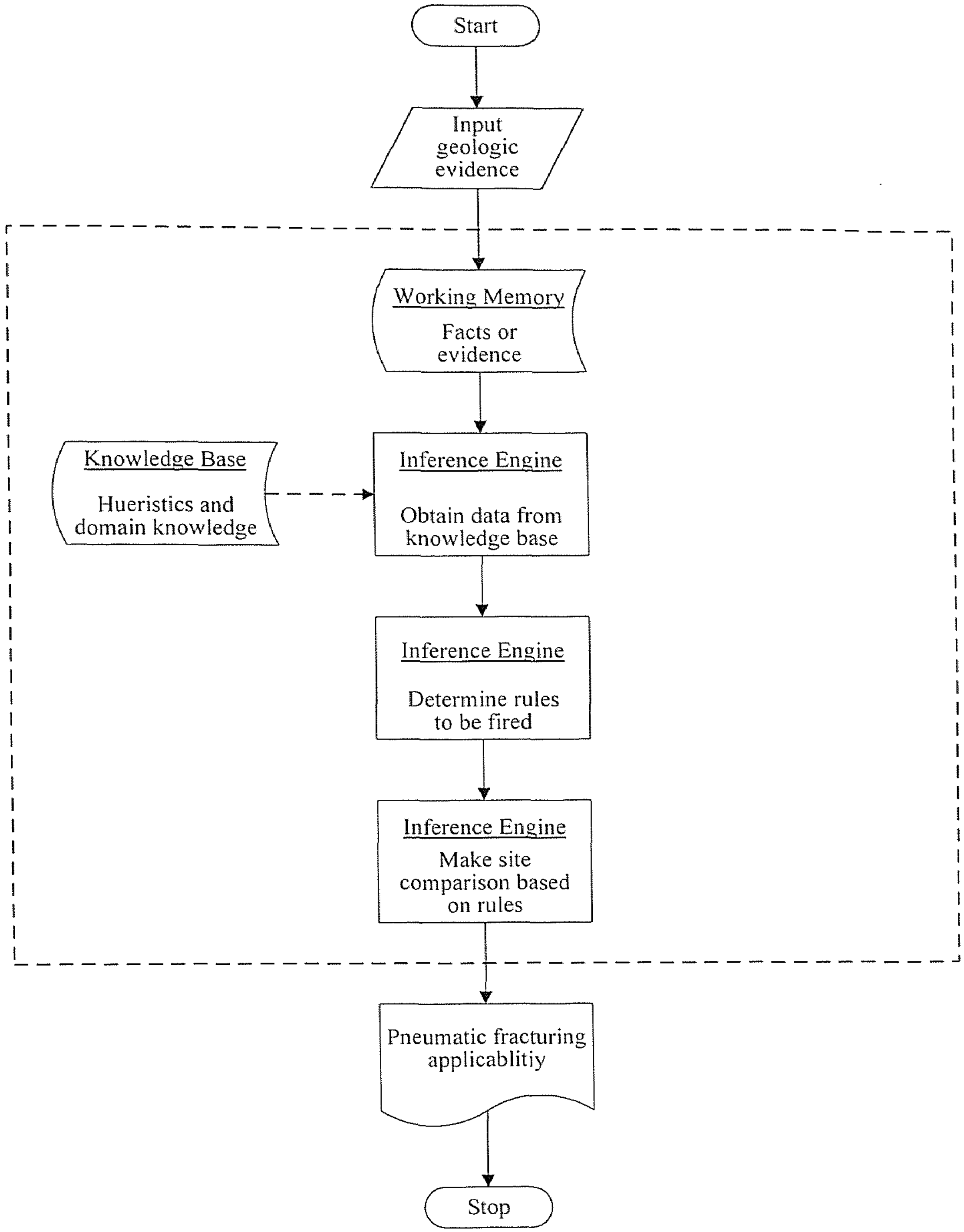


Figure 3.3 Flow Chart of Site Screening Component.

The critical aspect of any expert system is the selection of which uncertainty theory to use, which is strongly dependent on the problem domain and any existing conditions. For reasons discussed in Chapter 2, it was determined that subjective probability theory is the most appropriate for PF-Model since it has outperformed the other competing theories (Wise and Henrion, 1986) and experts were available for technical conversations. Forward chaining acts as the control strategy of PF-Model's expert system since the pneumatic fracturing process starts out with pieces of geological evidence proceeding toward a single conclusion, *i.e.*, the applicability of the pneumatic fracturing technology.

The probabilities that are required to determine pneumatic fracturing applicability ratings are stored in the knowledge base. Table 3.3 on the following page shows the assigned probabilities in the knowledge base for permeability enhancement. The probabilities for dry and liquid media injection are located in Appendix E.

The probabilities for the three different technology variants were established through discussions with pneumatic fracturing experts over a period of months. The dominant consideration was past performance of pneumatic fracturing under a variety of geologic conditions. Careful attention was given to the "relative scale" of probabilities between the various formations, as well as the "absolute scale" which acknowledged the importance of a particular type of evidence. It is noted that field reference data are limited and some probabilities are speculative based upon the inherent geotechnical properties of a particular formation.

Table 3.3 Assigned Permeability Enhancement Probabilities for the Site Screening Component of PF-Model.

Formation		***Plasticity*** [b]	
Clay	0.65	$w < PL$	0.60
Clayey Sand	0.70	$PL < w < LL$	0.45
Clayey Silt	0.75	$w > LL$	0.10
Silty Clay	0.70		
		Consistency [b]	
Silt	0.50	Soft	0.40
Silty Sand	0.45	Medium	0.50
Sand	0.25	Stiff	0.60
Sand & Gravel	0.20		
Gravel	0.10	***Relative Density*** [c]	
		Loose	0.40
Shale/Siltstone	0.75	Medium dense	0.50
Sandstone	0.65	Dense	0.60
Limestone/Dolomite	0.65		
Granite/Gneiss/Schist	0.55	***Weathering*** [a]	
Basalt	0.50	Slightly weathered	0.45
		Moderately weathered	0.60
Depth		Heavily weathered	0.55
< 4 ft [a]	0.40		
4 - 8 ft [a]	0.55	***Fracture Frequency*** [a]	
> 8 ft [a]	0.65	Widely jointed	0.20
		Medium jointed	0.50
< 6 ft [b, c]	0.25	Closely jointed	0.60
6 - 12 ft [b, c]	0.50		
> 12 ft [b, c]	0.55	***Water Table***	
		Fracturing is above	0.52
		Fracturing is below	0.48

Notes: a - applicable to rocks
b - applicable to fine-grained soils
c - applicable to coarse-grained soils

Note that for certain formation types, some geotechnical properties may not be applicable as evidence. For example, if the formation is a silty sand, the only applicable geotechnical properties are depth (for soils), relative density, and water table. It is therefore the task of the inference engine to determine which probabilities are applicable and which rules are to be fired.

The rules to be fired can be categorized by their overall interactions. Since some of the geotechnical properties listed in Table 3.3 apply to certain types of formations (*i.e.*, only clay soils exhibit plasticity), while other properties had different states for the categorized formations (*i.e.*, the states of depth for soil and rock are different), interpretation by the inference engine is difficult. Therefore, in order to minimize internal code, processing time, and logic, the geologic formations are arranged into three different categories which are accessed separately by the inference engine. These are shown in Tables 3.4 to 3.6 which follow.

Table 3.4 Geologic Properties that Apply to Fine-Grained Soils (Clay, Clayey Sand, Clayey Silt, Silty Clay).

• Depth < 6 ft 6 - 12 ft > 12 ft
• Consistency soft medium stiff
• Plasticity $w < PL$ $PL < w < LL$ $w > LL$
• Water Table fracturing is above fracturing is below

Table 3.5 Geologic Properties that Apply to Coarse-Grained Soils (Silt, Silty Sand, Sand, Sand & Gravel, Gravel).

• Depth < 6 ft 6 - 12 ft > 12 ft
• Density loose medium dense dense
• Water Table fracturing is above fracturing is below

Table 3.6 Geologic Properties that Apply to Rocks (Shale/Siltstone, Sandstone, Limestone/Dolomite, Granite/Gneiss/Schist, and Basalt).

• Depth < 4 ft 4 - 8 ft > 8 ft
• Fracture Frequency widely jointed medium jointed closely jointed
• Weathering slightly weathered moderately weathered heavily weathered
• Water Table fracturing is above fracturing is below

Figure 3.4 on the following page is a flow chart that shows how the inference engine will access each probability from the knowledge base. By examining the flow

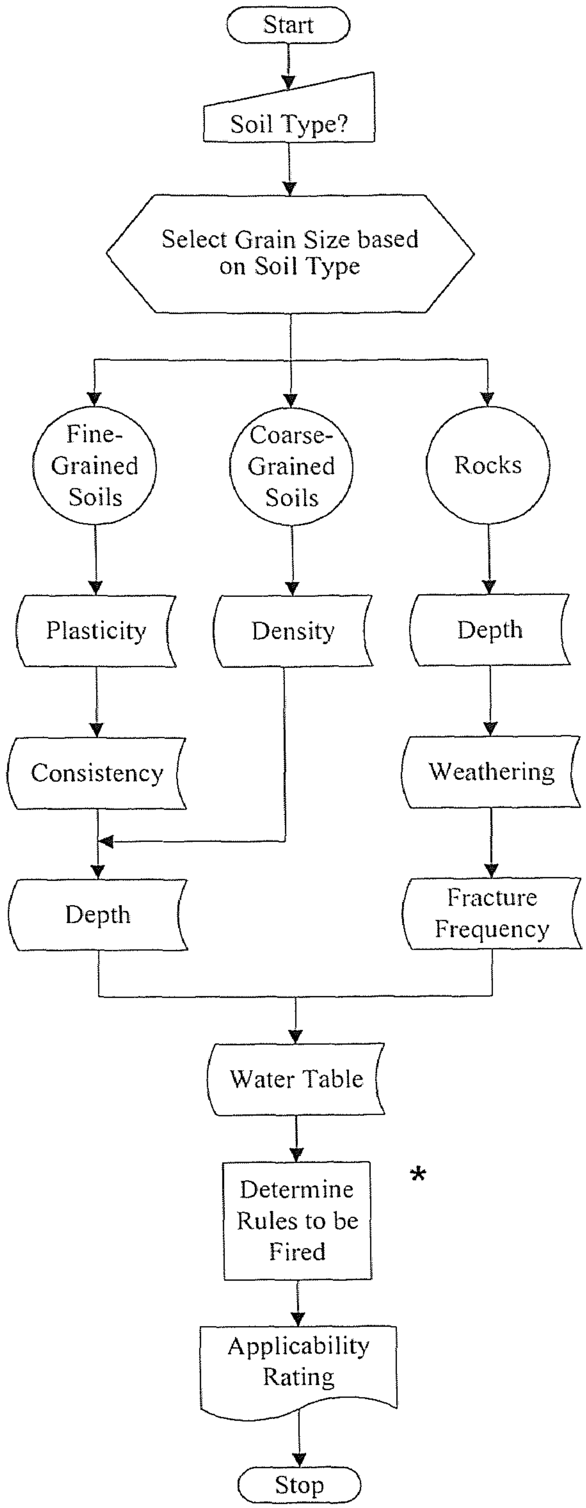


Figure 3.4 Flow Chart Representing How Inference Engine Accesses Probabilities From Knowledge Base.

chart, it can be seen that the model obtains evidence and then proceeds toward a desired goal (*i.e.*, forward chaining).

Figure 3.4 also shows the step in the heuristic process where the inference engine determines the rules that are to be fired (refer to the "*" in the figure). As pointed out previously in Chapter 2, the selection of the rule and the uncertainty theory used is the most important aspect of the inference engine, and the discussion which follows will provide a clearer understanding of the implementational logic used.

In order to clarify the implementational logic (or which rules are fired) in the inference engine, it is advantageous to change the terms *A* and *B* of Equation 2-2. In subjective probability, if we let *p(H)* be the prior probabilities of all possible hypotheses, and *p(E|H)* be the conditional probabilities for observing a piece of evidence given a hypothesis, Equation 2-2 can be rewritten in terms of *H* and *E*. This yields:

$$p(H|E) = \frac{p(E|H) \times p(H)}{p(E|H) \times p(H) + p(E|-H) \times p(-H)} \qquad \textbf{(3-1)}$$

Initially, the user will give the system information about characteristics of the site (*i.e.*, the evidence). The posterior possibility, $p(H_i|E_j \ldots E_k)$, is computed for all hypotheses $(H_1 \ldots H_m)$ from the supplied evidence $(E_j \ldots E_k)$ and stored probabilities.

The Site Screening component of PF-Model has two hypotheses; pneumatic fracturing is applicable and pneumatic fracturing is not applicable. There is also the possibility that numerous pieces of evidence are available. In order to account for both multiple hypotheses and multiple pieces of evidence, Equation 3-1 can be generalized in a manner proposed by Ng and Abramson (1990). This is accomplished by first considering a single piece of evidence with multiple (mutually exclusive and exhaustive) hypotheses. The relation becomes:

$$p(H_i|E) = \frac{p(E|H_i) \times p(H_i)}{\sum_{k=1}^{m} p(E|H_k) \times p(H_k)} \tag{3-2}$$

For multiple evidence and multiple (mutually exclusive and exhaustive) hypotheses, the following is obtained:

$$p(H_i|E_1E_2 \ldots E_n) = \frac{p(E_1E_2 \ldots E_n|H_i) \times p(H_i)}{\sum_{k=1}^{m} p(E_1E_2 \ldots E_n|H_k) \times p(H_k)} \tag{3-3}$$

In order to simplify Equation 3-3, conditional independence can be assumed among the pieces of geological evidence given the hypothesis. Therefore,

$$p(H_i|E_1E_2 \ldots E_n) = \frac{p(E_1|H_i) \times p(E_2|H_i) \times \ldots \times p(E_n|H_i) \times p(H_i)}{\sum_{k=1}^{m} p(E_1|H_k) \times p(E_2|H_k) \times \ldots \times p(E_n|H_k) \times p(H_k)} \tag{3-4}$$

This is the general equation used by the inference engine in determining the applicability of pneumatic fracturing in the Site Screening component.

Appendix F contains an illustrative example of how subjective probability theory is used to perform site screening. The example shows how various pieces of evidence such as grain size, overburden, and plasticity result in a belief for the applicability of pneumatic fracturing.

3.3 System Design Approach

Over the years, there has been extensive research in the field of pneumatically induced fractures and its controlling physical processes. Recent efforts by Puppala (1998) have led to the development of a mathematical model that determines the radius of pneumatic fractures in soil and rock formations. This section will present the background information leading to the final conclusions of that study regarding fracture propagation, followed by a detailed discussion of PF-Model's System Design algorithm.

3.3.1 Physical Processes

There are three physical processes that control pneumatically induced fractures. They are pressure distribution, leakoff, and deflection. These three processes are coupled to predict the radius of fracture propagation. This section briefly discusses each of the three models.

Pressure Distribution Model. A model has been developed at NJIT that defines the relationship between air flow and artificially induced fractures (Nautiyal, 1994). The model accounts for the pressure dissipation in a fracture which states that as radial distance increases from the injection well, pressure head decreases within the fracture. The solution is based on Poiseuille type flow between two infinite, smooth parallel plates and is given by:

$$\frac{d\phi}{dx} = \frac{\mu}{g\rho}\frac{d}{dy}\left(\frac{du}{dy}\right) \tag{3-5}$$

where ϕ is the potential function, u is the velocity of the fluid, μ is the dynamic viscosity of the fluid, and ρ is the fluid's density. Accounting for compressibility and solving the differential equation yields:

$$p_{n+1} = \sqrt{p_n^{\,2} - \frac{12 p_n Q \mu \ln\left(\frac{r_{n+1}}{r_n}\right)}{\pi g \rho b^3}} \tag{3-6}$$

where p_n and p_{n+1} are pressures at distance r_n and r_{n+1} respectively, Q is the flow between r_n and r_{n+1}, b is the fracture aperture, and g is acceleration due to gravity.

Leakoff Model. Fracture propagation is also affected by leakoff, the physical process where gas escapes from the fracture plane and into the formation. Leakoff is modeled in three dimensions to account for pressure variations with respect to the distance from the injection well. Formation anisotropy and fluid losses at the fracture tip are also considered. The leakoff model uses two approaches to predict the complex pattern of leakoff that occurs in a fracture: a graphical method and an analytical method.

In the graphical (or flownet) method, Darcy's law is modified to account for the variation in leakoff with radial distance. Darcy's equation for two-dimensional flow is given as:

$$Q_{leak} = K_{gas} H \left(\frac{N_f}{N_d} \right) \tag{3-7}$$

where Q_{leak} is the air flow lost, K_{gas} is the effective pneumatic conductivity of the formation, H is the total head driving the flow, N_f is the number of flow tubes, and N_d is the number of potential drops.

To account for pressure variation with respect to radial distance, the length of the fracture is divided into 'n' segments and then the number of flow tubes leaving each segment is counted. The leakoff occurring in each segment can then be computed as:

$$Q_{leak} = \sum_{r_0 = r_w}^{r_n = R} K_{gas} H_n \left(\frac{N_f}{N_d} \right)_n \tag{3-8}$$

where r_w is the well radius, R is the final fracture radius, and H_n is the total head driving the flow in the n^{th} segment.

By further segmenting the radial fracture into concentric annular rings, the formula for total leakoff in three dimensions can be derived as:

$$Q_{leak} = \sum_{r_0 = r_w}^{r_n = R} K_{gas} H_n \left(\frac{N_f}{N_d} \right)_n \pi \left(r_n + r_{n+1} \right) \tag{3-9}$$

where r_n is the inner radial distance and r_{n+1} is the outer radial distance of the annular ring.

The analytical method calculates leakoff by summing the lost flow from successive annular rings of the fracture surface. This is given by:

$$Q_{leak} = \sum_{r_0 = r_w}^{r_n = R} \sqrt{\left(K_{h-gas} K_{v-gas} \right)} \left(\frac{p_d}{l_{grad}} \right)_n \pi \left(r_n^2 - r_{n-1}^2 \right) \tag{3-10}$$

where $K_{h\text{-}gas}$ and $K_{v\text{-}gas}$ are respectively the horizontal and vertical pneumatic conductivities of the formation, p_d is the driving pressure, and l_{grad} is the flowpath length along which the pressure is dissipated along the n^{th} segment.

Deflection Model. It is assumed that pneumatic fractures are due to overburden deflection which is a function of the pressure distribution within the fracture (Canino, 1997). A model to predict the overburden deflection was investigated which uses a non-linear distribution to predict a tapering fracture (Canino, 1997 and Puppala, 1998).

Field observations have shown ground surface heave contours circular in shape. Therefore, overburden can be modeled as the bending of an elastic circular plate clamped at the edges. The derived "deflection" equation is:

$$b = \frac{r^4}{128D}\left[2p_d + 3k - 2k\ln\left(\frac{r}{r_w}\right)\right]$$
$$+\frac{r^2}{256D}\left[R^2\left(8kp_d - 8p_d - 10k\right) + r_w^2\left(8k + 16p_d - 16k\ln\left(\frac{r}{r_w}\right)\right)\right] \tag{3-11}$$
$$+\frac{kR^4}{64D} - \frac{kr_w^2}{32D}R^2$$

where $k = \frac{p_d}{\ln\left(\frac{R}{r_w}\right)}$, $D = \frac{Ez^3}{12\left(1-\upsilon^2\right)}$,

b is the fracture aperture at a distance r from the injection well, p_d is the driving pressure at the well, r_w is the well radius, R is the radial extent of the fracture, E is Young's Modulus, υ is Poisson's ratio, and z is the depth of fracturing.

3.3.2 Coupling the Physical Processes

By coupling the three physical processes, pressure distribution, leakoff, and deflection, the extent of fracture propagation can be determined. This is due to the dependency of the physical processes with each other. Each physical process is expressed below as a function of its formation and system parameters:

$$p_r = f\left(Q_{res}, \mu_{gas}, \rho_{gas}, r, b, p_w\right) \tag{3-12}$$

$$Q_{leak} = f\left(R, p_r, K_{h-gas}, K_{v-gas}, z, {N_f}/{N_d}, t\right) \tag{3-13}$$

$$b = f\left(R, E, \upsilon, p_r, z, t\right) \tag{3-14}$$

The above equations demonstrate this interdependency, since each dependent variable appears within one of the other processes' list of independent variables. This coupling of the physical processes is handled with an algorithm that is described in the following section.

3.3.3 System Design Algorithm

The System Design algorithm is represented by three nested subroutines. They are the System Design, Model Engine, and PDF Subroutines and are presented in the following three sections.

3.3.3.1 System Design Subroutine: This is the "top level" of the System Design algorithm. The subroutine is shown in Figure 3.5 on the following page. In this subroutine, many of the initializations and preparations of data required in the later subroutines are carried out as detailed in the following discussion.

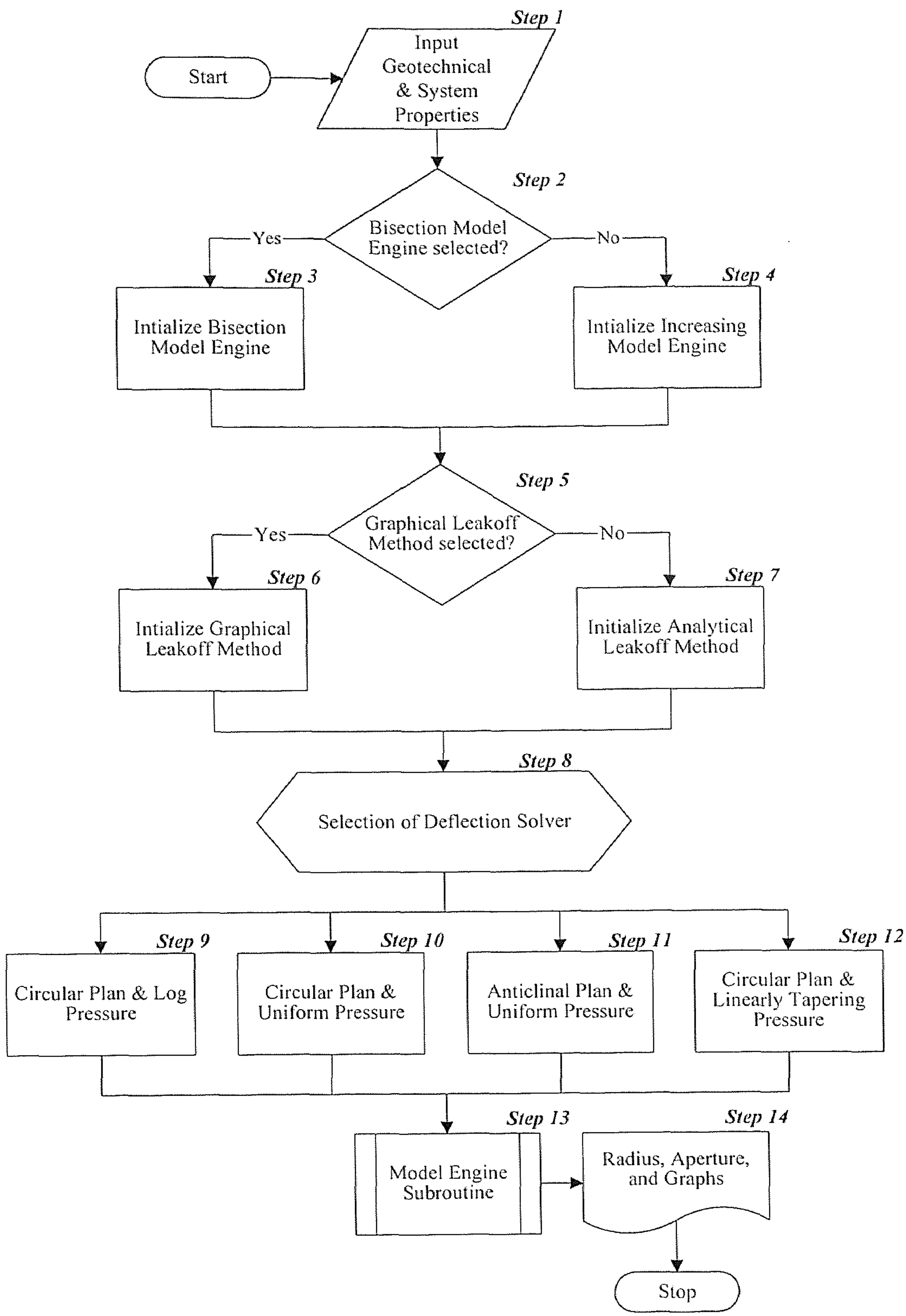


Figure 3.5 The System Design Subroutine.

Step 1 - Input. The geotechnical and system parameters required by the algorithm are entered first. Certain geotechnical parameters are site specific and will be known beforehand if a site characterization has been performed. Any unknown geotechnical parameters are assigned default values based on the selected geologic formation. System parameters are based on the anticipated injection event and can always be entered as data, although defaults will be assigned if required. Table 3.7 summarizes these various inputs.

Table 3.7 Input Parameters for the System Design Subroutine.

Geotechnical Properties (usually known)	Geotechnical Properties (usually unknown)	System Properties (usually known)
Formation type	Pneumatic conductivity	Flow rate
Depth	Young's modulus	Maintenance pressure
Depth to water table	Poisson's ratio	Well radius
Boring Log Data *	Formation density	

Note: * - Can include information such as consistency, density, fracture frequency, etc.

Steps 2, 3, & 4 - Selection of Model Engine. PF-Model allows the user to select from two different types of model engines: the Bisection Engine and the Increasing Engine. In this step of the subroutine, it is determined which model engine is to be used. The subroutine then initializes the selected model engine for use. Should the user not specify which model engine to run, the Bisection Engine will be used as the default. The discussion of the two model engines is presented in the following section, the Model Engine Subroutine.

Steps 5, 6, & 7 - Selection of Leakoff Method. In this step the method of leakoff is selected, which can be either the graphical method or the analytical method as discussed previously in Section 3.3.1, "Geophysical Processes." The graphical method is based on the construction of a flownet and obtaining the "shape factor" associated with it. Appendix G contains the shape factors used as the default in PF-Model's advanced menu function, Flownet Parameters. As this method is believed to give the most accurate representation of leakoff within a fractured formation, it will be the default should the user not specify a leakoff method.

The other method is the analytical method as described by Equation 3-10. The difference in this method is that an "effective" pneumatic conductivity must be used when calculating leakoff in anisotropic formations. It is therefore simpler than the graphical method, but less accurate since variations in gradient and formation anisotropy are not accounted for.

Steps 8 through 12 - Selection of Deflection Solver Method. In PF-Model, four Deflection Solvers are available, each with a different fracture aperture geometry. After the user selects the desired Deflection Solver, the subroutine then prepares the Solver to be passed to the PDF Subroutine. Table 3.8 lists the four Solvers and the corresponding equations.

Table 3.8 Deflection Solvers and Corresponding Equations.

Solver (fracture geometry)	Equation
circular plan fracture and log pressure	$b = \frac{r_n^4}{128D}\left[2p_d + 3k - 2k\,ln\left(\frac{r_n}{r_w}\right)\right] + \frac{r_n^2}{256D}\left[-10kR^2 + r_w^2\left(8k + 16p_d - 16k\,ln\left(\frac{r_n}{r_w}\right)\right)\right] + \frac{kR^4}{64D} - \frac{kr_w^2}{32D}R^2$
circular plan fracture and uniform pressure	$b = \frac{3p_d\left(1-\nu^2\right)\left(r_n^4 - 2R^2r_n^2 + R^4\right)}{16Ez^3}$
anticlinal plan fracture and uniform pressure	$b = \frac{p_d\left(1-\nu^2\right)\left(r_n^4 - 2R^2r_n^2 + R^4\right)}{2Ez^3}$
circular plan fracture and linearly tapering pressure	$b = \left(-\frac{b_w}{R}r_n + b_w\right)$

Notes: $k = \frac{p_d}{ln\left(\frac{R}{r_w}\right)}$, $D = \frac{Ez^3}{12\left(1-\nu^2\right)}$, and $b_w = \frac{3p_d\left(1-\nu^2\right)R^4}{16Ez^3}$

The choice of Deflection Solver has a significant effect on the estimated fracture radius. Regressive analyses have shown that the equation for bending of a circular plate fixed at its edges best approximates field results (Canino, 1997). Therefore, the circular plan fracture and log pressure distribution will be the default selection in PF-Model.

Step 13 - Model Engine Subroutine. At this point in the System Design Subroutine, control is passed to the Model Engine Subroutine which is discussed in the following section.

Step 14 - System Design Output. When control is passed back from the Model Engine Subroutine, the final output is then presented to the user. The fracture radius and aperture that satisfy the flow and pressure conditions are presented in numerical form, while aperture width, residual flow, and pressure distributions within the fracture as a function of radial distance are presented in graphical form.

3.3.3.2 Model Engine Subroutine: This subroutine controls the associated logic of the Bisection and Increasing Model Engines which are selected by the user during the System Design Subroutine. Figure 3.6 on the following page shows the logic of the Model Engine Subroutine.

The Bisection Model Engine (Steps 16 through 28) is based on the method of bisections (also known as binary chopping, interval halving, or Bolozano's method). This method has the ability to substantially reduce the number of iterations and processing time required, which is why this method is preferred and is the default engine for PF-Model. The method of bisections works by dividing the interval in half, and then determining in which half the root resides. The selected interval is halved again, and the process repeats itself until the root converges to zero. At this point the fracture radius has attained its maximum value.

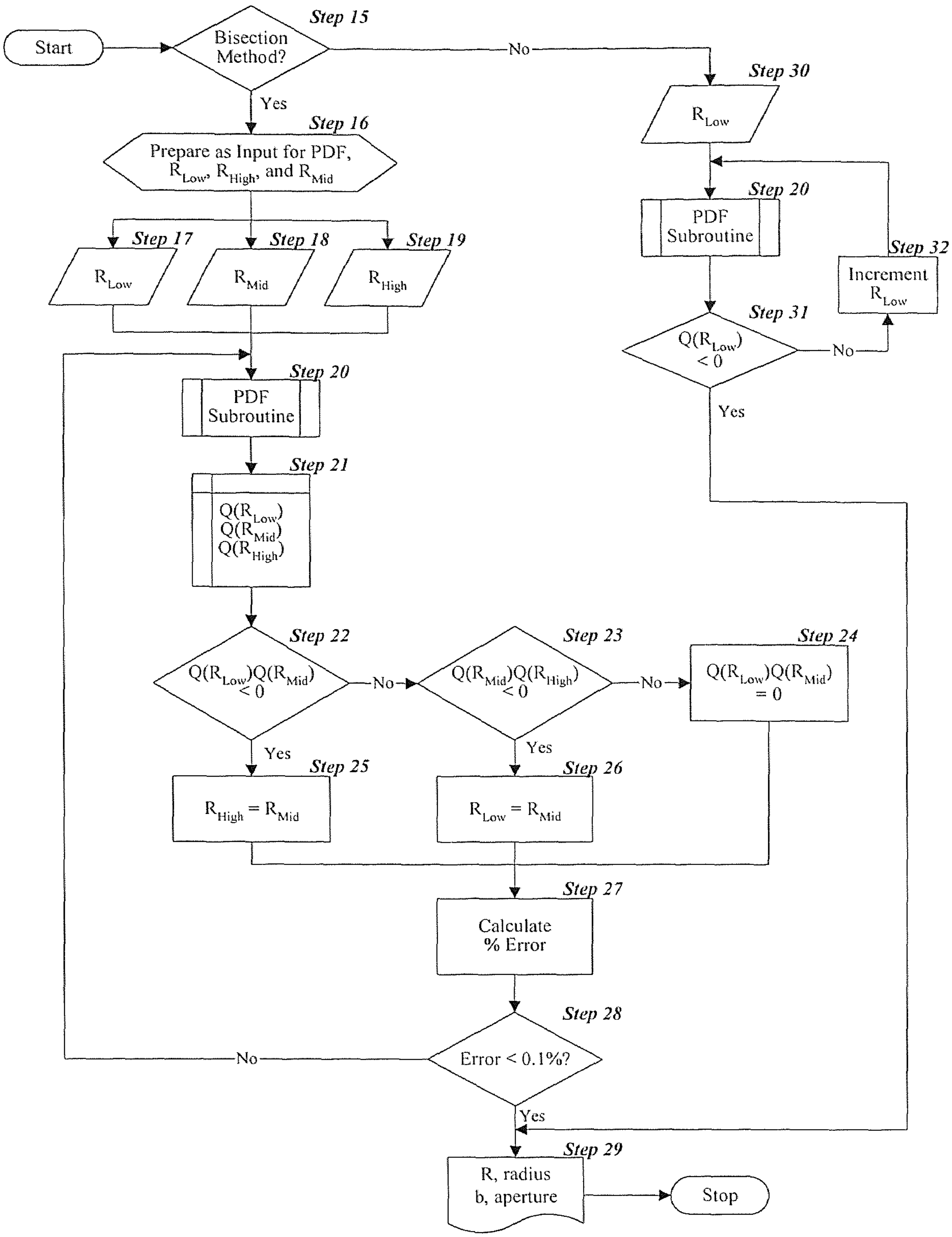


Figure 3.6 The Model Engine Subroutine.

The Increasing Model Engine (Steps 20, 30 through 32) is the alternative to the Bisection Engine. The increasing method starts at the smallest radius (*i.e.*, the well radius) and increases until the pressure and continuity conditions at the fracture tip are satisfied during the same segment of the subroutine. This is repeated for each increment in radius. Therefore, when the fracture radius extends past 7 ft, the processing time can become quite lengthy.

The steps involved in the subroutine are presented below.

Step 15 - Engine Selection. When control of the algorithm is passed to this subroutine, it passes which model engine has been selected. This step determines which subsequent logic to follow: bisection or increasing. If Bisection is selected, the subroutine proceeds to Step 16. Otherwise, the subroutine proceeds to Step 30 for the Increasing Engine.

Steps 16 through 19 - Radius Initialization. The initialization of the upper and lower bounds of the radius interval are chosen such that the actual radius lies within this interval. From experience, the lower limit, R_{Low}, is chosen to be the well radius (in most cases, 0.25 ft). For the upper limit, R_{High}, a value of 200 ft is selected. Next, the value of R_{Mid} is prepared, which is:

$$R_{Mid} = \frac{R_{High} + R_{Low}}{2} \tag{3-15}$$

All three values are then passed as input to the PDF Subroutine which processes the values as a parallel operation in logic.

Step 20 - PDF Subroutine. The PDF (or Pressure, Deflection, and Flow) Subroutine is passed control with values of the radii determined in the Model Engine Subroutine. The PDF Subroutine is discussed in Section 3.3.3.3.

Step 21 - Internal Storage of PDF Subroutine Results. As control passes back to the Model Engine Subroutine, the results of the PDF Subroutine are stored internally for later comparison using the bisection method.

Steps 22 through 26 - Flow Function and Interval Determination. The results held in the internal storage (Step 21) are compared in order to determine the location of the radius along the entire interval. The comparison is shown in Table 3.9 along with the actions the Bisection Engine is to perform.

Table 3.9 Rules, Interval Determination, and Actions for the Bisection Engine.

If function is:	The radius lies within:	Action:
$Q(R_{low}) \times Q(R_{mid}) < 0$	R_{low} to R_{mid}	Set $R_{high} = R_{mid}$
$Q(R_{mid}) \times Q(R_{high}) < 0$	R_{mid} to R_{high}	Set $R_{low} = R_{mid}$
$Q(R_{low}) \times Q(R_{mid}) = 0$	R_{low}	None

Steps 27 and 28 - Error Calculation and Error Comparison. These steps determine if the actual radius, given the current iteration's flow and pressure conditions, has been reached. First, the relative error is calculated as:

$$\%error = \left| \frac{R_{new} - R_{old}}{R_{new}} \right| \times 100\% \tag{3-16}$$

Equation 3-16 can be simplified further by making the following substitutions:

$$R_{new} = \frac{R_{High} + R_{Low}}{2} \text{ and } \left(R_{new} - R_{old}\right) = \frac{R_{High} - R_{Low}}{2}$$

therefore giving as the relative error,

$$\%error = \left| \frac{R_{High} - R_{Low}}{R_{High} + R_{Low}} \right| \times 100\% \tag{3-17}$$

As long as this error is greater that 0.1%, the Bisection Engine will pass control back to the PDF Subroutine (Step 20) with new values for R_{Low}, R_{Mid}, and R_{High} (determined from Steps 25 and 26). If the error is less that 0.1%, the subroutine has converged on the radius and proceeds to Step 29.

Step 29 - Output. Upon reaching this step in the subroutine, the values for the aperture and radius, as well as subroutine control, are passed back to the System Design Subroutine (Step 13).

Step 30 - Input Radius, Increasing Engine. The input radius for the Increasing Engine starts at the value of the well radius (usually 0.25 ft). This value is then passed to the PDF Subroutine (Step 20).

Step 31 - Flow Comparison. Should the PDF Subroutine return a flow value less than zero, then the actual radius has been reached and the subroutine proceeds to provide the output (Step 29).

Step 32 - Increment Radius. If the value of $Q(R_{Low})$ from Step 31 is greater than zero, the radius R_{Low} is incremented by 0.1. This value is then passed along with control back to the PDF Subroutine (Step 20).

3.3.3.3 PDF Subroutine (Pressure, Deflection, and Flow): This section outlines the logic of the PDF Subroutine which is presented in Figure 3.7 on the following page. When the fracture radii (R_{Low}, R_{Mid}, and R_{High}) are passed to this subroutine, the fracture extent is discretized into smaller segments. The residual flow, Q_{res}, and pressure distribution at the fracture tip, p, are calculated for this first segment. If the Q_{res} is greater than zero or the pressure at the tip is greater than the propagation pressure, p_{prop}, the algorithm steps the radius incrementally. This process continues until the three controlling conditions, elastic form, pressure distribution, and formation leakoff, which correspond to the calculations of Steps 36, 37, and 39 respectively, are satisfied. These three steps, as well as the others that make up the PDF subroutine, are discussed below.

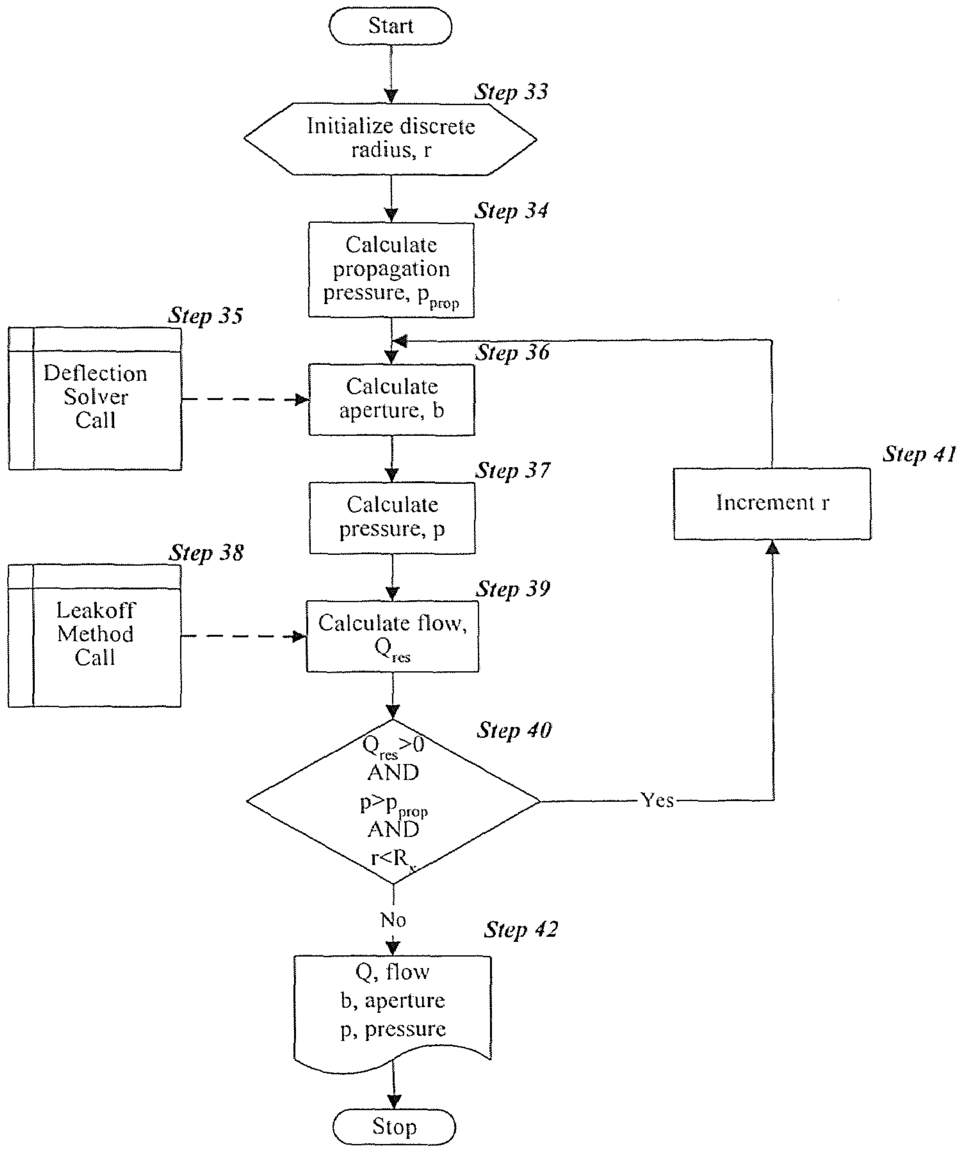


Figure 3.7 The PDF Subroutine (Pressure, Deflection, and Flow).

Step 33 - Discretize the Fracture Radius. The fracture radius is discretized into a number of segments equal to R/r_{incr}, where r_{incr} is defined as:

$$r_{incr} = 0.001 \text{ if } (R\text{-}r_n) < 1 \text{ ft}, \quad \textbf{(3-18)}$$

otherwise,

$$r_{incr} = 0.1 \tag{3-19}$$

Step 34- Calculate Propagation Pressure. The pressure required to propagate fractures, p_{prop}, is given by:

$$p_{prop} = p_m + p_k \tag{3-20}$$

where p_m is the maintenance pressure and p_k is the pressure required to overcome fracture toughness. A semi-empirical relationship is available for estimating maintenance pressures in the saturated zone is given by (King, 1993):

$$p_m = \left[\lambda \times \left(z - z_w\right) \times \gamma\right] + \left[\lambda \times z_w \times \left(\gamma - \gamma_w\right)\right] + \left[z_w \times \gamma_w\right] \tag{3-21}$$

where λ is a coefficient, z is the depth of the fracture, z_w is the depth to the water table, γ is the bulk weight of the formation, and γ_w is the specific weight of water. If the fracturing occurs in the vadose zone, the above equation reduces to:

$$p_m = \lambda \times \left(z \times \gamma\right) \tag{3-22}$$

In the Fracture Prediction Mode, the user will rarely know the maintenance pressure, so instead the program performs the computation and provides a default value. For simplicity, Equation 3-22 is used for both the vadose and saturated zones, although if fracturing in the latter, the coefficient, λ, is increased by 1.0. This adjustment accounts for the superior "seal" and heavier weight of the saturated formation. Note that this adjustment would not apply if multiple injections have dewatered the formation.

In addition, prior research has shown that maintenance pressure increases with increasing flow rate (Heres, 1994). A regression of available data yielded the values of the coefficient, λ, shown in Table 3.10. Examination of Table 3.10 shows that for flow rates above 1600 scfm, the coefficient increases linearly by 10% (thereby corresponding to a 10% linear increase in maintenance pressure) for each 500 scfm increase in flow rate.

Table 3.10 The Coefficient, λ , for Soil and Rock Formations Varying with Injection Flow Rate.

Injection Flow Rate (scfm)	Coefficient, λ	
	Soils [a]	Rocks [a, b]
500 - 1600	3.00	2.50
1600 - 2100	3.30	2.75
2100 - 2600	3.60	3.00
2600 - 3000	3.90	3.25

Notes: **a** - Coefficient, λ, is increased by 1.0 if fracturing in the saturated zone.
b - Unfractured and highly weathered rocks behave closer to soil, and should use the soil coefficient instead.

The value of the pressure, p_k, required to overcome fracture toughness is given by Sneddon (1946) as:

$$p_k = \frac{K_{ic}}{\sqrt{\pi \times r}} \tag{3-23}$$

where K_{ic} is the formation's fracture toughness and r is the fracture radius.

Steps 35 & 36 - Aperture Calculation. The Deflection Solver selected previously during the System Design Subroutine (Steps 8 through 12) is called from internal storage (Step 35) and is now used to calculate the aperture (Step 36). Table 3.8, shown previously, summarizes the equations used for each deflection model in the Deflection Solver.

Step 37 - Pressure Distribution Calculation. After the aperture has been calculated, the pressure model of Section 3.3.1 is solved. The pressure distribution in the current segment is calculated using Equation 3-6, which is repeated below:

$$p_{n+1} = \sqrt{p_n^2 - \frac{12 p_n Q \mu \ln\left(\frac{r_{n+1}}{r_n}\right)}{\pi g \rho b^3}} \tag{3-6}$$

where p_n and p_{n+1} are the pressures at radial distances r_n and r_{n+1}, respectively, Q is the flow between r_n and r_{n+1}, μ is the dynamic viscosity of the gas, ρ is the density of the injected gas, b is the fracture width, and g is the acceleration due to gravity.

Steps 38 & 39 - Leakoff and Residual Flow Calculations. The next step in the PDF Subroutine is calculation of the residual flow, Q_{res}. This is done by first calculating the leakoff from the fracture, Q_{leak}. One of the two leakoff methods determined during the System Design Subroutine (Steps 5 through 7) is called from internal storage (Step 38). The related equations were discussed previously in Section 3.3.1, and are repeated below for convenience. For the graphical (or flownet) method, leakoff is given by:

$$Q_{leak} = \sum_{r_0 = r_w}^{r_n = R} K_{gas} H_n \left(\frac{N_f}{N_d} \right)_n \pi \left(r_n + r_{n+1} \right) \quad \textbf{(3-9)}$$

and for the analytical method, leakoff is given by:

$$Q_{leak} = \sum_{r_0 = r_w}^{r_n = R} \sqrt{\left(K_{h-gas} K_{v-gas} \right)} \left(\frac{p_d}{l_{grad}} \right)_n \pi \left(r_n^{\,2} - r_{n-1}^{\,2} \right) \quad \textbf{(3-10)}$$

The residual flow left in the current segment after leakoff, Q_{res_n}, is then found by determining the overall mass-balance of the flow. Ignoring fracture volume,

$$Q_{res_n} = Q_{res_{n-1}} - Q_{leak_n} \tag{3-24}$$

where $Q_{res_{n-1}}$ is the residual flow of the previous segment, and Q_{leak_n} is the leakoff flow loss of the current segment. This step of the subroutine satisfies the leakoff model discussed in Section 3.3.1.

Step 40 - PDF Criteria Comparison. Residual flow, fracture pressure distribution, and radius at the end of the segment are compared to the conditions that would exist at the fracture tip if in equilibrium, as shown in Step 40 of Figure 3.7. If this condition is satisfied, control passes to Step 41, otherwise, execution is passed to Step 42.

Step 41 - Increase the Segmentized Fracture Radius. If the conditions of equilibrium of Step 40 are satisfied, then the discretized fracture radius is increased by r_{incr} given by:

$$r_{n+1} = r_n + r_{incr} \tag{3-25}$$

where r_{n+1} is the new segmental fracture radius, r_n is the segmental fracture radius for the current iteration, and r_{incr} is the size of the incremental radius which was defined previously in Equations 3-18 and 3-19.

Execution then passes back to Step 36 where the current values for residual flow and pressure are used as the input for the next segment about to be executed.

Step 42 - Output. The values of residual flow, aperture, propagation radius, and pressure are returned along with the process control back to the System Design Subroutine if the conditions of Step 40 are not satisfied. Control is passed if and only if all three conditions are not satisfied, which corresponds to the convergence of all three physical processes and indicates that the final propagation radius has been reached.

3.4 Calibration Mode

A "Calibration Mode" was implemented into PF-Model to aid in analysis of field pilot tests during the site characterization phase of a project. In this program mode, actual field measurements of ground surface heave are input into PF-Model to regress the actual post-fracture Young's modulus and pneumatic conductivity for the formation being tested. These values are then used directly in the System Design component to design full scale fracturing for the site. As might be expected, the accuracy of design predictions made after running the Calibration Mode will be superior to those made without running it.

3.4.1 Calibration Algorithm

In many ways, the Calibration Mode is similar in logic to the System Design mode discussed previously. With some minor differences, the same three subroutines of the System Design mode are nested within the main subroutine of the Calibration Mode. This is explained in the following section.

3.4.1.1 Calibration Subroutine: The subroutine first regresses the post-fracture Young's modulus, and then uses the method of bisections to converge on the post-fracture pneumatic conductivity of the site.

The method of bisections was chosen as the model engine for processing speed considerations due to the fact that the Calibration Subroutine converges on two solutions in two separate intervals (*i.e.*, the pneumatic conductivity and the corresponding residual flow rate that satisfy the conductivity in the current iteration). The method of bisections keeps the processing times to a manageable level. Figure 3.8 on the following page shows the steps involved in the Calibration Subroutine and an explanation of the figure follows.

Step 1 - Data Input. The system properties from the pilot test, *i.e.*, the depth of fracturing, injection flow rate, and maintenance pressure, are entered with the resulting measured aperture and radius of fracture. Other properties (*i.e.*, unit weight, Poisson's ratio, etc.) can also be entered if known, or PF-Model can assign the default values instead.

Step 2 - Regress Modulus. Deflection of the overburden can be modeled by assuming the bending of an elastic circular plate that is clamped at its edges with a logarithmically varying load. In this step the Young's modulus for the formation is calculated by manipulating Equation 3-11 into a more useful form. Based on

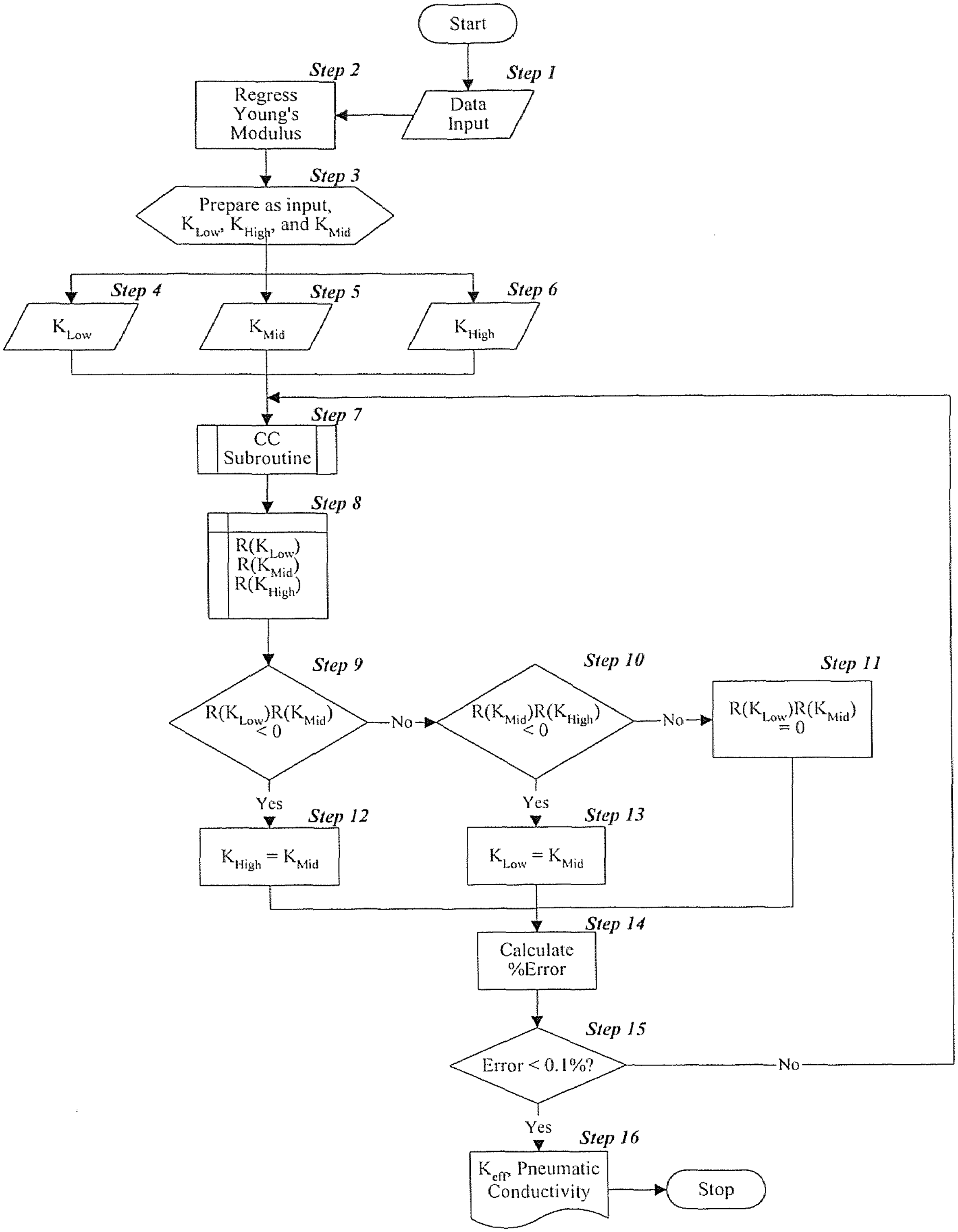


Figure 3.8 The Calibration Subroutine.

the maximum measured radius, R, and the maximum measured ground heave at the well, b_w, it is possible to solve for Young's modulus, E, as follows:

$$E = \frac{12(1-\upsilon^2)p_m\left[\left(\frac{R^4}{64}\right)-\left(\frac{r_w^2R^2}{32}\right)\right]}{ln\left(\frac{R}{r_w}\right)b_w z^3} \tag{3-26}$$

Steps 3 through 6. The initialization of the upper and lower bounds of the post-fracture pneumatic conductivity interval are chosen such that the actual conductivity lies within this interval. The lower limit, K_{Low}, is chosen to be zero. For the upper limit, K_{High}, a value of 100 ft/day is selected. Next, the value of K_{Mid} is prepared, which is:

$$K_{Mid} = \frac{K_{High} + K_{Low}}{2} \tag{3-27}$$

All three values are then passed as input to the Composite Calibration Subroutine which processes the values as a parallel operation in logic.

Step 7 - Composite Calibration Subroutine. The Composite Calibration Subroutine (or CC Subroutine) receives its name in that it contains the three subroutines found in the System Design component, but with three major differences. The first is that only the method of bisections is used as the Composite Calibration Subroutine's model engine. Second, the Deflection Solver in the CC Subroutine is the circular plan fracture subjected to a logarithmically varying load distribution. And last, the Analytical method is used as the leakoff model. It is important to note that this deviates from the Fracture Prediction Mode of PF-Model, which uses the Graphical method as a default. The Analytical method is considered more appropriate for the Calibration Mode since in virtually all instances the actual field results will yield an effective conductivity, K_{eff}. Subsequent flow charts and process descriptions for these subroutines are not provided, since they are basically the same as those shown in Figures 3.5, 3.6, and 3.7, but with the obvious modifications as described above.

Step 8 - Internal Storage of CC Subroutine Results. As control passes back to the Calibration Subroutine, the results of the CC Subroutine are stored internally for later comparison.

Steps 9 through 13 - Conductivity Function and Interval Determination. The results held in the internal storage (Step 8) are compared in order to determine the value of the radius corresponding to the effective conductivity along the entire interval. The comparison rules and actions to be taken are shown in Table 3.11 on the following page. Note that the functions ($R(K_{Low})$, etc.) are returning radius values which are based on the conductivity of the current iteration. If one of the rules are true, the corresponding action to update the conductivity is then executed (*i.e.*, set $K_{High} = K_{Mid}$, etc.).

Table 3.11 Rules, Interval Determination, and Actions taken for the Calibration Mode.

If function is:	The conductivity lies within:	Action:
$R(K_{Low}) \times R(K_{Mid}) < 0$	K_{Low} to K_{Mid}	Set $K_{High} = K_{Mid}$
$R(K_{Mid}) \times R(K_{High}) < 0$	K_{Mid} to K_{High}	Set $K_{Low} = K_{Mid}$
$R(K_{Low}) \times R(K_{Mid}) = 0$	K_{Low}	None

Steps 14 and 15 - Error Calculation and Error Comparison. These steps determine if the actual effective conductivity has been reached. The relative error is calculated in a similar manner as presented in Equations 3-16 and 3-17 of the Model Engine Subroutine. Therefore, the relative error is given by:

$$\%error = \left| \frac{K_{High} - K_{Low}}{K_{High} + K_{Low}} \right| \times 100\% \qquad \textbf{(3-28)}$$

As long as this error is greater that 0.1%, the subroutine will pass control back to the CC Subroutine (Step 7) with new values for K_{Low}, K_{Mid}, and K_{High} (determined from Steps 12 and 13). If the error is less that 0.1%, the subroutine has converged on the effective conductivity and executes Step 16.

Step 16 - Output. Upon reaching this step in the subroutine, the post-fracture values for Young's modulus, E, and effective pneumatic conductivity, K_{eff}, are returned. These values represent an estimation of the actual field conditions. Now, instead of using default values for E and K_{eff} in the System Design component, these values can be used.

3.5 Program Language and Structure

Several application development tools were available for development of PF-Model and include, Borland C++ Builder, Borland Delphi, IBM VisualAge C++, Microsoft Visual C++, and Microsoft Visual Basic. Although these development tools can create powerful and robust applications, many are aimed at different audiences. For example, Visual Basic is aimed at developers who are using Microsoft products exclusively.

These development tools each have different features, and therefore exhibit different advantages over the others. In the instance of VisualAge C++, it uses a debugger and automatic memory manager, and is specifically designed to improve programmer productivity through incremental compilation. Even the degree of sophistication between two development tools aimed at the same audience can vary, such as Delphi and Visual Basic. Delphi uses Decision Cube components, which help create local multidimensional data stores that can be summarized into cross-tabulated views and graphs. Although these cross-tab queries can be created in Visual Basic, Delphi's Decision Cube can more easily pivot and re-slice the data, allowing the analysis to be done faster.

Eventually, it was decided to use Microsoft Visual Basic for PF-Model. An important reason for selecting Visual Basic was to facilitate future modifications and additions to the program, which are inevitable. Visual Basic allows those students and faculty not proficient in higher level computer languages the ability to access and modify the program code.

Like the alternative development tools, Visual Basic allows for the creation of robust and powerful applications for Microsoft Windows operating systems, yet retains the programming ease of standard Basic. Visual Basic also allows programmers to incorporate an extensive graphical user interface (GUI) into the program.

A new feature of Visual Basic allows PF-Model to be compiled in *native code* similar to the other development tools. This provides for several options for optimizing and debugging that aren't available in standard *pseudo code*, or *p-code*. P-code is described as an intermediate step between the high level instructions in the actual Basic program and the low level native code executed by the computer processor. Normally, at run time, each p-code statement is translated into native code. By compiling to native code directly, the intermediate p-code step is eliminated, thereby extending performance up to 20 times faster (Microsoft, 1997).

Another advantage is compiled native code can be debugged with other standard native code debugging software, such as Visual C++. One can also optimize the native code for speed or size in any of the other native code debugging software environments (Microsoft, 1997).

PF-Model is a menu driven (as opposed to command driven) program and this is apparent when the user runs the program and views the GUI. The GUI for the model consists of objects, such as "buttons," "arrows," "pull down menus," etc., all familiar to computer users today. The interface reacts with the user by responding to events that occur in the interface. The user in turn is able to handle otherwise difficult situations easily and rapidly.

For example, the entry of large amounts of data needed for any application can be daunting. Needed information may not be available at all times, or it may not be of significant importance for the application to run and produce results for the user. This is the situation, for example, in one of PF-Model's advanced functions, "Input Parameters." The approach for alleviating this potential problem was to have the program select default values for certain parameters by activating a "button" on the GUI. Thus, with the ease of a mouse click, default values are entered and the application can return results to the user. This is particularly useful for the pneumatic fracturing computer model, since detailed geologic data are not always available for analysis.

The program manual for PF-Model is presented in Appendix H. It contains various screen shots of the GUI, sample output graphs, and a step-by-step example that will guide the user through both the Site Screening and System Design components. By reviewing the manual and working through the step-by-step example, the user becomes acquainted with PF-Model's menu driven GUI and the various functions available.

A quick examination of either the manual, or the actual program, will show that the key element in the entire program is the Data Input Screen since it interacts with both the Site Screening component and the System Design component. The Data Input Screen stores all the required information needed by the other model components to perform their functions. The interaction of the data set and the model components allows the user to easily move from one component to another component within the program.

Figure 3.9 is a schematic of the different screens and components of PF-Model, showing the global interactions of all the components, engines, and data bases.

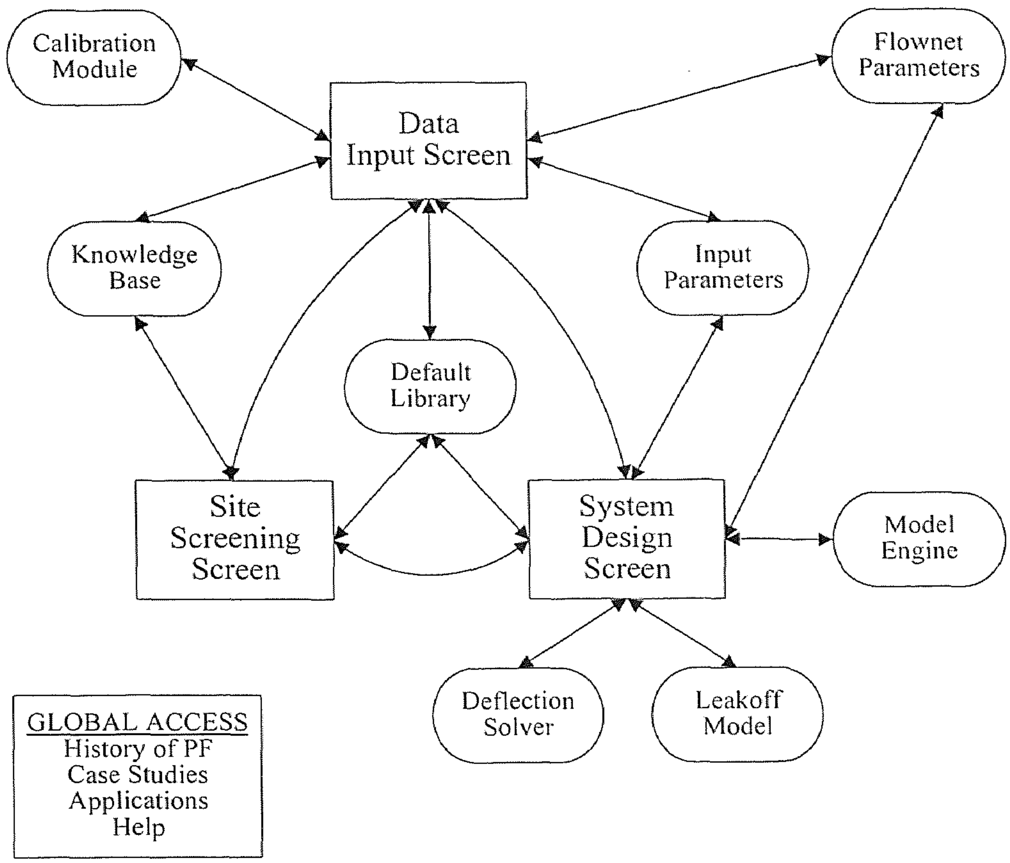


Figure 3.9 Interaction of Components, Engines, and Data Bases.

Appendix I contains select portions of code used in programming PF-Model, as the entire code would be too extensive to list as part of this work. The selected code is included for review of programming style and copyright protection purposes.

Floppy disks of PF-Model can be obtained with a manual from the Center for Environmental Engineering and Science (CEES) located at the New Jersey Institute of Technology, 138 Warren St., Newark, NJ, 07102. The phone number is 973/596-2457.

CHAPTER 4

VALIDATION AND CALIBRATION OF PF-MODEL

4.1 Introduction

In order for PF-Model to be useful for consultants, designers, and researchers, it must provide reasonable results. Since PF-Model has two different components, Site Screening and System Design, two distinctive evaluation methods will be used.

The approach for evaluating the Site Screening component was *system validation* and *user acceptance* (Section 4.2). The System Design component was verified more traditionally, *i.e.*, *validation* and *calibration* (Section 4.3). The results of each of these evaluation procedures will now be examined.

4.2 Site Screening

Since the Site Screening component is an expert system, its evaluation differs greatly from conventional computer programs. In conventional programs, *verification* is the major concern since this determines if the program completely satisfies the initial conditions (Adrion *et al.*, 1982). As discussed previously in Chapter 2, conventional programs have well defined algorithms and structures, and therefore can be measured against some objective standard. On the other hand, an expert system is designed to answer questions heuristically for which there is no right <u>or</u> wrong answer. That is, there is no "gold standard" against which the performance of the expert system can be measured absolutely (Gasching *et al.*, 1983).

Because of the lack of an absolute standard, the Site Screening component was evaluated using *system validation* and *user acceptance* (Preece, 1990). The evaluation methods are somewhat more relaxed than the stringent verification process that the System Design component has undergone (see Section 4.3). System validation tries to determine if the system performs the intended task "satisfactorily" (Hollinger, 1989). User acceptance evaluates whether the system meets the needs of the user. It is noted that the procedures of system validation and user acceptance are somewhat subjective, and therefore make the evaluation of an expert system complex (Durkin, 1994).

4.2.1 System Validation of Site Screening Component

Since the Site Screening component models the decision making process of a human expert, PF-Model should obtain the same results as the expert. Therefore, the system validation of the Site Screening component involved the use of test cases. The selected test cases were based on a blend of actual and hypothetical field experiences which varied in success. During the validation procedure, the site evidence was given to both the expert system and several expert "evaluators," and the results were compared.

It should be noted that when the evaluators agree with the system, the results are viewed as correct, otherwise, they are wrong. This approach assumes that the test case result is 100% correct and that any different answer is incorrect. This is not necessarily the case, since the findings represent an *expert opinion*, not a "gold standard."

The system validation step was based on three major considerations. They were:

- test criterion,
- test cases, and
- selection of evaluators.

Test Criterion. The test criterion was selected to directly reflect the Site Screening component. The applicability of pneumatic fracturing at the sites were rated using three categories: technology recommended, technology marginal, and technology not recommended. In addition three different variants of pneumatic fracturing were evaluated, *i.e.*, permeability enhancement, dry media injection, and liquid media injection.

Test Cases. Likewise, the selection of the test cases was based on the goal of the Site Screening component and original objective of the expert system. The test cases were selected to be *typical* sites that one expects to encounter in remediation work. It is believed that if the Site Screening component can make reliable recommendations 80% of the time for typical sites, the other more difficult sites can be handled by a human expert. Fifteen different test cases were selected and are shown in Table 4.1. These cases include common geologic situations for pneumatic fracturing, as well as more challenging geologic conditions.

Selection of Evaluators. The selection of evaluators was also consistent with the original goal and objective of the Site Screening component. A total of five evaluators were used for system validation. This included the two experts who were largely responsible for development of the PF-Model program and whose knowledge the expert system reflects. In addition, three evaluators were selected from the remediation field who are considered to be the foremost experts in the relatively new process of pneumatic fracturing.

System Validation Results. The results of the system validation are presented in Table 4.1 for the permeability enhancement variant, and additional results for dry and liquid media variants are contained in Tables J.1 and J.2 of Appendix J, respectively. The first column in each table summarizes the available geotechnical evidence for the test cases. The results of the five expert evaluators are presented in the second column. Each evaluator was asked to rate each site as: variant recommended (Y), variant marginally recommended (M), and variant not recommended (N). Finally, the corresponding expert system result and technology rating for each case are shown in the last column.

These system results and ratings were determined through an iterative testing process. Starting with the original knowledge base, the results of the expert system were compared to the results of the evaluators. If the expert system agreed with the majority opinion for a selected site, the system results were deemed satisfactory. If the system differed with the majority opinion, some "fine tuning" of the knowledge base was required to bring the expert system results into agreement. The expert system was then reevaluated for each site to insure that the changes to the knowledge base did not alter the system results elsewhere. This process was repeated until the results in the tables were obtained.

Table 4.1 System Validation of Permeability Enhancement Variant.

Formation Type	Depth (ft)	Depth to W.T. (ft)	Consistency	Plasticity	Relative Density	Fracture Frequency	Weathering	Evaluator Results † A	B	C	D	E	System Result	System Rating
Silty Clay	18	10	medium	???	n/a	n/a	n/a	Y	Y	Y	Y	M	Y	72
Clayey Silt	10	18	medium	brittle	n/a	n/a	n/a	Y	Y	Y	Y	Y	Y	83
Clay	8	4	soft	plastic	n/a	n/a	n/a	M	Y	M	Y	M	M	48
Silty Clay	12	10	medium	liquid	n/a	n/a	n/a	N	M_Y	N	M	N	N	23
Clay	10	???	???	???	n/a	n/a	n/a	Y_M	Y	Y	Y	M	Y	65
Clay	4	10	very stiff	brittle	n/a	n/a	n/a	M	M	M	M	Y	M	60
Silty Sand	14	8	n/a	n/a	med. dense	n/a	n/a	M	N	M	N	M	M	48
Sand	24	10	n/a	n/a	dense	n/a	n/a	N	N	N	N	N	N	36
Sand and Gravel	14	20	n/a	n/a	very dense	n/a	n/a	N	N	N	N	N	N	33
Siltstone	20	12	n/a	n/a	n/a	closely	slightly	Y	Y	Y	Y	Y	Y	86
Shale	10	???	n/a	n/a	n/a	???	???	Y_M	Y	Y	Y_M	Y	Y	85
Shale/Siltstone	12	18	n/a	n/a	n/a	widely	highly	Y_M	Y	M	Y	Y	Y	65
Sandstone	10	16	n/a	n/a	n/a	widely	slightly	N	M	N	Y	Y	N	43
Basalt	15	???	n/a	n/a	n/a	medium	slightly	M	M	M	M	M	M	60
Sandstone	12	8	n/a	n/a	n/a	???	???	M	M	M	Y	Y	Y	76

Notes: † - Evaluators are:
A) Dr. J. Schuring, Patent Holder of PF, NJIT
B) T. Boland, PF Design Engineer, NJIT
C) B. Sielski, PF Research Assistant, NJIT
D) J. Liskowitz, President, ARS Technologies, Inc.
E) T. King, Sr. Engineer, McLaren/Hart Environmental Engineering Corp.

Y = recommended, rating = 60 - 100
M = marginally recommended, rating = 45 - 60
N = not recommended, rating = 0 - 45
n/a = not applicable
??? = unknown (not provided to evaluator)

The system results in Tables 4.1, J.1, and J.2 show an agreement of 93, 93, and 80 per cent, respectively. This represents an overall average of 89 per cent among the three pneumatic fracturing variants.

It should be noted that the subscripts shown for certain recommendations in Table 4.1 represent the original opinion of the expert. It was inevitable that evaluators would assess each recommendation differently. Therefore, evaluators were also asked to rate each site numerically (*i.e.*, from 1 to 10). In some instances, it was apparent that the original recommendation was a "gray" area for the evaluator. In these instances, the relative "weight" of the rating further defined their opinion, and was adjusted accordingly.

Although this may seem like an end to system validation, that is not the case. The Site Screening component of PF-Model, like most expert systems, contains knowledge that evolves. Therefore, the way the pneumatic fracturing technology is viewed by experts may change over time. This can be due to a number of factors including development of new equipment, modifications of existing equipment, change in work procedures, and even new research results. Conversely, as the expert system is used, deficiencies may also be discovered. Therefore, the validation of the expert system is a continuous process.

4.2.2 User Acceptance of Site Screening Component

This is perhaps the ultimate test of an expert system. If the Site Screening component is not accepted by the end-user, the expert system will then be of little worth. At this point a base of 50 or more users are expected, including pneumatic fracturing vendors, design consultants, and government regulators. Of course, the final determination of user acceptance will not be known until after the program is released to the public.

The major issues of user acceptance are:

- ease of use,
- presentation of results,
- clarity of explanations, and
- system utilities.

Ease of Use. During the development of the technical features of PF-Model, an effort was made to present the program in an easy to use format since some users are reluctant to even try new software. Throughout the programming of PF-Model's interface, the following features were incorporated to make it user friendly:

- easy one step installation,
- explanation/help facility,
- menu and/or command driven GUI.

This was the major reason why the programming language used was Visual Basic, as discussed previously in Chapter 3. With the click of a mouse button, all program files will install in the correct folder locations, a technology recommendation can be obtained, or the explanation facility can be accessed.

Different users also prefer different styles of programs. For instance, some users prefer to work with menu driven programs, others command driven, or even a combination of both. PF-Model is menu driven, but was designed to be versatile enough so a user can use only a keyboard (*i.e.*, command driven) if desired.

Presentation of Results. Several different approaches were explored to present the final technology recommendation of the Site Screening Component. Originally, the recommendation was simply verbal, *e.g.*, "technology recommended." However, because subjective probability was used in the inference engine, it was possible to present technology recommendations numerically, thereby reflecting a quantitative belief in the result. In addition, an explanation facility was developed to aid in interpretation of the numeric as discussed in the next section, "Clarity of Explanations."

Another justification for using a numeric was that when a human expert makes a recommendation, that recommendation is never absolute. Rather, it is an opinion that contains some degree of uncertainty (for the success of the technology). This can arise from the user's wish to protect himself legally, or simply from the fact that site geology and geotechnical properties vary greatly over the same site.

Clarity of Explanations. Many expert systems provide the user with explanations on the reasoning of the system, *i.e.*, "Why does the system require the depth of injection?" Since it is expected that most users of PF-Model will either be experts or designers with some geotechnical knowledge, the reasoning of the expert system will normally be apparent. However, should a user require more information, an explanation can be easily accessed through PF-Model's Help Function.

In the design of the Site Screening component, it was considered critical to provide an explanation facility for interpretation of the numeric rating. This is intended to provide a comfort level in the degree of belief by the expert system. The recommendation rating is broken into three categories, or ranges, and each range has a corresponding recommendation that the rating falls in, as detailed below:

- 0 to 45 - The technology is not recommended for traditional applications.
- 45 to 60 - The technology is deemed to be marginally effective. Although the technology may provide some degree of enhancement, a cost to benefit analysis may be appropriate. Also, it is recommended that further evidence be acquired to refine the analysis.
- 60 to 100 - The technology is likely to be effective.

System Utilities. Throughout the development of the Site Screening component, human experts were consulted to determine the system utilities, as well as their design. This process was done over many months with different pneumatic fracturing experts.

The most important step in this process was to determine which geotechnical parameters influence the success of pneumatic fracturing. After extensive discussion, it was determined that the seven geotechnical properties detailed in Chapter 2 (*i.e.*, formation type, depth, plasticity, etc.) have the greatest influence on the pneumatic fracturing process. Further discussions led to the following conclusions about these properties:

- formation type was the most important property to effect pneumatic fracturing and therefore should always be required as input data for the expert system,
- a hierarchical order was established for the remaining geotechnical properties, and
- the geotechnical properties are independent of each other.

The importance of formation type and the other geotechnical properties, as applied to pneumatic fracturing, was previously discussed in Chapter 2. The hierarchical order of the geotechnical properties is shown below in Table 4.2 and are grouped according to soil or rock type.

Table 4.2 Hierarchical Order of Geotechnical Properties.

Fine-Grained Soils	Coarse-Grained Soils	Rocks
Soil type	Soil type	Rock type
Depth	Depth	Depth
Plasticity	Relative Density	Weathering
Consistency	Water table depth	Fracture Frequency
Water table depth		Water table depth

These geotechnical properties in turn were divided into qualifiers, in order to quantify the geological evidence for analysis by the expert system. This was done in subsequent discussions with human experts. Table 4.3 below shows how the geotechnical properties were qualified.

Table 4.3 Breakdown of Geotechnical Properties Into Qualifiers.

Formation Type	***Consistency***
Clay	Soft
Clayey Sand	Medium
Clayey Silt	Stiff
Silty Clay	
	Relative Density
Silt	Loose
Silty Sand	Medium dense
Sand	Dense
Sand & Gravel	
Gravel	***Plasticity***
	$w < PL$
Shale/Siltstone	$PL < w < LL$
Sandstone	$w > LL$
Limestone/Dolomite	
Granite/Gneiss/Schist	***Fracture Frequency***
Basalt	Widely jointed
	Medium jointed
Depth for Rocks	Closely jointed
< 4 ft	
4 - 8 ft	***Weathering***
> 8 ft	Slightly weathered
	Moderately weathered
Depth for Soils	Heavily weathered
< 6 ft	
6 - 12 ft	***Water Table***
> 12 ft	Fracturing is above
	Fracturing is below

Once the geotechnical properties were firmly established, a system utility to access this information was developed for an early version of PF-Model. This utility was subsequently evaluated by experts for ease of use, understanding, and visual aesthetics. After some minor GUI modifications, the final system utility was coded.

Finally, it was decided to create a system utility that would give users access to the knowledge base. This approach allows the expert system to be updated as the technology evolves and also permits licensed technology vendors to create a knowledge base with their own proprietary data. It should be noted that if the knowledge base is modified and multiple experts are not consulted, the expert system may in effect become insular, and therefore would not truly represent the consensus of expert opinion for the technology.

4.3 System Design

As opposed to the heuristic structure of the previous section, the System Design component is programmed with structured algorithms. Therefore, validation and calibration of this component is relatively straight forward. The validation step confirms that the model is reasonably representative of the pneumatic fracturing process, while the calibration step establishes the necessary coefficients and default values to insure proper functioning of the model. PF-Model was subjected to both these procedures.

Currently, with over 40 sites pneumatically fractured to date, a reasonable data base exists for validation and calibration purposes. The sites selected for validation and calibration were previously screened (Puppala, 1998) to insure that sites of only acceptable data quality were used in the evaluation process. Six different sites were selected, three involving soil formations and three involving rock formations. The field data for these sites are presented in the tables throughout this section.

It should be noted that PF-Model will continue to be calibrated as future sites are further added to the data base.

4.3.1 Validation of the System Design Component

The System Design component was validated by comparing PF-Model's predicted results with actual field results. This approach confirms that PF-Model represents the currently established fracture propagation mathematical models. Since the System Design component has two modes of operation, the Calibration Mode and the Fracture Prediction Mode, two separate validations were done. The results are presented in the following two sections.

4.3.1.1 Validation of Calibration Mode: As previously discussed, the Calibration Mode regresses the post-fracture Young's modulus and pneumatic conductivity from actual field data. Therefore, successful validation of the Calibration Mode will require agreement of these two geotechnical parameters with the results from the original mathematical model.

Table 4.4 on the following page shows the results for the validation of Young's modulus. The first two columns summarize the site data. The third column consists of two values. The first is a "back calculation" of Young's modulus, E_{bc}. That is, the observed field radius and aperture were used to back calculate the modulus for the given site. The calculation of E_{bc} was performed using the mathematical model in conjunction with Mathcad Plus 6.0, a technical calculation program. The second value, E_{pf}, is the

Table 4.4 Validation of Calibration Mode for Estimating Young's Modulus.

Site Name	z (ft)	Q (scfm)	P_m (psi)	b (ft)	R (ft)	E_{bc} per MCad (psi)	E_{pf} per PF-Model (psi)	E_{bc}/E_{pf}
Frelinghuysen-1 [a]	3.5	300	10	0.0792	4.2	38	37.5	1.01
	3.5	300	10	0.0533	4.2	56	55.7	1.01
	3.5	300	7	0.0208	4.2	86	85.3	1.01
	3.5	300	8	0.0317	4.2	69	68.5	1.01
Frelinghuysen-2 [a]	6	715	13	0.0342	8.5	272	271.2	1.00
	6	1227	14	0.0367	8.5	283	282	1.00
	6	1157	15	0.0075	5.7	347	345.7	1.00
	8.3	1500	18	0.0233	11.7	688	686.8	1.00
	6	1500	17	0.0375	8.6	379	378.1	1.00
	8.6	1339	17	0.0390	11.3	291	290.8	1.00
Frelinghuysen-3 [a]	6	857	15	0.0167	4.2	51	50.4	1.01
	6	964	11.4	0.0275	12.6	1197	1195.6	1.00
	6	1000	11	0.0250	9.6	449	448.5	1.00
	9	943	16.5	0.0183	14.1	1149	1148.3	1.00
	9	1114	14.7	0.0150	16.1	1890	1888.9	1.00
	6	722	12.5	0.0275	11.7	1049	1047.5	1.00
	8.3	984	17	0.0158	11.4	843	842.1	1.00
Tinker [a]	8	1716	31	0.0417	19	5585	5582.3	1.00
	19	1759	130	0.0125	30.8	39881	39874.8	1.00
	8	1716	28	0.1000	23	4219	4217.8	1.00
Marcus Hook [a]	6	1200	12	0.0500	16.2	1835	1834.1	1.00
	6	1276	19	0.0500	15.8	3204	3202.1	1.00
	6	1400	14	0.0700	15.1	1270	1269.4	1.00
Hillsborough-2 [b]	10	1500	21	0.0320	27.9	7960	7958.5	1.00
	12	1607	25	0.0258	29.4	8238	8236.2	1.00
	14	1886	30	0.0317	27.7	4141	4140.3	1.00
Hillsborough-3 [b]	14	1029	28	0.0333	30	4683	4681.8	1.00
Newark [b]	10	771	37.5	0.0133	25	31135	31127	1.00
	16	857	53	0.0108	30	25171	25166.2	1.00
Flemington [b]	16	2286	35	0.0260	24.5	2522	2520.9	1.00
	27	1886	75	0.0104	33	10166	10164.8	1.00

Abbr.: z, fracture depth; Q, injected flow rate; P_m, maintenance pressure; b, aperture; R, radius; E, Young's modulus

Notes: a - soil density is γ= 105 pcf and Poisson's ratio is υ = 0.40
b - rock density is γ= 140 pcf and Poisson's ratio is υ = 0.25

estimated post-fracture modulus determined by PF-Model's Calibration Mode. If both of these results agree, then the post-fracture modulus is adequately represented. This is indicated in the last column which is the ratio of E_{bc}/E_{pf}. As can be seen, the modulus ratio ranged between 1.00 or 1.01 confirming that the Calibration Mode of PF-Model is a valid representation of the mathematical model in estimating post-fracture Young's modulus.

The validation of the post-fracture pneumatic conductivity is shown in Table 4.5 on the following page. Again, the first two columns represent the site data, while the third column lists values of post-fracture pneumatic conductivity, K_{mc} and K_{pf}, which have been calculated using Mathcad and PF-Model, respectively. The final column gives the ratio, K_{mc}/K_{pf}, which ranged from 0.94 to 1.06. The average of all the sites was 0.99, thus demonstrating reasonable agreement. It is surmised that the slightly higher variation in the ratio K_{mc}/K_{pf} is related to how Mathcad and PF-Model handle significant figures. Since the convergence algorithm consists of thousands of iterations, any difference in significant figures is compounded as the algorithm propagates, thereby creating the higher variation.

4.3.1.2 Validation of Fracture Prediction Mode: The Fracture Prediction Mode estimates the maximum fracture radius and aperture upon inputting geological and operational data. Therefore, in a manner similar to the Calibration Mode, successful validation requires agreement between PF-Model and the original mathematical model.

Table 4.5 Validation of Calibration Mode for Estimating Pneumatic Conductivity.

Site Name	z (ft)	Q (scfm)	P_m (psi)	b (ft)	R (ft)	K_{mc} per MCad (cm/sec)	K_{pf} per PF-Model (cm/sec)	K_{mc}/K_{pf}
Frelinghuysen-1 [a]	3.5	300	10	0.0792	4.2	6.70e-4	6.76e-4	0.99
	3.5	300	10	0.0533	4.2	6.70e-4	6.86e-4	0.98
	3.5	300	7	0.0208	4.2	1.28e-3	1.25e-3	1.02
	3.5	300	8	0.0317	4.2	9.36e-4	9.71e-4	0.96
Frelinghuysen-2 [a]	6	715	13	0.0342	8.5	6.24e-4	6.11e-4	1.02
	6	1227	14	0.0367	8.5	1.00e-3	9.43e-4	1.06
	6	1157	15	0.0075	5.7	2.46e-3	2.61e-3	0.94
	8.3	1500	18	0.0233	11.7	7.10e-4	7.16e-4	0.99
	6	1500	17	0.0375	8.6	8.50e-4	8.55e-4	0.99
	8.6	1339	17	0.0390	11.3	7.40e-4	7.49e-4	0.99
Frelinghuysen-3 [a]	6	857	15	0.0167	4.2	2.64e-3	2.65e-3	1.00
	6	964	11.4	0.0275	12.6	4.84e-4	4.80e-4	1.01
	6	1000	11	0.0250	9.6	9.44e-4	9.26e-4	1.02
	9	943	16.5	0.0183	14.1	3.96e-4	4.15e-4	0.95
	9	1114	14.7	0.0150	16.1	5.04e-4	5.06e-4	1.00
	6	722	12.5	0.0275	11.7	3.50e-4	3.54e-4	0.99
	8.3	984	17	0.0158	11.4	5.50e-4	5.66e-4	0.97
Tinker [a]	8	1716	31	0.0417	19	1.32e-4	1.32e-4	1.00
	19	1759	130	0.0125	30.8	2.80e-5	2.80e-5	1.00
	8	1716	28	0.1000	23	9.84e-5	9.83e-5	1.00
Marcus Hook [a]	6	1200	12	0.0500	16.2	3.14e-4	3.16e-4	0.99
	6	1276	19	0.0500	15.8	1.81e-4	1.81e-4	1.00
	6	1400	14	0.0700	15.1	3.28e-4	3.29e-4	1.00
Hillsborough-2 [b]	10	1500	21	0.0320	27.9	1.58e-4	1.59e-4	0.99
	12	1607	25	0.0258	29.4	1.55e-4	1.60e-4	0.97
	14	1886	30	0.0317	27.7	1.94e-4	1.93e-4	1.01
Hillsborough-3 [b]	14	1029	28	0.0333	30	1.03e-4	1.04e-4	0.99
Newark [b]	10	771	37.5	0.0133	25	4.16e-5	4.19e-5	0.99
	16	857	53	0.0108	30	3.93e-5	3.95e-5	0.99
Flemington [b]	16	2286	35	0.0260	24.5	2.96e-4	2.94e-4	1.01
	27	1886	75	0.0104	33	9.77e-5	9.74e-5	1.00

Abbr.: z, fracture depth; Q, injected flow rate; P_m, maintenance pressure; b, aperture; R, radius; K, pneumatic conductivity

Notes: a - soil density is γ= 105 pcf and Poisson's ratio is υ = 0.40
b - rock density is γ= 140 pcf and Poisson's ratio is υ = 0.25

Table 4.6 on the following page shows the validation of the graphical leakoff method (where $K_h = 5K_v$) using the bisection model engine, which also happens to be the default selections for PF-Model. The 11 entries in the first two columns represent actual field data. This is followed by two entries for *R/z*, which is a shape factor for the flownet (see Appendix G). The first is the actual *R/z* value based on site data, and the second is the ratio used by the Mathcad model.

It should be noted that due to the limitations of Mathcad, only the final *R/z* shape factor ratio is used for each iteration performed by Mathcad's "equivalent" PDF Subroutine (as shown in the fourth column). On the other hand, PF-Model has a full library of shape factors available for each iteration in the PDF Subroutine, thus, the true *R/z* value is assigned during each iteration.

The results in the final column represent the ratio, PF-Model to Mathcad, for both aperture and radius. The estimated maximum aperture ratio varied ±0.04 with the average being 1.01, while the radius ratio varied ±0.01 with the average being 1.00.

Validation results for the other graphical leakoff methods (*i.e.*, $K_h = K_v$ and $K_h = 10K_v$), as well as the analytical leakoff method, are contained in Appendix J. Overall, the results from Table 4.6 and Appendix J indicate that the Fracture Prediction Mode of PF-Model accurately represents the mathematical model.

4.3.2 Calibration of the System Design Component

The System Design component was calibrated by referring to existing data. The field data was based on the 6 sites comprised of 31 injections shown previously in Table 4.6 as

Table 4.6 Validation of Graphical Leakoff Method ($K_h = 5K_v$) Using Bisection Model Engine.

Site Name	K_h	K_v	z	γ_{soil}	υ	Q	P_m	b	R	E	R/z	R/z	b	R	b	R	b	R
	(cm/sec)	(cm/sec)	fracture depth (ft)	(pcf)		Injected flow (scfm)	Maint. pres. (psi)	(measured) (ft)		Young's modulus (psi)	(actual)	(used in MCad)	(Mcad) (w/ single R/z useage) (ft)		(PF-Model) (w/ full R/z usage) (ft)		PF-M/Mcad	PF-M/Mcad
Frelinghuysen - 1	9.35E-04	1.87E-04	3.5	105	0.40	300	10	0.0792	4.2	38	1.20	1.14	0.0800	4.231	0.0824	4.261	1.03	1.01
	9.70E-04	1.94E-04	3.5	105	0.40	300	10	0.0533	4.2	56	1.20	1.14	0.0543	4.231	0.0554	4.249	1.02	1.00
	1.72E-03	3.44E-04	3.5	105	0.40	300	7	0.0208	4.2	86	1.20	1.14	0.0202	4.182	0.0202	4.176	1.00	1.00
	1.36E-03	2.72E-04	3.5	105	0.40	300	8	0.0317	4.2	69	1.20	1.14	0.0309	4.182	0.0308	4.176	1.00	1.00
Frelinghuysen - 2	9.70E-04	1.94E-04	6	105	0.40	715	13	0.0342	8.5	272	1.42	1.14	0.0345	8.531	0.0347	8.543	1.01	1.00
	1.59E-03	3.18E-04	6	105	0.40	1227	14	0.0367	8.5	283	1.42	1.14	0.0370	8.531	0.0369	8.518	1.00	1.00
	3.92E-03	7.84E-04	6	105	0.40	1157	15	0.0075	5.7	347	0.95	1.00	0.0071	5.616	0.0073	5.670	1.04	1.01
	1.23E-03	2.46E-04	8.3	105	0.40	1500	18	0.0233	11.7	688	1.41	1.14	0.0224	11.591	0.0233	11.701	1.04	1.01
	1.57E-03	3.14E-04	6	105	0.40	1500	17	0.0375	8.6	379	1.43	1.14	0.0378	8.628	0.0381	8.640	1.01	1.00
	1.07E-03	2.14E-04	8.6	105	0.40	1339	17	0.0390	11.3	291	1.31	1.14	0.0377	11.203	0.0376	11.190	1.00	1.00
Frelinghuysen - 3	3.03E-03	6.06E-04	6	105	0.40	857	15	0.0167	4.2	51	0.70	0.71	0.0162	4.182	0.0161	4.176	0.99	1.00
	8.56E-04	1.71E-04	6	105	0.40	964	11.4	0.0275	12.6	1197	2.10	2.00	0.0272	12.563	0.0278	12.636	1.02	1.01
	1.22E-03	2.44E-04	6	105	0.40	1000	11	0.0250	9.6	449	1.60	2.00	0.0259	9.697	0.0260	9.709	1.00	1.00
	7.23E-04	1.45E-04	9	105	0.40	943	16.5	0.0183	14.1	1149	1.57	1.14	0.0184	14.118	0.0185	14.142	1.01	1.00
	7.09E-04	1.42E-04	9	105	0.40	1114	14.7	0.0150	16.1	1890	1.79	2.00	0.0148	16.061	0.0149	16.085	1.01	1.00
	6.13E-04	1.23E-04	6	105	0.40	722	12.5	0.0275	11.7	1049	1.95	2.00	0.0282	11.786	0.0275	11.701	0.98	0.99
	9.35E-04	1.87E-04	8.3	105	0.40	984	17	0.0158	11.4	843	1.37	1.14	0.0158	11.397	0.0162	11.482	1.03	1.01
Tinker	3.33E-04	6.66E-05	8	105	0.40	1716	31	0.0417	19	5585	2.38	2.00	0.0415	18.976	0.0421	19.049	1.01	1.00
	5.82E-05	1.16E-05	19	105	0.40	1759	130	0.0125	30.8	39881	1.62	2.00	0.0124	30.733	0.0127	30.976	1.02	1.01
	2.79E-04	5.58E-05	8	105	0.40	1716	28	0.1000	23	4219	2.88	2.00	0.1058	23.349	0.1029	23.179	0.97	0.99
Marcus Hook	7.14E-04	1.43E-04	6	105	0.40	1200	12	0.0500	16.2	1835	2.70	2.00	0.0506	16.255	0.0498	16.183	0.98	1.00
	4.80E-04	9.60E-05	6	105	0.40	1276	19	0.0500	15.8	3204	2.63	2.00	0.0508	15.867	0.0505	15.842	0.99	1.00
	7.18E-04	1.44E-04	6	105	0.40	1400	14	0.0700	15.1	1270	2.52	2.00	0.0732	15.284	0.0737	15.308	1.01	1.00
Hillsborough-2	3.14E-04	6.28E-05	10	140	0.25	1500	21	0.0320	27.9	7960	2.79	2.00	0.0325	28.013	0.0327	28.061	1.01	1.00
	2.79E-04	5.58E-05	12	140	0.25	1607	25	0.0258	29.4	8238	2.45	2.00	0.0264	29.567	0.0259	29.422	0.98	1.00
	2.76E-04	5.52E-05	14	140	0.25	1886	30	0.0317	27.7	4141	1.98	2.00	0.0314	27.624	0.0320	27.770	1.02	1.01
Hillsborough-3	1.39E-04	2.78E-05	14	140	0.25	1029	28	0.0333	30	4683	2.14	2.00	0.0365	30.733	0.0363	30.685	0.99	1.00
Newark	1.11E-04	2.22E-05	10	140	0.25	771	37.5	0.0133	25	31135	2.50	2.00	0.0131	24.903	0.0134	25.049	1.02	1.01
	7.57E-05	1.51E-05	16	140	0.25	857	53	0.0108	30	25171	1.88	2.00	0.0107	29.956	0.0109	30.102	1.02	1.00
Flemington	4.41E-04	8.82E-05	16	140	0.25	2286	35	0.0260	24.5	2522	1.53	1.14	0.0260	24.515	0.0255	24.369	0.98	0.99
	1.50E-04	3.00E-05	27	140	0.25	1886	75	0.0104	33	10166	1.22	1.14	0.0100	32.677	0.0103	32.920	1.03	1.01

screened by Puppala (1998). It is acknowledged that field data for calibration purposes are not available for all the formation types that are specified in PF-Model.

The calibration of the program was done in three steps, corresponding to the soil grain size or rock type. The following sections describe the process.

4.3.2.1 Calibration of Fine-Grained Soils: Fine-grained soils were selected as the first formation type to be calibrated since the most field data was available for this formation type. Specifically, clayey silt had the largest amount of data and therefore was selected as the base case for calibration.

First, using all the clayey silts from Table 4.6, the arithmetic averages for Young's modulus, E, and pneumatic conductivity, K, were calculated. These values were input into PF-Model to observe the general response. Next, the sensitivity of PF-Model was established by slightly varying the values for E and K. This process continued until optimum values for modulus and conductivity were selected. The goal of the calibration was to reproduce, in general, average behavior of the actual site data. Obviously, data points for individual injections exhibited a certain amount of scatter.

Once the E and K values for the given consistency of clayey silt were established, the consistency level was changed (*i.e.*, from stiff to medium, etc.) and the process was repeated. Unfortunately, large amounts of data were not available for each consistency. It was therefore necessary to use trends from the literature to extrapolate the modulus to extreme cases. In addition, it was not felt that there was enough regressive information on K to warrant an adjustment. Therefore, in general, a single value of K was used for each soil type.

After PF-Model was calibrated to clayey silt, the other fine-grained soil types (*i.e.*, clay, clayey sand, and silty clay) were analyzed. Although limited data were available for these soils, the amount was not as large as for clayey silt. Therefore, the calibration was made on a relative basis. In other words, the expected trends between pneumatic conductivity and grain size were used. The moduli were calibrated in a similar manner.

Table 4.7 Calibration of Default Values for Fine-Grained Soils.

	Defaults				Predictions		
	E (psi)	K (cm/sec)	z (ft)	Q (scfm)	P_m (psi)	b (in.)	R (ft)
Clay							
Unknown	2000	2.7×10^{-4}	10	1500	21	0.23	16.5
Soft	500	2.7×10^{-4}	10	1500	21	0.76	15.7
Medium	2000	2.7×10^{-4}	10	1500	21	0.23	16.5
Stiff	6,000	2.7×10^{-4}	10	1500	21	0.14	19.4
Clayey Sand							
Unknown	2500	3.8×10^{-4}	10	1500	21	0.15	15.7
Soft	600	3.8×10^{-4}	10	1500	21	0.35	13.4
Medium	2500	3.8×10^{-4}	10	1500	21	0.15	15.7
Stiff	8,000	3.8×10^{-4}	10	1500	21	0.08	18.2
Clayey Silt							
Unknown	600	3.5×10^{-4}	10	1500	21	0.42	14.0
Soft	200	3.5×10^{-4}	10	1500	21	0.84	12.6
Medium	600	3.5×10^{-4}	10	1500	21	0.42	14.0
Stiff	3,000	3.5×10^{-4}	10	1500	21	0.13	15.7
Silty Clay							
Unknown	1,000	3.2×10^{-4}	10	1500	21	0.38	15.7
Soft	400	3.2×10^{-4}	10	1500	21	0.65	14.2
Medium	1,000	3.2×10^{-4}	10	1500	21	0.38	15.7
Stiff	5,000	3.2×10^{-4}	10	1500	21	0.12	17.6

Abbr.: E, Young's modulus; K, pneumatic conductivity; z, fracture depth; Q, injection flow rate; P_m, maintenance pressure; b, aperture; R, radius

Notes: Other default values; soil density is $\gamma = 105$ pcf, Poisson's ratio is $\upsilon = 0.40$, fracture toughness is $K_{ic} = 0.0$, and fracturing is above the water table. Graphical leakoff method ($K_h = 5K_v$) used.

After the calibration for fine-grained soils was completed, cases were analyzed as shown in Table 4.7 on the previous page. This was done to insure that, at extreme instances of consistency and/or soil type, unexpected behavior would not occur. In addition, flow rates and depths were varied.

4.3.2.2 Calibration of Rock Formations: For rock formations, most of the available data were for siltstone formations that were closely jointed. As for clayey silt and fine-grained soils, siltstone formed the base case for the calibration of rock.

A similar calibration procedure as that previously described for clayey silt was performed for siltstone. The modulus and conductivity were varied until a final set of parameters were selected. Following the siltstone calibration, the other rock formations were calibrated on a relative basis.

After completing the calibration for rock formations, a range of standard cases was computed as shown in Table 4.8 on the following page. Extreme cases for rock type, fracture frequency, flow rates, and depth were examined to insure that unexpected behavior would not occur.

It is important to note that the data available for rock were limited to the depth range of 10-27 ft, and therefore, the calibration of PF-Model was custom tailored to that range. It was noticed that at depths shallower than 10 ft, unrealistically high surface heaves (*i.e.*, apertures) are predicted. This was attributed to the fact that the fundamental mathematical model for the System Design component is in fact a bending deflection model, *i.e.*, it treats the formation as if it were a deep beam or plate. Thus, the *equivalent depths* of injection compared with soil is much greater on account of the higher stiffness and modulus of rock. Deep injections involve not just bending phenomena, but also localized elastic compression above and below the fracture.

Table 4.8 Calibration of Default Values for Rocks.

	Defaults				Predictions		
	E (psi)	K (cm/sec)	z (ft)	Q (scfm)	P_m (psi)	b (in.)	R (ft)
Shale/Siltstone							
Unknown	6,000	1.1×10^{-4}	15	1700	40	0.19	24.1
Widely jointed	N.R.	N.R.	N.R.	N.R.	-	-	-
Medium jointed	12,000	9.0×10^{-5}	15	1700	40	0.20	29.0
Closely jointed	6,000	1.1×10^{-4}	15	1700	40	0.19	24.1
Sandstone							
Unknown	8,000	1.3×10^{-4}	15	1700	40	0.14	23.6
Widely jointed	N.R.	N.R.	N.R.	N.R.	-	-	-
Medium jointed	16,000	1.1×10^{-4}	15	1700	40	0.12	27.7
Closely jointed	8,000	1.3×10^{-4}	15	1700	40	0.14	23.6
Limestone/Dolomite							
Unknown	8,000 *	1.1×10^{-4}	15	1700	40	0.17	25.1
Widely jointed	N.R.	N.R.	N.R.	N.R.	-	-	-
Medium jointed	16,000 *	9.0×10^{-5}	15	1700	40	0.17	30.3
Closely jointed	8,000 *	1.1×10^{-4}	15	1700	40	0.17	25.1
Granite/Gneiss/Schist							
Unknown	10,000 *	1.1×10^{-4}	15	1700	40	0.15	25.8
Widely jointed	N.R.	N.R.	N.R.	N.R.	-	-	-
Medium jointed	20,000 *	9.0×10^{-5}	15	1700	40	0.16	31.2
Closely jointed	10,000 *	1.1×10^{-4}	15	1700	40	0.15	25.8
Basalt							
Unknown	15,000 *	1.1×10^{-4}	15	1700	40	0.13	27.4
Widely jointed	N.R.	N.R.	N.R.	N.R.	-	-	-
Medium jointed	30,000 *	9.0×10^{-5}	15	1700	40	0.13	33.2
Closely jointed	15,000 *	1.1×10^{-4}	15	1700	40	0.13	27.4

Abbr.: E, Young's modulus; K, pneumatic conductivity; z, fracture depth; Q, injection flow rate; P_m, maintenance pressure; b, aperture; R, radius; N.R., fracturing not recommended

Notes: Other default values; soil density is γ = 140 pcf, Poisson's ratio is υ = 0.25, fracture toughness is K_{ic} = 0.0, and fracturing is above the water table.
* - Value based on standard published rock properties only. No experience with pneumatic fracturing in this kind of formation to date (May 1999).
Graphical leakoff method ($K_h = 5K_v$) used.

In view of the inherent assumption of the model and the lack of shallow data, it was decided to calibrate the model for the specific range of 10-30 ft. As future field data becomes available, the calibration should be revisited. This current limitation also makes it clear that an entirely new fracture propagation model that incorporates both bending and localized elastic compression needs to be developed.

4.3.2.3 Calibration of Coarse-Grained Soils: Coarse-grained soils behave somewhat differently than either fine-grained soils or rocks when subjected to pneumatic fracturing. Field observations to date show that surface heaves are minimal, and it is difficult to determine precise propagation radii. It is not known whether truly discrete fractures occur as they do in a cohesive formation.

Therefore, the approach for calibrating coarse-grained soil was to use pneumatic conductivity data and pneumatic conductivity trends found in literature. Conductivity has a major influence on leakoff rate into the formation and thus largely determine the dimension of the fracture. Similarly, the moduli and moduli trends for coarse-grained soils were taken from the literature, but were also calibrated against the values used for fine-grained soils.

The final default values for coarse-grained soils are shown in Table 4.9 on the following page. In general, the deflections calculated for coarse-grained soils are much smaller. This is as expected since the degree of flow and pressure confinement is less than for fine-grained soils.

Table 4.9 Calibration of Default Values for Coarse-Grained Soils.

	Defaults				Predictions		
	E (psi)	K (cm/sec)	z (ft)	Q (scfm)	P_m (psi)	b (in.)	R (ft)
Silt							
Unknown	500	1.0×10^{-3}	10	1500	21	0.10	9.1
Loose	200	1.0×10^{-3}	10	1500	21	0.14	7.8
Medium dense	500	1.0×10^{-3}	10	1500	21	0.10	9.1
Dense	2,500	1.0×10^{-3}	10	1500	21	0.06	12.3
Silty Sand							
Unknown	2,000	1.0×10^{-3}	10	1500	21	0.06	11.75
Loose	1,000	1.0×10^{-3}	10	1500	21	0.08	10.24
Medium dense	2,000	1.0×10^{-3}	10	1500	21	0.06	11.75
Dense	5,000	1.0×10^{-3}	10	1500	21	0.06	14.53
Sand							
Unknown	4,000	5.0×10^{-2}	10	1500	21	0.04	12.3
Loose	2,000	5.0×10^{-2}	10	1500	21	0.04	10.3
Medium dense	4,000	5.0×10^{-2}	10	1500	21	0.04	12.3
Dense	8,000	5.0×10^{-2}	10	1500	21	0.04	14.8
Sand & Gravel							
Unknown	10,000	1.0×10^{-2}	10	1500	21	0.04	15.5
Loose	5,000	1.0×10^{-2}	10	1500	21	0.04	12.8
Medium dense	10,000	1.0×10^{-2}	10	1500	21	0.04	15.5
Dense	20,000	1.0×10^{-2}	10	1500	21	0.04	18.5
Gravel							
Unknown	10,000	1.0×10^{-1}	10	1500	21	0.03	14.6
Loose	5,000	1.0×10^{-1}	10	1500	21	0.03	12.1
Medium dense	10,000	1.0×10^{-1}	10	1500	21	0.03	14.6
Dense	20,000	1.0×10^{-1}	10	1500	21	0.03	17.5

Abbr.: E, Young's modulus; K, pneumatic conductivity; z, fracture depth; Q, injection flow rate; P_m, maintenance pressure; b, aperture; R, radius

Notes: Other default values; soil density is γ = 105 pcf, Poisson's ratio is υ = 0.40, fracture toughness is K_{ic} = 0.0, and fracturing is above the water table. Graphical leakoff method ($K_h = 5K_v$) used.

CHAPTER 5

RESULTS, CONCLUSIONS, AND RECOMMENDATIONS

5.1 Results and Conclusions

The objective of this study has been the development of a new computer program called PF-Model. PF-Model is designed to support pneumatic fracturing, which is an *in situ* remediation process that involves the injection of high pressure gas into geologic formations to enhance permeability, as well as to introduce liquid and solid amendments. Now that the pneumatic fracturing process has been receiving considerable industrial attention, there is an increasing need for a computer model to aid in analysis.

PF-Model has been designed with two principal components. The first is Site Screening, which heuristically evaluates sites with regard to process applicability. The second component is System Design, which uses the numerical solution of a coupled algorithm to generate preliminary design parameters.

The following are the results and conclusions of the current study:

1. The selection of appropriate technologies is an essential step in successful site remediation. The Site Screening component of PF-Model was designed as an expert system in order to aid in that analysis. An important characteristic of an expert system is that it is limited to a solvable problem. The Site Screening component focuses expertise on a well defined process to determine the success (or failure) of the pneumatic fracturing technology.

2. The major components of the expert system architecture for the Site Screening component are the user interface, knowledge base, and inference engine. The functions of the user interface include entry of site data, adjustment of rules or facts, response to user requests, and support of all other communication between the system and the user. The knowledge base contains the knowledge of the foremost experts in the field of pneumatic fracturing. The inference engine uses the information provided from the knowledge base and the user to make a technology recommendation. In doing so, it simulates the thought process of an expert.

   To increase functionality, an explanation facility and a knowledge acquisition facility were added to the expert system. The explanation facility can be accessed at any time in order to give an explanation on a certain line of reasoning. The knowledge acquisition facility allows the program to acquire knowledge as the expert system is updated and expanded over the lifetime of the system.

3. Three different control strategies were investigated to manage the knowledge base: forward chaining, backward chaining, and mixed chaining. Forward chaining was selected since it became obvious that pneumatic fracturing experts mostly mirrored forward chaining , that is, they began with the gathering of site data (*i.e.*, evidence) in order to reach a decision (*i.e.*, the success of the technology).

4. Three different approaches were investigated to handle uncertainty in the inference engine. They were the Dempster-Shafer theory (DST), Bayesian networks (BNs), and subjective probability theory.

Although the Dempster-Shafer theory can explicitly express ignorance, it suffers by its use of unfamiliar terminology and lack of formal semantics. Limiting the theory further was the fact that a huge subset of probability assignments must be assigned by the expert, since the representation of all hypotheses in DST is the power set of all possible hypotheses.

Bayesian networks, on the other hand, showed promise. BNs handle uncertainty using probability theory and the use of formal diagrams, where the diagrams show important conceptual information about the network. One important advantage of BNs is that probabilities assigned in a network are conditional and quantify conceptual relationships in one's own mind. This makes it easier to quantify directed links with local nodes, turning a very large network into a globally consistent knowledge base. Ultimately, however, BNs were not chosen for PF-Model on account of the difficulty in assigning priori probabilities and interpreting posterior probabilities.

Subjective probability theory though was finally chosen to handle uncertainty. The main advantage of subjective probability is that the heuristic knowledge and facts stored in the knowledge base are viewed as subjective. This coincides best with how the pneumatic fracturing technology is viewed by others, and therefore is appropriate to act as the control strategy in the inference engine.

5. In order to implement subjective probability into the model, geotechnical parameters that affect pneumatic fracturing (called the evidence) were identified. Further, a hierarchy of importance among these pieces of evidence was established in order to

help quantify the final probabilities chosen in the knowledge base. The geotechnical properties and their hierarchical order are:

- formation type
- depth
- consistency/relative density
- plasticity
- fracture frequency
- weathering
- water table

Each of the geotechnical properties above were further divided into qualifiers. After numerous discussions with experts in pneumatic fracturing, a library of probabilistic defaults were established for each of the qualifiers in the knowledge base. By quantifying this evidence, the expert system was able to make technology recommendations with greater belief. Probabilities were generated for the three main variant applications of pneumatic fracturing: permeability enhancement, dry media injection, and liquid media injection.

6. The Site Screening component is designed to rate prospective sites according to three criteria: pneumatic fracturing effective, pneumatic fracturing marginally effective,

and pneumatic fracturing not recommended. The result is accompanied with a numerical rating to reflect the level of belief in the recommendation.

7. The Site Screening component was evaluated using both system validation and user acceptance. For system validation, a panel of 5 experts subjectively rated 15 sites for each of the pneumatic fracturing variants and the results were compared with model recommendations. The system agreed with the majority of expert opinions, although some fine adjustments to the knowledge base were made as part of the validation process.

8. Perhaps the ultimate test of the expert system is user acceptance. Therefore, the program was designed with an interactive and user-friendly graphical user interface. The GUI is menu driven, with "buttons," "dialogues," "pull-down menus," etc. The program can also be command driven if desired. In order to further assure user acceptance, early versions were shown to potential users and feedback was solicited. The final determination of acceptance, though, will not be known until after the program is released.

9. The System Design component was programmed traditionally and therefore consisted of structured algorithms. The System Design component has two main algorithms, the Fracture Prediction and Calibration Modes.

   The Fracture Prediction Mode estimates the maximum aperture and radius for the pneumatic fracturing process. The algorithm arrives at the solution by the convergence of three physical processes that include pressure distribution, leakoff, and deflection.

The Calibration Mode determines the post-fracture Young's modulus and pneumatic conductivity of a site that has already been fractured (*i.e.*, a pilot test). This algorithm regresses the modulus using the modified deflection equation, then converges on the conductivity in an algorithm similar to the Fracture Prediction Mode.

10. The algorithm for the Fracture Prediction Mode of the System Design component has two solution methods: bisection and increasing. It also uses two methods to determine leakoff: graphical and analytical. Finally, there are four deflection solvers to model overburden deflection. These options are coded into three nested subroutines that allow the user to select any of the above methods to determine the aperture and radius.

    The Calibration Mode uses the Bisection Engine due to processing speed considerations since the algorithm converges on two solutions in two separate intervals (*i.e.*, the pneumatic conductivity and the corresponding residual flow rate that satisfies the conductivity in the current iteration of the subroutine). The leakoff method used is the Analytical method, since in virtually all instances the actual field results use the effective conductivity, K_{eff}. However, all four Deflection solvers are available in this mode.

11. While calibrating the System Design algorithm, a flaw was detected in the original pressure distribution mathematical model. Instead of absolute pressure, gauge pressure was used in selected steps. Further investigation showed that this did not cause a significant error in the program due to the effects of the "cubic law," since pressure remains relatively constant until it suddenly converges near the fracture tip. In nearly all cases, the equation flaw did not affect convergence until the calculation was within 0.0001 in. of the final radius. Therefore, the original calibrations performed by Puppala (1998) are valid despite the use of gauge pressure.

The coding of the pressure distribution model in the PDF Subroutine was corrected to reflect absolute pressure. Validation of PF-Model agreed with the earlier calibrations, as expected.

12. Specific site data were used to validate PF-Model. The field data consisted of 6 sites comprised of 31 injections previously screened (Puppala 1998). The estimated aperture and radius were then calculated using Mathcad.

The Fracture Prediction Mode was validated by comparing the estimated aperture and radius to these results. All four leakoff methods (*i.e.*, Analytical, Graphical $K_h = K_v$, Graphical $K_h = 5K_v$, and Graphical $K_h = 10K_v$) were validated using the Bisection engine with the Circular Plan/Log Distribution Deflection Solver. In all instances, PF-Model agreed within ±4% of the mathematical model.

To validate the Calibration Mode, post-fracture Young's moduli were regressed using the modified deflection equation Post-fracture pneumatic conductivities were then estimated using the Calibration algorithm. In the Calibration Mode, PF-Model agreed within ±5% of the mathematical model.

13. The System Design component was calibrated for 14 formation types by establishing default values for 6 parameters. They were Young's modulus, pneumatic conductivity, fracture depth, injection flow rate, formation density, and Poisson's ratio. Average values were used for depth, flow rate, density, and Poisson's ratio. Post-fracture Young's modulus and pneumatic conductivity were established by regression until optimum values were obtained which reproduced, in general, the average behavior of the actual site data.

    In cases where site data were either limited or not available, the calibration was made on a relative basis. That is, the expected trends between pneumatic conductivity and grain size were used. The moduli were calibrated in a similar manner.

5.2 Recommendations

A number of recommendations are suggested based upon the completed study. They are:

1. The expert system should go through system validation annually. Pneumatic fracturing is an evolving technology, and as knowledge increases, the expert system needs to be updated concurrently in order for PF-Model to be of maximum value to end-users. All new field data should be collected and archived so that these annual validations will reflect new knowledge or experience. The foremost experts of

pneumatic fracturing should participate in the validation. Since the inference engine and knowledge base are robust, any annual validation should only be considered as "fine tuning" the model. No additional programming will be needed.

2. Although the inference engine of the expert system uses subjective probability, research in the area of Bayesian networks showed promise as an alternative and should be considered as a viable method to handle uncertainty. Implementation of a BN would allow for more complex interactions between evidence, and may allow for interdependence among evidence should such conditions in the technology exist.

   An ActiveX control for Bayesian networks has recently been released from Hugin A/S (Denmark), which would greatly assist in programming a new inference engine for the expert system. By using the ActiveX control, extensive redesign of the Site Screening component and PF-Model can be avoided.

3. After many discussions with experts during the knowledge acquisition process of the Site Screening component, it became clear that some felt that the three technology variants are too general. For example, Permeability Enhancement is normally coupled with different treatment technologies, such as pump and treat or soil vapor extraction (SVE). It is possible that pump and treat might be "recommended" while SVE for the same site and parameters might be "not recommended." Thus, these experts preferred that the technology variants be more specific, thereby moving away from any "marginal" recommendations caused by the coupling technologies. However, the disadvantage of a more specific approach is that the recommendations

may become too complex and cause confusion for users that are just interested in the overall validity of the technology for a site. Future versions of PF-Model will need to address which of the two groups of users to accommodate: vendors and experts or consultants and government agencies.

4. PF-Model should be used in conjunction with field operations at the earliest possible date to assess its predictive ability, as well as to obtain feedback on the graphical user interface. Comments and suggestions should be complied and reviewed for possible inclusion into future versions of PF-Model.

5. The Default Library should be updated to reflect any new site data as it becomes available. At a minimum, an annual review of sites should be undertaken to insure that the defaults provide reasonable results, and updated accordingly. Over the next two years, the defaults for rocks and the coarse-grained soils should receive the greatest effort, as data available for default calibration of these formation types were limited during this study.

6. Currently there are two anisotropic conditions supported by PF-Model: $K_h = 5K_v$ and $K_h = 10K_v$. Other anisotropic conditions could be supported, including instances for when $K_v > K_h$, so that a wider range of formation conditions are available to the user. Any new anisotropic conditions will of course require the development of corresponding flownet shape factors.

7. To expand the usefulness of the program, two additional components, Supplemental Media Injection and Contaminant Transport, should be added when research is completed in these areas.

8. Visual Basic 6.0 has recently been released. Although PF-Model was written in Visual Basic 5.0, there is no need to update the program. However, when Visual Basic 7.0 is released, it is highly recommended that the code, interface, and functionality of PF-Model be carefully evaluated in order to determine if an upgrade is advantageous. No release date has yet been announced for Visual Basic 7.0.

9. The running of PF-Model as a *multiple-document interface* (MDI) should be investigated. Currently, PF-Model is a *single-document interface* (SDI). A SDI allows for only a single document to be open; the current document must be closed in order to open another. For example, the WordPad™ application that is distributed with Microsoft Windows is a SDI. Examples of MDIs are applications such as Microsoft Excel and Microsoft Word for Windows. In these applications, multiple documents can be displayed at the same time, where each document is displayed in its own window.

    A survey of some sort should be undertaken regarding a SDI/MDI design for the program. The conversion of PF-Model to a MDI would require an extensive redesign, and should only be considered if the program is to be rebuilt from the ground up.

10. On some machines PF-Model tends to run into an "Out of Memory" error. This can result from a number of factors, including, but not limited to, the number of forms open, the size of a form (*i.e.*, the Default Library), or the size of a procedure. One action taken to minimize the chance of this error was to unload default libraries not being accessed by the program. Although this slowed down the access time between model components, platform stability appears to have increased dramatically. Other means to streamline and minimize the code should be investigated. The most obvious would be to reduce the number of forms used in the design environment, and break up long procedures into smaller ones.

    In addition, it was found that other programs can cause PF-Model to crash. For example, some large memory programs continue to stay resident in memory even after the user "terminates" them. These are termed terminate-and-stay-resident programs. It was found that if PF-Model is run after exiting one of these programs, there was insufficient memory to run PF-Model.

11. During the design of the Site Screening component, the effects of water table on the pneumatic fracturing process were not widely studied, and therefore, the probabilities for water table are based on expected results. Further investigation of fracturing in the vadose and saturated zones should be carried out in order to more fully understand the effects of the water table on the different pneumatic fracturing variants. This would increase belief in the technology recommendations.

12. During calibration of the System Design component, it was observed that PF-Model does not accurately predict fracture dimensions for the extreme ranges of rock depths, *i.e.*, very shallow and very deep. It is hypothesized that this may be due to the effects of modulus "averaging." For example, some of the existing sites used in this study to calibrate rock had a significant thickness of soil overburden. Since moduli for rock are much greater than that for soil, it is clear that the current model is analyzing an effective modulus, rather than the actual modulus for these cases. Further investigation into the effect of this condition on model results is recommended, and it may be appropriate to change the model to reflect actual soil and rock depths.

    It is also important to note that high surface heaves at shallow depths can be attributed to the fact that the fundamental mathematical model is in fact a bending deflection model. Deep injections involve not just bending phenomena, but also localized elastic compression above and below the fracture. This current limitation makes it clear that an entirely new fracture propagation model that incorporates both bending and localized elastic compression should be developed.

13. Currently the System Design component of PF-Model utilizes formation type and fracture frequency as qualifiers for determining the system and geotechnical default values of rocks formations. While fracture frequency is certainly considered to have the greatest influence on fracture propagation, the degree of weathering can significantly affect modulus and conductivity as well. Therefore, future version of

PF-Model should consider incorporating formation type, fracture frequency, and weathering as default qualifiers for rock formations.

14. A User's Manual produced with sophisticated desktop publishing software will greatly enhance the aesthetics of the entire software package. Currently, the manual is produced with only a word processing program. As an alternative, the manual could be contracted out to a professional desktop publisher.

15. It is desirable to refine some sections of the manual. For example, Chapter 2 titled "Theoretical Background" should be developed for future inclusion. Currently, the reader is directed to other references which detail the theory behind the program, *e.g.*, subjective probability, expert systems, and System Design algorithms. If a user wishes to alter the defaults or knowledge base, an understanding of the theory is essential. Thus, the inclusion of theoretical background would be advantageous.

16. As an alternative to a hard copy distribution which requires three disks and a printed manual, it is possible to create a single directory application available for downloading. PF-Model could be then sent to a prospective user via e-mail, or downloaded from a web site. An accompanying electronic manual for downloading would need to be developed. The current manual could be used as a basis, but the electronic manual would need to be reformatted for the many different possible text readers that may be encountered.

APPENDIX A

SUBJECTIVE PROBABILITY THEORY

Subjective (or Bayesian) probability is favored by expert system developers and is used in most expert systems (Levitt, 1988 and Tzvieli, 1992). The main reason is that it allows the programmer to represent the human's expert knowledge in the program as subjective, which it is.

Bayes' Theorem, which forms the basis of subjective probability theory, will now be presented (after Ng and Abramson, 1990).

Let A be an event and let Ω be the sample space. The probability of event A is $p(A)$ where following three axioms must be satisfied:

1) The probability of event A is positive, or $\forall A \in \Omega : p(A) \geq 0$.
2) The probability of the entire sample space is one, or $p(\Omega) = 1$.
3) If k events $A_1, A_2, \ldots A_k$ are mutually exclusive, then the probability that at least one of these events will occur is the sum of the individual probabilities, or $p(A_1 \cup A_2 \cup \ldots \cup A_k) = \sum_{i=1}^{k} p(A)$.

Combining axioms 1 and 2 yields,

$$\forall A \in \Omega : 0 \leq p(A) \leq 1 \qquad \textbf{(A-1)}$$

Equation A-1 states that the probability of any event is between 0 and 1. A's complement ($-A$) contains all the events in Ω except A. Since A and $-A$ are mutually exclusive and $A \cup -A = \Omega$, axiom 3 yields,

$$\begin{aligned} p(A) + p(-A) &= p(A \cup -A) \\ &= p(\Omega) \\ &= 1 \end{aligned} \qquad \textbf{(A-2)}$$

This can be rewritten in order to compute $p(-A)$ from $p(A)$ more easily as,

$$p(-A) = 1 - p(A) \qquad \textbf{(A-3)}$$

Let $B \in \Omega$ be another event. The probability that A will occur given that B occurs, is called the conditional probability of A given B, or $p(A|B)$. The probability that A and B will both occur is called the joint probability of A and B, and is written as $p(A \cap B)$. By definition, the conditional probability $p(A|B)$ is equal to the ratio of the joint probability $p(A \cap B)$ to the probability of B (if B is nonzero). This can be written as,

$$p(A|B) = \frac{p(A \cap B)}{p(B)} \qquad \textbf{(A-4)}$$

Similarly, the conditional probability of B given A is,

$$p(B|A) = \frac{p(B \cap A)}{p(A)} \tag{A-5}$$

and thus,

$$p(B \cap A) = p(B|A) \times p(A) \tag{A-6}$$

Since joint probability is commutative, $p\ (A \cap B) = p\ (B \cap A)$. Therefore,

$$p(A \cap B) = p(B \cap A) = p(B|A) \times p(A) \tag{A-7}$$

Substituting equation A-7 into A-4 yields Bayes' rule,

$$p(A|B) = \frac{p(B|A) \times p(A)}{p(B)} \tag{A-8}$$

which was previously stated in Chapter 2 as Equation 2-1.

For Bayes' rule to be useful for the uncertainty found in expert systems, it must be developed further. If the events *A* and *B* are independent, then by definition,

$$p(A|B) = p(A) \text{ and } p(B|A) = p(B) \tag{A-9}$$

This is based on the premise that if the two events A and B are independent, then the occurrence of the first has no effect on the occurrence of the second. This suggests a relationship between set theory and probability theory. If A and B are disjoint sets, then,

$$p(A \cup B) = p(A) + p(B) \quad \text{and} \quad p(A \cap B) = p(A) \times p(B) \tag{A-10}$$

If the two events are truly independent, the set union corresponds to a sum of probabilities and set intersection corresponds to a product of probabilities.

B can be written in set theory notation as the disjoint union $(B \cap A) \cup (B \cap -A)$. Therefore,

$$\begin{aligned} p(B) &= p((B \cap A) \cup (B \cap -A)) \\ &= p(B \cap A) + p(B \cap -A) \\ &= p(B|A) \times p(A) + p(B|-A) \times p(-A) \end{aligned} \tag{A-11}$$

Combining equations A-8 and A-11 and rewriting, we obtain,

$$p(A|B) = \frac{p(B|A) \times p(A)}{p(B|A) \times p(A) + p(B|-A) \times p(-A)} \tag{A-12}$$

This is the basic equation that was stated in Chapter 2 as Equation 2-2. It allows probability theory to manage uncertainty in expert systems and states the conditional probability of A given B from the conditional probability of B given A. It also allows determination of the probability of A if A is unknown and B is observed.

APPENDIX B

DEMPSTER-SHAFER THEORY

As previously shown in probability theory, once the probability of the occurrence is known, the probability of the hypothesis' negation is fixed, *i.e.*, $p(H) + p(-H) = 1$. Shafer believed that evidence that partially favors a hypothesis should not be construed as also supporting its negation (Shafer, 1976).

The Dempster-Shafer theory (DST), as summarized by Ng and Abramson (1990), will now be presented.

Let the frame of discernment, Θ, be defined as an exhaustive set of mutually exclusive events. Consider the simple case of four different competing events: {W}, {X}, {Y}, and {Z}. Therefore Θ has four different elements. The number of possible hypotheses is $|2^{\Theta}|$ representing all possible subsets of Θ, or 16 elements. In DST, if the evidence shows that an event is disconfirmed, it is equivalent to confirming the other events. For example, disconfirming {W} is equivalent to confirming {X, Y, Z}, or everything but W.

Let A be a subset of Θ, in that the basic probability assigned to the set A is defined as $m(A)$. This is the total belief of A if the function m satisfies:

1) The basic probability number of a null event is 0, $m(\varnothing) = 0$.
2) The sum of the basic probability numbers for all subsets of Θ is 1,

$$\sum_{A \subset \Theta} m(A) = 1 .$$

Let *Bel(A)* be the total amount of belief in *A*, which can be expressed as $Bel(A) = \sum_{B \subset A} m(B)$. *Bel* is called a belief function if the following conditions are satisfied:

1) The belief in a null hypothesis is 0, $Bel(\varnothing) = 0$.
2) The belief in Θ is 1, $Bel(\Theta) = 1$.
3) The sum of beliefs of *A* and *-A* must be less than or equal to 1, $Bel(A) + Bel(-A) \leq 1$.

As an example, assume the basic probability assignments are $m(\{W\}) = 0.1$, $m(\{X\}) = 0.2$, $m(\{Y\}) = 0.3$, $m(\{Z\}) = 0.4$, and $m(\{W, X\}) = 0.5$. The belief $Bel(\{W\}) = m(\{W\})$, or 0.1, shows that the *Bel* equals *m* for single events. But, $Bel(\{W, X\}) = m(\{W\}) + m(\{X\}) + m(\{W, X\}) = 0.1 + 0.2 + 0.5 = 0.8$, where the *Bel* function is greater than or equal to *m* for sets that contain more than one element.

Although the Dempster-Shafer theory can explicitly express ignorance, the theory suffers from the use of unfamiliar terminology and lacks formal semantics. Since the representation of all hypotheses in DST is the power set of all possible hypotheses, a huge subset of probability assignments must be assigned by the expert. It is not surprising that there are few expert systems built using DST (Ng and Abramson, 1990).

APPENDIX C

BAYESIAN NETWORKS APPLIED TO PF-MODEL

C.1 Background

Bayesian networks (BNs) are used to model domains that contain some element of uncertainty. A BN is a directed acyclic graph (DAG) where each node of the DAG represents a random variable. Each node has a conditional probability table for the states of the random variable it represents. The conditional probability table contains the probabilities of the node being in a specific state given the state of its parents (URL://Hugin, 1998).

An extension of BNs is the concept of influence diagrams. Influence diagrams are used in place of BNs when working with decision making. This is not to say that a model for decision making can not be constructed with a pure BN. An influence diagram is simply a BN with utility and decision nodes which are not explicitly covered in BNs (URL://Hugin, 1998).

As part of the current study, the use of BNs was investigated as a means to handle uncertainty in PF-Model. Preliminary studies showed that pneumatic fracturing can be modeled directly with a BN, yet further investigation indicated that an influence diagram might be more appropriate. It also appeared to be feasible to model pneumatic fracturing as a combination BN/influence diagram.

The purpose of this appendix is to present what has been researched to date, and to report on some of the difficulties of applying BNs to pneumatic fracturing. Ultimately, after several months of study, it was decided to use subjective probability (Appendix A) to handle uncertainty. The study of BNs was nevertheless useful in identifying a causal dependency of the geologic properties (*i.e.*, depth, plasticity, weathering, etc.) on the success of pneumatic fracturing. The use of BNs in future versions of PF-Model is still considered possible.

C.2 Geologic Evidence

The design of PF-Model's expert system, which is based on subjective probability theory, was done in conjunction with research efforts in Bayesian networks. Bayesian networks and subjective probability theory are related in many aspects since both are derived from Bayes' theory, the difference being the use of DAGs/Influence diagrams in BNs. Therefore, most of the findings are shared between both models.

The base knowledge used in PF-Model's expert system is applicable to the pneumatic fracturing BN, as are the seven geotechnical properties discussed in Section 2.2.1, "Geotechnical Properties." The overall interactions discussed in Section 3.2, "Site Screening Approach," and corresponding Tables 3.4, 3.5, and 3.6, were actually derived from the early research of BNs, and therefore are applicable in this discussion.

These geotechnical properties and tables will not be repeated here, but the reader is encouraged to review these two sections before proceeding since they are referenced frequently in the next section.

C.3 Approaches

The initial approach for creating a BN for pneumatic fracturing was to use a converging connection. Figure C.1 shows an example of a converging connection, where the parents of A are B through E. The parents are said to be independent when nothing is known about A except what can be inferred from A's parents, B,…., E. Evidence on one of the parents has no influence on the others (Jensen, 1996).

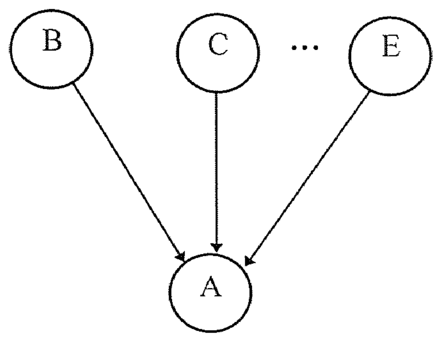


Figure C.1. Converging Connection.

Figure C.2 on the following page shows the earliest version of the pneumatic fracturing BN. The child *Results* has two states, either yes (pneumatic fracturing successful) or no (not successful). The parent *Formation* has 13 states, *i.e.*, each geologic formation type (clay, silt, shale, etc.). The parent *Depth* has six states. Three of these states, though, apply only to nine soil types, while the remaining three depths apply only to the five rock types, as discussed in Sections 2.2.1 and 3.2. The rest of the parents, *Plasticity*, *Relative Density/Consistency*, *Weathering*, and *Fracture Frequency*, each have three states while *Water Table* has two.

The obvious problem with the BN from Figure C.2 is its size. With these seven variables, there will be 25,272 distributions that need to be specified ($13\times6\times3\times3\times3\times2\times2 = 25{,}272$). To enter over 25,000 probabilities without any errors, as well as insure that their interactions provide the correct results, is daunting to say the least.

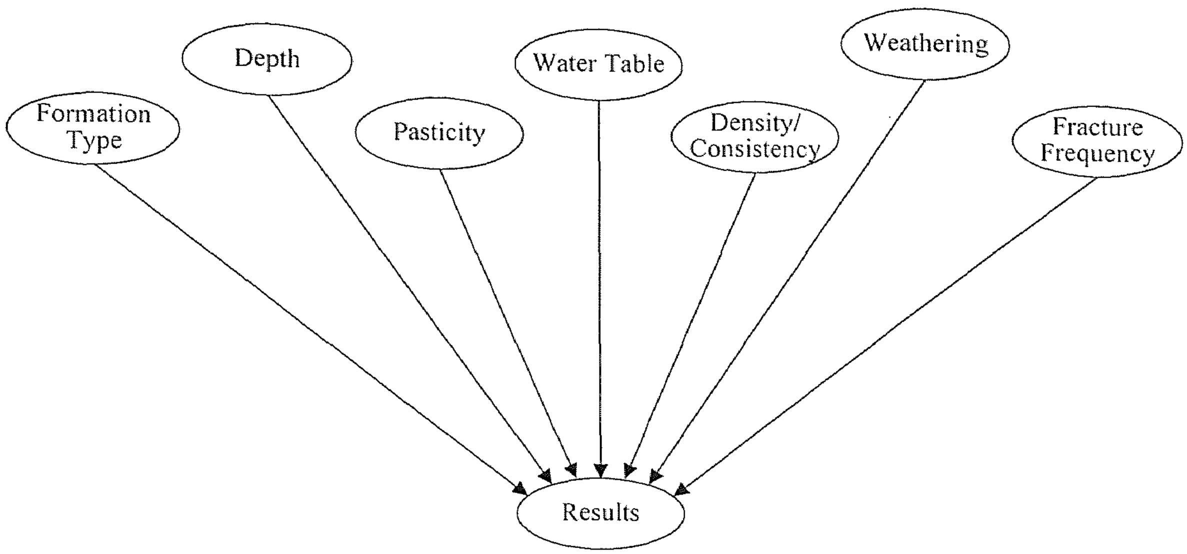


Figure C.2 Earliest Version of a Bayesian Network Applied to Pneumatic Fracturing.

Another difficulty with the BN in Figure C.2 is the handling of evidence that applies only to certain geologic formations. Specifically, there are three instances that need to be addressed. The first is that there are six states in the node *Depth*, yet three of these states do not apply to soils and three do not apply to rock. Secondly, some nodes apply only to soil and rock: *Relative Density/Consistency* is pertinent to soils; *Weathering* and *Fracture Frequency* are pertinent to rock. Finally, the *Plasticity* node applies only to the four soils with clay minerals.

Subsequent investigations led to dividing the network into three independent BNs along the same lines as Tables 3.4 through 3.6. Although a single BN is preferable due to programming considerations of the computer model (*i.e.*, it's more time efficient to program one BN instead of many), dividing (or divorcing) the BN of Figure C.2 into three separate networks has the effect of reducing the amount of specified distributions considerably.

Figure C.3 represents the BN that corresponds to Table 3.4, for plastic, fine-grained soils. The four soils with clay minerals represent the four states in the node *Soil Type*. The node *Depth* has been reduced to the three states that apply only to soils (refer to Table 3.4), while *Plasticity*, and *Relative Density/Consistency* are still comprised of three states. *Results* and *Water Table* remain the same each with only two states. This represents a network with 432 distributions that need to be specified.

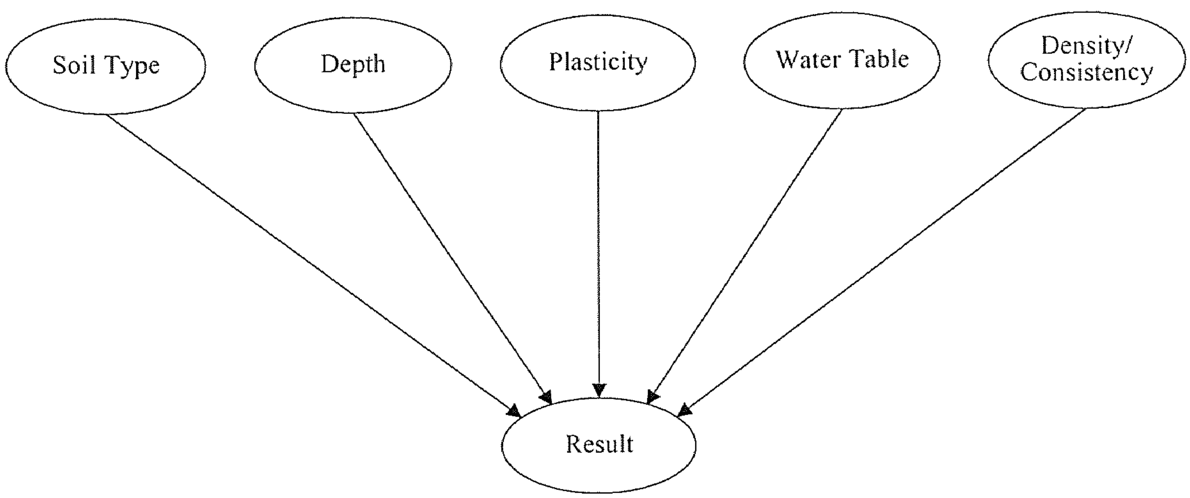


Figure C.3 A Bayesian Network for Plastic, Fine-Grained Soils.

Figure C.4 on the following page shows a BN for rocks. The *Rock Type* consists of five states while the *Depth* consists of the three states that apply only to rock (refer to Table 3.6). *Fracture Frequency* and *Weathering* each contain three states, while *Results* and *Water Table* remain unchanged each containing two states. This represents 540 distributions that need to be specified.

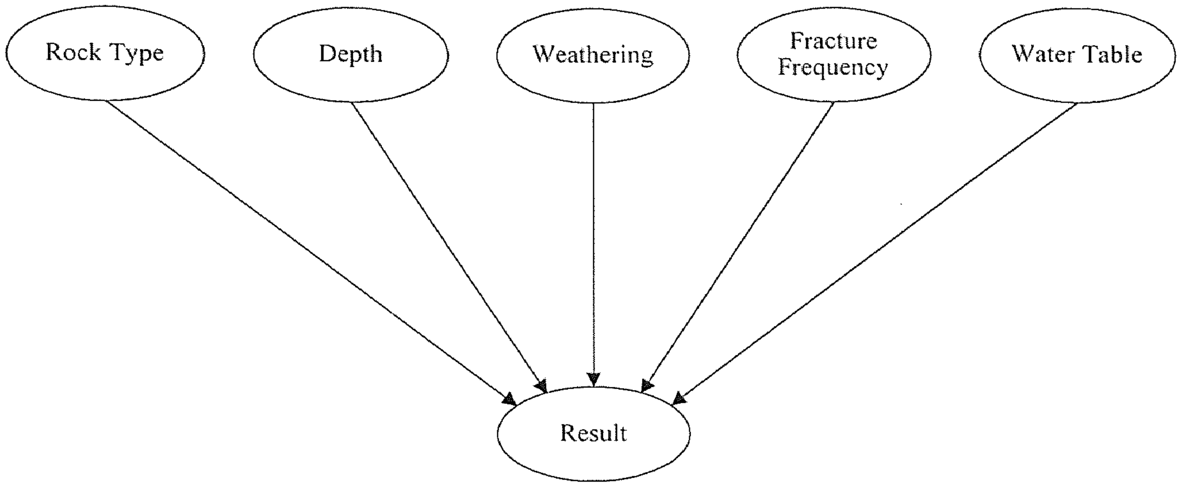


Figure C.4 Bayesian Network for Rocks.

Figure C.5 below shows the remaining BN for non-plastic soils. The *Soil Type* here consists of the four non-clay soils, while *Depth*, *Water Table*, *Consolidation*, and *Results* remain unchanged. The total number of distributions required are 144.

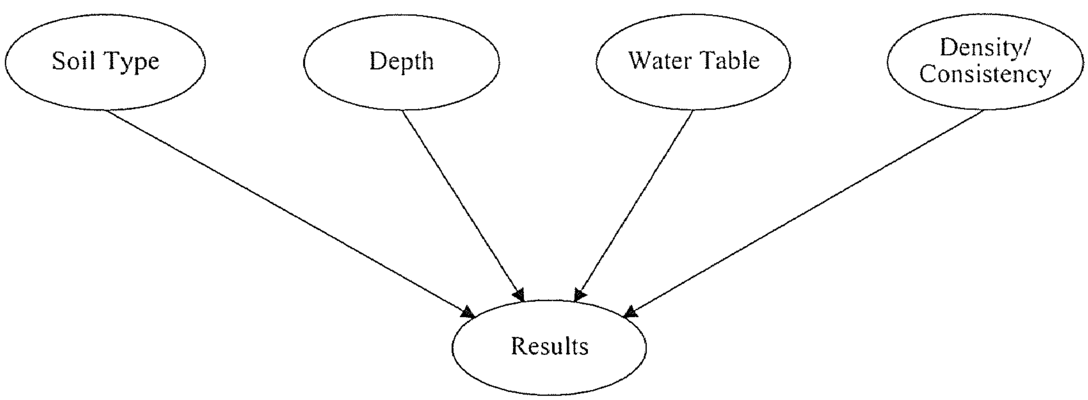


Figure C.5 Bayesian Network for Non-Plastic Soils.

For all three BNs then, the total number of distributions required are 1,116 (432 + 540 + 144). In effect, the original BN that required over 25,000 distributions has been reduced by the use of a modeling trick similar to "divorcing." Should divorcing be applied directly to the above BNs though, the effects would be dramatic.

Although the question of applying divorcing to pneumatic fracturing BNs requires further investigation, the introduction of a mediating variable would reduce further the number of required distributions. For example, if a mediating variable called *ST-P Result* was introduced into the BN of Figure C.3, the total number of distributions would be reduced from 432 to 72, another significant savings. The resulting BN is shown in Figure C.6.

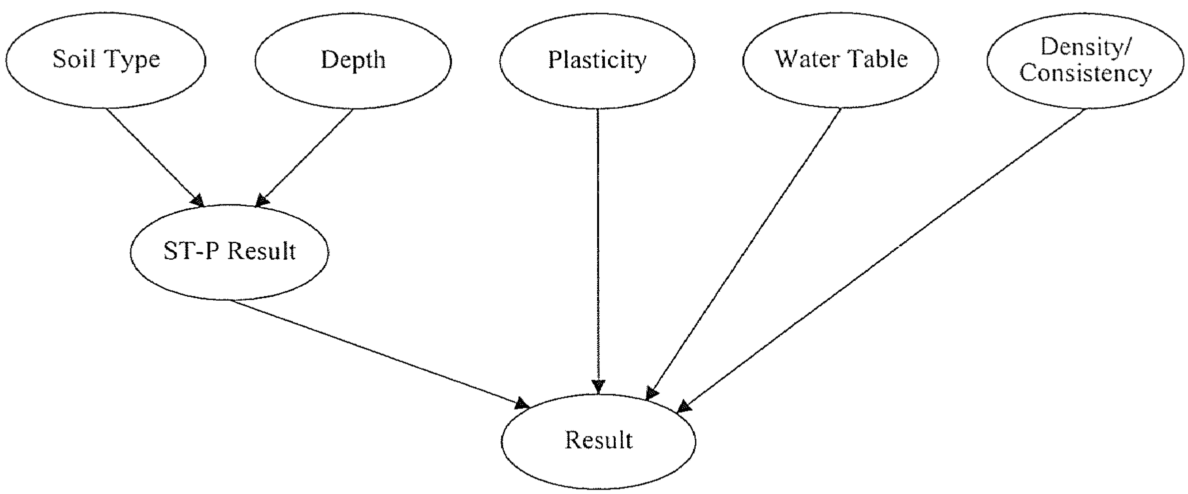


Figure C.6 Bayesian Network of Plastic, Fine-Grained Soils with Example of Divorced Parents.

Similarly, mediating variables may be introduced into any of the BNs previously discussed, reducing the required number of distributions overall.

A different approach to model the success of pneumatic fracturing in plastic, fine-grained soils is shown in Figure C.7 on the following page. Instead of the converging connection, the BN in Figure C.7 uses causal independence and the "noisy or." In this network, the number of distributions is reduced further to 62.

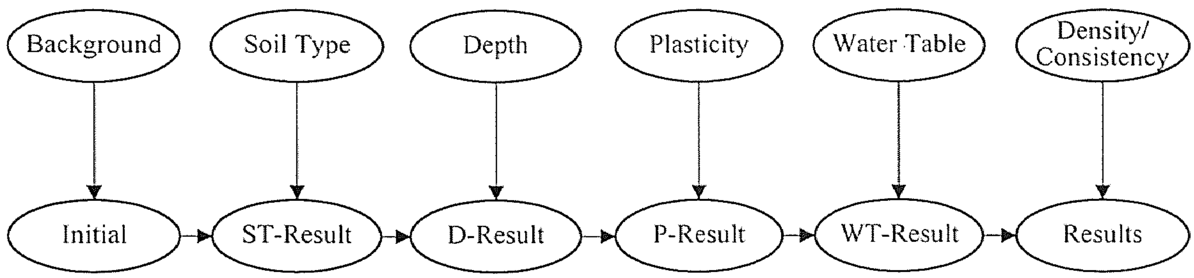


Figure C.7 Bayesian Network Modeling the Success of Pneumatic Fracturing for Plastic, Fine-Grained Soils.

C.4 Discussion

The most straightforward approach to modeling pneumatic fracturing with a Bayesian Network is to use the BN shown if Figure C.2. However, this approach has an almost unmanageable number of distributions at 25,272. These distributions for pneumatic fracturing could be known and implemented, albeit at a tremendous amount of effort and time, perhaps measured in months. Even by utilizing the three minimized BNs discussed, an extensive series of back calculations would still have to be carried out, with check after check, to concur that the 1000+ distributions compare exactly to the what the original 25,000+ would have produced anyway. In effect, 25,000+ distributions will still have to be known in order to insure that the 1000+ mirror exactly the 25,000+.

The answer, though, may lie in the fact that a minimized network will produce probabilities that provide a certain "feel" for the different states. This can be thought of as almost a "heuristic afterthought." For example, it is known fine-grained soils will most likely be successful, while coarse grained will not. If the advantageous evidence is entered and the minimized BN shows that the fine-grained soil's probabilities are always higher than the coarse-grained, the model works, and provides the right "heuristic feel."

Using HUGIN, a Bayesian Network software program, the final probabilities of the BN of Figure C.7 were calculated. It immediately became apparent that the output did not match field evidence, or expert knowledge and expectations. For example, an expert in the field of pneumatic fracturing would expect the final results for a clay soil, fracturing at a depth greater than 12 ft, stiff consistency, and $w < PL$, to be close to 90 per cent. This is the best case for the success of fracturing. The BN's *Result* was a success of 73.13%.

Each one of the states listed above was programmed in HUGIN with a belief of 90% or higher in success. The discrepancy occurs due to the nature of multiplying fractions ($0.90 \times 0.90 = 0.81$, $0.81 \times 0.90 = 0.729$, etc.). Unfortunately, this is not how the pneumatic fracturing expert thinks. If all the best conditions are satisfied, his confidence level of success would similarly exceed 90%.

In order to overcome the difficulty in perception, it was proposed to "scale" the 73.13% upwards toward 90%. This was found unsatisfactory as the scaling would not be linear, especially if one considers the comparison to a worse case for this BN's success of pneumatic fracturing. Naturally, it is preferred to think of success on a 1-100 scale, but in order to use a Bayesian Network (or several BNs) to model pneumatic fracturing, it may be necessary to utilize a different evaluative scale.

It is still preferable to have only one BN, but due to the complexity of the interactions of the geologic formations (*i.e.*, "this" applies only to "that" soil type) a single BN may be feasible only if modeling tricks are implemented without compromising the theory behind Bayesian networks. There are other untouched areas of Bayesian networks that may provide some solutions. For example, actions (intervening and non-intervening) utilities, symbol transmission, and causal independence should all be explored to help create a manageable BN.

APPENDIX D

DEFAULT VALUES FOR GEOTECHNICAL PROPERTIES IN PF-MODEL

This appendix contains the default values used by PF-Model version 3.0. The default values are broken up into three categories, as shown in Tables D.1 to D.3 on the following pages. The default values in Table D.1 are for plastic fine-grained soils. The default values are based on either the formation type, or the formation type and the known consistency. Table D.2 lists defaults for coarse-grained soils based on formation type, or formation type and relative density. Finally, Table D.3 shows the default values for rocks which is based on the formation type, or the formation type and fracture frequency. The calibration procedure is described in Chapter 4.

Table D.1 Default Values for Plastic, Fine-Grained Soils Used in PF-Model v3.0.

GEOTECHNICAL PROPERTY		**DEFAULT** (post-fracture)	
Formation Type	***Consistency***	***Pneumatic Conductivity, K_{air} (cm/sec)***	***Young's Modulus, E (psi)***
Clay	Unknown	2.7×10^{-4}	2,000
	Soft	2.7×10^{-4}	500
	Medium	2.7×10^{-4}	2,000
	Stiff	2.7×10^{-4}	6,000
Clayey Sand	Unknown	3.8×10^{-4}	2,500
	Soft	3.8×10^{-4}	600
	Medium	3.8×10^{-4}	2,500
	Stiff	3.8×10^{-4}	8,000
Clayey Silt	Unknown	3.5×10^{-4}	600
	Soft	3.5×10^{-4}	200
	Medium	3.5×10^{-4}	600
	Stiff	3.5×10^{-4}	3,000
Silty Clay	Unknown	3.2×10^{-4}	1,000
	Soft	3.2×10^{-4}	400
	Medium	3.2×10^{-4}	1,000
	Stiff	3.2×10^{-4}	5,000

Notes: For all cases, the dry unit weight, γ, is 105 lb/ft^3
For all cases, Poisson's ratio, υ, is 0.40
For all cases, fracture toughness, K_{ic}, is 0.0

Table D.2 Default Values for Coarse-Grained Soils Used in PF-Model v3.0.

GEOTECHNICAL PROPERTY		DEFAULT (post-fracture)	
Formation Type	*Relative Density*	*Pneumatic Conductivity, K_{air} (cm/sec)*	*Young's Modulus, E (psi)*
Silt	Unknown	1.0×10^{-3}	500
	Loose	1.0×10^{-3}	200
	Medium dense	1.0×10^{-3}	500
	Dense	1.0×10^{-3}	2,500
Silty Sand	Unknown	1.0×10^{-3}	2,000
	Loose	1.0×10^{-3}	1,000
	Medium dense	1.0×10^{-3}	2,000
	Dense	1.0×10^{-3}	5,000
Sand	Unknown	5.0×10^{-2}	4,000
	Loose	5.0×10^{-2}	2,000
	Medium dense	5.0×10^{-2}	4,000
	Dense	5.0×10^{-2}	8,000
Sand and Gravel	Unknown	1.0×10^{-2}	10,000
	Loose	1.0×10^{-2}	5,000
	Medium dense	1.0×10^{-2}	10,000
	Dense	1.0×10^{-2}	20,000
Gravel	Unknown	1.0×10^{-1}	10,000
	Loose	1.0×10^{-1}	5,000
	Medium dense	1.0×10^{-1}	10,000
	Dense	1.0×10^{-1}	20,000

Notes: For all cases, the dry unit weight, γ, is 105 lb/ft^3
For all cases, Poisson's ratio, υ, is 0.40
For all cases, fracture toughness, K_{ic}, is 0.0

Table D.3 Default Values for Rocks Used in PF-Model v3.0.

GEOTECHNICAL PROPERTY		DEFAULT (post-fracture)	
Formation Type	*Fracture Frequency*	*Pneumatic Conductivity, K_{air} (cm/sec)*	*Young's Modulus, E (psi)*
Shale/Siltstone	Unknown	1.1×10^{-4}	6,000
	Widely jointed	N.R.	N.R.
	Medium jointed	9.0×10^{-5}	12,000
	Closely jointed	1.1×10^{-4}	6,000
Sandstone	Unknown	1.3×10^{-4}	8,000
	Widely jointed	N.R.	N.R.
	Medium jointed	1.1×10^{-4}	16,000
	Closely jointed	1.3×10^{-4}	8,000
Limestone/Dolomite	Unknown	1.1×10^{-4}	8,000 *
	Widely jointed	N.R.	N.R.
	Medium jointed	9.0×10^{-5}	16,000 *
	Closely jointed	1.1×10^{-4}	8,000 *
Granite/Gneiss/Schist	Unknown	1.1×10^{-4}	10,000 *
	Widely jointed	N.R.	N.R.
	Medium jointed	9.0×10^{-5}	20,000 *
	Closely jointed	1.1×10^{-4}	10,000*
Basalt	Unknown	1.1×10^{-4}	15,000 *
	Widely jointed	N.R.	N.R.
	Medium jointed	9.0×10^{-5}	30,000 *
	Closely jointed	1.1×10^{-4}	15,000 *

Notes: For all cases, the dry unit weight, γ,is 140 lb/ft^3
For all cases, Poisson's ratio, υ, is 0.25
For all cases, fracture toughness, K_{ic}, is 0.0
N.R.= Technology generally not recommended
* = Value based on standard published rock properties only. No experience with pneumatic fracturing in this kind of formation to date (May. 1999).

APPENDIX E

PROBABILITIES FOR PF-MODEL'S KNOWLEDGE BASE

This appendix contains the probabilities used in PF-Model's expert system, the Site Screening component. The probabilities for the three domains (i.e., Permeability Enhancement, Dry Media Injection, and Liquid Media Injection) are presented in Table E.1. Following this table of probabilities are five selected examples showing the permutations of technology applicability for the following cases:

- Clayey Silt. *Evidence:* Depth, Plasticity, Consistency, Water Table. *Technology:* Permeability Enhancement.
- Silty Sand. *Evid.*: Depth, Relative Density, Water Table. *Tech.:* Permeability Enhancement.
- Shale. *Evid.:* Depth, Fracture Frequency, Weathering. *Tech.:* Permeability Enhancement.
- Sand. *Evid.:* Depth. *Tech.:* Dry Media Injection.
- Silty Clay. *Evid.:* Depth, Consistency, Water Table. *Tech.:* Liquid Media Injection.

These 5 cases were selected as they are considered representative of the types of formations that are encountered in pneumatic fracturing today. The known evidence among the cases varies between one and four pieces of evidence. This represents the fact that at times, certain sites may have very little information available, while at others, an extensive site characterization has been performed. Three of the cases are applied to the Fracturability technology, one to the Dry Media Injection technology, and one to the Liquid Media Injection technology in order to present the different technologies available when applying pneumatic fracturing.

Table E.1 PF-Model's Knowledge Base Probabilities for Three Pneumatic Fracturing Variants.

	Permeability Enhancement	Dry Media Injection	Liquid Media Injection
Formation			
Clay	65.0%	55.0%	70.0%
Clayey Sand	70.0%	60.0%	70.0%
Clayey Silt	75.0%	60.0%	70.0%
Silty Clay	70.0%	60.0%	70.0%
Silt	50.0%	75.0%	70.0%
Silty Sand	45.0%	75.0%	75.0%
Sand	25.0%	75.0%	75.0%
Sand and Gravel	20.0%	65.0%	65.0%
Gravel	10.0%	65.0%	65.0%
Shale/Siltstone	75.0%	65.0%	65.0%
Sandstone	65.0%	60.0%	60.0%
Limestone/Dolomite	65.0%	55.0%	55.0%
Granite/Gneiss/Schist	55.0%	55.0%	55.0%
Basalt	50.0%	50.0%	50.0%
Depth			
For Soils			
< 6 ft	25.0%	40.0%	30.0%
6 - 12 ft	50.0%	50.0%	50.0%
> 12 ft	55.0%	50.0%	55.0%
For Rocks			
< 4 ft	40.0%	40.0%	40.0%
4 - 8 ft	55.0%	50.0%	55.0%
> 8 ft	65.0%	50.0%	60.0%

Table E.1 (continued)

Consistency [a]			
Soft	40.0%	48.0%	48.0%
Medium	50.0%	50.0%	50.0%
Stiff	60.0%	52.0%	52.0%
Plasticity [a]			
w < PL	60.0%	55.0%	55.0%
PL < w < LL	45.0%	55.0%	50.0%
w > LL	10.0%	45.0%	45.0%
Relative Density [b]			
Loose	40.0%	60.0%	60.0%
Medium dense	50.0%	55.0%	55.0%
Dense	60.0%	50.0%	50.0%
Fracture Frequency [c]			
Widely jointed	20.0%	20.0%	20.0%
Medium jointed	50.0%	48.0%	50.0%
Closely jointed	60.0%	55.0%	60.0%
Weathering [c]			
Slightly weathered	45.0%	45.0%	45.0%
Moderately weathered	60.0%	50.0%	55.0%
Heavily weathered	55.0%	55.0%	60.0%
Water Table			
Fracturing is above	52.0%	55.0%	55.0%
Fracturing is below	48.0%	45.0%	45.0%

Notes: a - Applies only to cohesive soils.
b - Applies only to noncohesive soils.
c - Applies only to rock.

Permeability Enhancement

Formation:	Clayey Silt	75.0%
Depth:	< 6 ft	25.0%
	6 - 12 ft	50.0%
	> 12 ft	55.0%
Plasticity:	$w < PL$	60.0%
	$PL < w < LL$	45.0%
	$w > LL$	10.0%
Consistency:	Very soft to soft	40.0%
	Medium to stiff	50.0%
	Very stiff to hard	60.0%
Water Table:	above	52.0%
	below	48.0%

Clayey Silt	75.0%	75.0%	75.0%	75.0%	75.0%	75.0%
Depth:	55.0%	55.0%	55.0%	55.0%	55.0%	55.0%
Plasticity:	60.0%	60.0%	60.0%	60.0%	60.0%	60.0%
Consistency:	60.0%	60.0%	50.0%	50.0%	40.0%	40.0%
Water Table:	52.0%	48.0%	52.0%	48.0%	52.0%	48.0%
Probability	89.9%	88.4%	85.6%	83.5%	79.9%	77.2%

Clayey Silt	75.0%	75.0%	75.0%	75.0%	75.0%	75.0%
Depth:	55.0%	55.0%	55.0%	55.0%	55.0%	55.0%
Plasticity:	45.0%	45.0%	45.0%	45.0%	45.0%	45.0%
Consistency:	60.0%	60.0%	50.0%	50.0%	40.0%	40.0%
Water Table:	52.0%	48.0%	52.0%	48.0%	52.0%	48.0%
Probability	83.0%	80.6%	76.5%	73.5%	68.4%	64.9%

Clayey Silt	75.0%	75.0%	75.0%	75.0%	75.0%	75.0%
Depth:	55.0%	55.0%	55.0%	55.0%	55.0%	55.0%
Plasticity:	10.0%	10.0%	10.0%	10.0%	10.0%	10.0%
Consistency:	60.0%	60.0%	50.0%	50.0%	40.0%	40.0%
Water Table:	52.0%	48.0%	52.0%	48.0%	52.0%	48.0%
Probability	39.8%	36.1%	30.6%	27.3%	22.7%	20.0%

Clayey Silt	75.0%	75.0%	75.0%	75.0%	75.0%	75.0%
Depth:	50.0%	50.0%	50.0%	50.0%	50.0%	50.0%
Plasticity:	60.0%	60.0%	60.0%	60.0%	60.0%	60.0%
Consistency:	60.0%	60.0%	50.0%	50.0%	40.0%	40.0%
Water Table:	52.0%	48.0%	52.0%	48.0%	52.0%	48.0%
Probability	88.0%	86.2%	83.0%	80.6%	76.5%	73.5%

Clayey Silt	75.0%	75.0%	75.0%	75.0%	75.0%	75.0%
Depth:	50.0%	50.0%	50.0%	50.0%	50.0%	50.0%
Plasticity:	45.0%	45.0%	45.0%	45.0%	45.0%	45.0%
Consistency:	60.0%	60.0%	50.0%	50.0%	40.0%	40.0%
Water Table:	52.0%	48.0%	52.0%	48.0%	52.0%	48.0%
Probability	80.0%	77.3%	72.7%	69.4%	63.9%	60.2%

Clayey Silt	75.0%	75.0%	75.0%	75.0%	75.0%	75.0%
Depth:	50.0%	50.0%	50.0%	50.0%	50.0%	50.0%
Plasticity:	10.0%	10.0%	10.0%	10.0%	10.0%	10.0%
Consistency:	60.0%	60.0%	50.0%	50.0%	40.0%	40.0%
Water Table:	52.0%	48.0%	52.0%	48.0%	52.0%	48.0%
Probability	35.1%	31.6%	26.5%	23.5%	19.4%	17.0%

Clayey Silt	75.0%	75.0%	75.0%	75.0%	75.0%	75.0%
Depth:	25.0%	25.0%	25.0%	25.0%	25.0%	25.0%
Plasticity:	60.0%	60.0%	60.0%	60.0%	60.0%	60.0%
Consistency:	60.0%	60.0%	50.0%	50.0%	40.0%	40.0%
Water Table:	52.0%	48.0%	52.0%	48.0%	52.0%	48.0%
Probability	70.9%	67.5%	61.9%	58.1%	52.0%	48.0%

Clayey Silt	75.0%	75.0%	75.0%	75.0%	75.0%	75.0%
Depth:	25.0%	25.0%	25.0%	25.0%	25.0%	25.0%
Plasticity:	45.0%	45.0%	45.0%	45.0%	45.0%	45.0%
Consistency:	60.0%	60.0%	50.0%	50.0%	40.0%	40.0%
Water Table:	52.0%	48.0%	52.0%	48.0%	52.0%	48.0%
Probability	57.1%	53.1%	47.0%	43.0%	37.1%	33.5%

Clayey Silt	75.0%	75.0%	75.0%	75.0%	75.0%	75.0%
Depth:	25.0%	25.0%	25.0%	25.0%	25.0%	25.0%
Plasticity:	10.0%	10.0%	10.0%	10.0%	10.0%	10.0%
Consistency:	60.0%	60.0%	50.0%	50.0%	40.0%	40.0%
Water Table:	52.0%	48.0%	52.0%	48.0%	52.0%	48.0%
Probability	15.3%	13.3%	10.7%	9.3%	7.4%	6.4%

			Permeability Enhancement
Formation:	Silty Sand	45.0%	
Depth:	< 6 ft	25.0%	
	6 - 12 ft	50.0%	
	> 12 ft	55.0%	
Relative Density	Very loose to loose	40.0%	
	firm to very firm	50.0%	
	Dense to very dense	60.0%	
Water Table:	above	52.0%	
	below	48.0%	

Silty Sand	45.0%	45.0%	45.0%	45.0%	45.0%	45.0%
Depth:	55.0%	55.0%	55.0%	55.0%	55.0%	55.0%
Relative Density	60.0%	60.0%	50.0%	50.0%	40.0%	40.0%
Water Table:	52.0%	48.0%	52.0%	48.0%	52.0%	48.0%
Probability	61.9%	58.1%	52.0%	48.0%	41.9%	38.1%

Silty Sand	45.0%	45.0%	45.0%	45.0%	45.0%	45.0%
Depth:	50.0%	50.0%	50.0%	50.0%	50.0%	50.0%
Relative Density	60.0%	60.0%	50.0%	50.0%	40.0%	40.0%
Water Table:	52.0%	48.0%	52.0%	48.0%	52.0%	48.0%
Probability	57.1%	53.1%	47.0%	43.0%	37.1%	33.5%

Silty Sand	45.0%	45.0%	45.0%	45.0%	45.0%	45.0%
Depth:	25.0%	25.0%	25.0%	25.0%	25.0%	25.0%
Relative Density	60.0%	60.0%	50.0%	50.0%	40.0%	40.0%
Water Table:	52.0%	48.0%	52.0%	48.0%	52.0%	48.0%
Probability	30.7%	27.4%	22.8%	20.1%	16.5%	14.4%

Permeability Enhancement

Formation:	Shale/Siltstone	75.0%
Depth:	< 4 ft	40.0%
	4 - 8 ft	55.0%
	> 8 ft	65.0%
Weathering:	slightly wea.	45.0%
	moderately wea.	60.0%
	heavily wea.	55.0%
Frac. Freq.:	widely jointed	20.0%
	medium jointed	50.0%
	closely jointed	60.0%

Shale/Siltstone	75.0%	75.0%	75.0%	75.0%	75.0%	75.0%	75.0%	75.0%	75.0%
Depth:	65.0%	65.0%	65.0%	65.0%	65.0%	65.0%	65.0%	65.0%	65.0%
Weathering:	55.0%	55.0%	55.0%	60.0%	60.0%	60.0%	45.0%	45.0%	45.0%
Frac. Freq.:	60.0%	50.0%	20.0%	60.0%	50.0%	20.0%	60.0%	50.0%	20.0%
Probability	91.1%	87.2%	63.0%	92.6%	89.3%	67.6%	87.2%	82.0%	53.3%

Shale/Siltstone	75.0%	75.0%	75.0%	75.0%	75.0%	75.0%	75.0%	75.0%	75.0%
Depth:	55.0%	55.0%	55.0%	55.0%	55.0%	55.0%	55.0%	55.0%	55.0%
Weathering:	55.0%	55.0%	55.0%	60.0%	60.0%	60.0%	45.0%	45.0%	45.0%
Frac. Freq.:	60.0%	50.0%	20.0%	60.0%	50.0%	20.0%	60.0%	50.0%	20.0%
Probability	87.1%	81.8%	52.8%	89.2%	84.6%	57.9%	81.8%	75.0%	42.9%

Shale/Siltstone	75.0%	75.0%	75.0%	75.0%	75.0%	75.0%	75.0%	75.0%	75.0%
Depth:	40.0%	40.0%	40.0%	40.0%	40.0%	40.0%	40.0%	40.0%	40.0%
Weathering:	55.0%	55.0%	55.0%	60.0%	60.0%	60.0%	45.0%	45.0%	45.0%
Frac. Freq.:	60.0%	50.0%	20.0%	60.0%	50.0%	20.0%	60.0%	50.0%	20.0%
Probability	78.6%	71.0%	37.9%	81.8%	75.0%	42.9%	71.1%	62.1%	29.0%

Dry Media Injection

		Probability
Formation:	Sand	75.0%
Depth:	< 6 ft	40.0%
	6 - 12 ft	50.0%
	> 12 ft	50.0%
Relative Density:	Very loose to loose	60.0%
	Firm to very firm	55.0%
	Dense to very dense	50.0%
Water Table:	above	55.0%
	below	45.0%

Formation:	Sand	75.0%
Depth:	< 6 ft	40.0%
	6 - 12 ft	50.0%
	> 12 ft	50.0%

Sand	75.0%	75.0%	75.0%
Depth:	50.0%	50.0%	40.0%
Probability	75.0%	75.0%	66.7%

Liquid Media Injection

Formation:	Silty Clay	70.0%
Depth:	< 6 ft	30.0%
	6 - 12 ft	50.0%
	> 12 ft	55.0%
Consistency:	Very soft to soft	48.0%
	Medium to stiff	50.0%
	Very stiff to hard	52.0%
Water Table:	above	55.0%
	below	45.0%

Silty Clay	70.0%	70.0%	70.0%	70.0%	70.0%	70.0%
Depth:	55.0%	55.0%	55.0%	55.0%	55.0%	55.0%
Consistency:	52.0%	52.0%	50.0%	50.0%	48.0%	48.0%
Water Table:	55.0%	45.0%	55.0%	45.0%	55.0%	45.0%
Probability	79.1%	71.7%	77.7%	70.0%	76.3%	68.3%

Silty Clay	70.0%	70.0%	70.0%	70.0%	70.0%	70.0%
Depth:	50.0%	50.0%	50.0%	50.0%	50.0%	50.0%
Consistency:	52.0%	52.0%	50.0%	50.0%	48.0%	48.0%
Water Table:	55.0%	45.0%	55.0%	45.0%	55.0%	45.0%
Probability	75.5%	67.4%	74.0%	65.6%	72.5%	63.8%

Silty Clay	70.0%	70.0%	70.0%	70.0%	70.0%	70.0%
Depth:	30.0%	30.0%	30.0%	30.0%	30.0%	30.0%
Consistency:	52.0%	52.0%	50.0%	50.0%	48.0%	48.0%
Water Table:	55.0%	45.0%	55.0%	45.0%	55.0%	45.0%
Probability	57.0%	47.0%	55.0%	45.0%	53.0%	43.0%

APPENDIX F

SUBJECTIVE PROBABILITY SITE SCREENING EXAMPLE

This appendix will demonstrate how subjective probability theory is used in the Site Screening component of PF-Model. In subjective probability theory, when a piece of evidence is introduced, the hypothesis belief will change. As succeeding pieces of evidence are introduced, each hypotheses belief subsequently changes until no further evidence is available or given to the computer model. At this point, a recommendation for the applicability of pneumatic fracturing can be made based on the final values of the hypotheses.

For this example, the Site Screening component will determine if pneumatic fracturing is suitable for permeability enhancement at a particular site. Three pieces of evidence, grain size, overburden, and plasticity, will be introduced showing how evidence effects the belief in hypotheses. The site soil is a clayey silt where the soil moisture content is less than the plastic limit (*i.e.*, $w < PL$). The depth of injection is 17 to 20 feet. Past experience has shown that pneumatic fracturing would be beneficial for enhancing the permeability of this site.

Let two mutually exclusive and exhaustive hypotheses, H_1, and H_2, represent the effectiveness of pneumatic fracturing being applicable or not applicable, respectively. Prior probabilities $p(H_1)$ and $p(H_2)$, already assigned during the creation of the expert system's knowledge base, are shown below.

1) Fracturing applicable, $p(H_1) = 0.50$,

2) Fracturing not applicable, $p(H_2) = 0.50$.

The initial hypotheses are weighted equally because in all instances, nothing is known about the site and each has an equal chance of occurring. At this point in the analysis, it would be trivial to continue to find the solution of H_2, for the user is not concerned with pneumatic fracturing being 'not applicable.' Even if this value is desired by the user, it is nothing more than the complement of fracturing being applicable, or 1 - $p(H_1)$.

The first piece of evidence, grain size, is introduced in subjective probability as E_1. In PF-Model, the expert system's inference engine accesses "E_1" from the knowledge base, the probability for a Clayey Silt, and subsequently enters this value into the working memory. The inference engine performs the same process for the remaining pieces of evidence till none remain. Therefore, in this example, it will access two more probabilities, one each for depth and plasticity. Below are the probabilities for the three pieces of evidence accessed from the knowledge base and are the same as those listed in Table 3.3.

- Clayey Silt = 0.75
- Depth > 12 ft = 0.55
- Plasticity, $w < PL$ = 0.60

After the inference engine has determined how many pieces of evidence are available, it will determine which rule will be fired to determine the applicability of pneumatic fracturing. The posterior probability for the hypothesis is calculated using Equation 3-4 restated below,

$$p(H_i|E_1E_2...E_n) = \frac{p(E_1|H_i) \times p(E_2|H_i) \times ... \times p(E_n|H_i) \times p(H_i)}{\sum_{k=1}^{m} p(E_1|H_k) \times p(E_2|H_k) \times ... \times p(E_n|H_k) \times p(H_k)} \quad \textbf{(F-1)}$$

where,

- $p(E_1|H_1) = 0.75$ $\quad p(E_1|H_2) = 0.25$
- $p(E_2|H_1) = 0.55$ $\quad p(E_2|H_2) = 0.45$
- $p(E_3|H_1) = 0.60$ $\quad p(E_3|H_2) = 0.40$

thus the rule to be fired and solved is,

$$p(H_1|E_1E_2E_3) = \frac{0.75 \times 0.55 \times 0.60 \times 0.50}{(0.75 \times 0.55 \times 0.60 \times 0.50) + (0.25 \times 0.45 \times 0.40 \times 0.50)} = 0.846$$

(F-2)

This states that for the site in this example which is a clayey silt, $w < PL$, and fracturing occurring at a depth of 17-20 ft, pneumatic fracturing is applicable 84.6% of the time (conversely, it is not applicable 15.4% of the time). The Site Screening component's applicability rating of 84.6% coincides with the initial statement that historically, sites similar to this proved excellent sites to apply pneumatic fracturing.

APPENDIX G

SHAPE FACTORS USED BY PF-MODEL'S GRAPHICAL ENGINE

This appendix contains the shape factors of flownets for different fracture geometries used by the Graphical Leakoff method of PF-Model. Table G.1 is for the isotropic condition of when $K_h = K_v$. Tables G.2 and G.3 are for the anisotropic conditions of $K_h = 5K_v$ and $K_h = 10K_v$, respectively. The *R/z* ratio is the current iteration's radius divided by the depth of fracturing. The *r/R* ratio is the iteration's descretized radius divided by the current iteration's radius.

Table G.1 Shape Factors for Isotropic Condition $K_h = K_v$.

R/z	r/R	N_f
0.14	0.1	1.48
	0.2	1.59
	0.3	1.50
	0.4	1.64
	0.5	1.60
	0.6	1.74
	0.7	1.80
	0.8	1.91
	0.9	2.63
	1.0	7.69
0.29	0.1	1.90
	0.2	1.90
	0.3	1.91
	0.4	2.02
	0.5	1.95
	0.6	2.21
	0.7	2.63
	0.8	5.47
	0.9	3.18
	1.0	8.64
0.43	0.1	1.89
	0.2	2.07
	0.3	2.21
	0.4	2.41
	0.5	2.38
	0.6	2.68
	0.7	2.76
	0.8	3.11
	0.9	3.84
	1.0	9.45
0.57	0.1	2.53
	0.2	2.55
	0.3	2.46
	0.4	2.76
	0.5	2.64
	0.6	2.98
	0.7	3.15
	0.8	3.68
	0.9	4.57
	1.0	10.18
0.71	0.1	2.98
	0.2	2.55
	0.3	3.05
	0.4	2.90
	0.5	3.07
0.71 (cont.)	0.6	3.36
	0.7	3.41
	0.8	4.31
	0.9	4.77
	1.0	11.10
0.86	0.1	3.06
	0.2	2.99
	0.3	3.17
	0.4	3.05
	0.5	3.61
	0.6	3.23
	0.7	4.16
	0.8	4.18
	0.9	5.70
	1.0	11.60
1.00	0.1	3.39
	0.2	3.46
	0.3	3.32
	0.4	3.74
	0.5	3.50
	0.6	3.94
	0.7	4.01
	0.8	4.65
	0.9	5.72
	1.0	12.59
1.14	0.1	3.56
	0.2	3.81
	0.3	3.57
	0.4	3.90
	0.5	3.94
	0.6	4.08
	0.7	4.59
	0.8	4.92
	0.9	6.46
	1.0	13.32
2.00	0.1	5.80
	0.2	5.77
	0.3	5.97
	0.4	6.02
	0.5	6.11
	0.6	6.31
	0.7	6.75
	0.8	7.30
	0.9	8.70
	1.0	17.47

Note: The number of head drops, N_f, is 24 for all flownets.

Table G.2 Shape Factors for Anisotropic Condition $K_h = 5K_v$.

R/z	r/R	N_f
0.14	0.1	1.16
	0.2	1.35
	0.3	1.12
	0.4	1.20
	0.5	1.13
	0.6	1.22
	0.7	1.32
	0.8	1.44
	0.9	1.77
	1.0	7.28
0.29	0.1	1.35
	0.2	1.69
	0.3	1.43
	0.4	1.40
	0.5	1.42
	0.6	1.62
	0.7	1.69
	0.8	1.64
	0.9	2.18
	1.0	7.17
0.43	0.1	1.49
	0.2	1.50
	0.3	1.55
	0.4	1.63
	0.5	1.84
	0.6	1.66
	0.7	1.89
	0.8	2.20
	0.9	2.47
	1.0	7.43
0.57	0.1	1.78
	0.2	1.60
	0.3	1.63
	0.4	1.74
	0.5	1.86
	0.6	1.89
	0.7	2.16
	0.8	2.34
	0.9	2.90
	1.0	7.68
0.71	0.1	1.87
	0.2	1.73
	0.3	1.73
	0.4	1.99
	0.5	1.92
0.71 (cont.)	0.6	2.22
	0.7	2.19
	0.8	2.71
	0.9	3.10
	1.0	7.98
0.86	0.1	1.95
	0.2	1.98
	0.3	1.95
	0.4	1.98
	0.5	2.18
	0.6	2.29
	0.7	2.48
	0.8	2.59
	0.9	3.53
	1.0	7.88
1.00	0.1	2.05
	0.2	2.02
	0.3	2.01
	0.4	2.13
	0.5	2.19
	0.6	2.42
	0.7	2.68
	0.8	2.93
	0.9	3.66
	1.0	8.43
1.14	0.1	2.10
	0.2	2.16
	0.3	2.11
	0.4	2.32
	0.5	2.32
	0.6	2.61
	0.7	2.57
	0.8	3.34
	0.9	3.98
	1.0	8.57
2.00	0.1	2.89
	0.2	2.89
	0.3	3.09
	0.4	3.15
	0.5	3.22
	0.6	3.32
	0.7	3.55
	0.8	4.06
	0.9	5.11
	1.0	10.00

Note: The number of head drops, N_f, is 24 for all flownets.

Table G.3 Shape Factors for Anisotropic Condition $K_h = 10K_v$.

R/z	r/R	N_r
0.14	0.1	1.06
	0.2	0.92
	0.3	0.91
	0.4	1.01
	0.5	1.01
	0.6	1.04
	0.7	1.06
	0.8	1.23
	0.9	1.45
	1.0	7.06
0.29	0.1	1.23
	0.2	1.08
	0.3	1.20
	0.4	1.21
	0.5	1.26
	0.6	1.30
	0.7	1.39
	0.8	1.40
	0.9	1.85
	1.0	6.63
0.43	0.1	1.32
	0.2	1.27
	0.3	1.37
	0.4	1.24
	0.5	1.43
	0.6	1.52
	0.7	1.57
	0.8	1.76
	0.9	1.89
	1.0	6.73
0.57	0.1	1.35
	0.2	1.37
	0.3	1.42
	0.4	1.58
	0.5	1.32
	0.6	1.67
	0.7	1.88
	0.8	1.90
	0.9	2.21
	1.0	6.79
0.71	0.1	1.62
	0.2	1.44
	0.3	1.53
	0.4	1.69
	0.5	1.42
0.71 (cont.)	0.6	1.80
	0.7	1.74
	0.8	2.33
	0.9	2.17
	1.0	6.91
0.86	0.1	1.42
	0.2	1.45
	0.3	1.57
	0.4	1.58
	0.5	1.73
	0.6	1.76
	0.7	2.00
	0.8	2.29
	0.9	2.76
	1.0	6.75
1.00	0.1	1.47
	0.2	1.49
	0.3	1.58
	0.4	1.65
	0.5	1.79
	0.6	1.92
	0.7	2.13
	0.8	2.38
	0.9	2.87
	1.0	7.08
1.14	0.1	1.39
	0.2	1.73
	0.3	1.55
	0.4	1.84
	0.5	1.75
	0.6	2.08
	0.7	2.23
	0.8	2.55
	0.9	3.06
	1.0	7.11
2.00	0.1	1.90
	0.2	1.99
	0.3	2.10
	0.4	2.06
	0.5	2.20
	0.6	2.45
	0.7	2.66
	0.8	3.16
	0.9	3.50
	1.0	8.06

Note: The number of head drops, N_f, is 24 for all flownets.

APPENDIX H

USER'S MANUAL FOR PF-MODEL

The following appendix contains the manual for version 3.0 of PF-Model. Installation disks may be obtained upon request from NJIT/CEES (address found in manual). This version of PF-Model contains a Site Screening component and System Design component, and future components may be added at a alter date. A user should have some familiarity with Windows based computer programs and should have a basic geotechnical background.

IMPORTANT NOTE: This version of the computer model is a 32-bit application. Due to compatibility issues, it is recommended that this program be run only on 32-bit operating systems (*e.g.*, Windows 95 or Windows 98).

QUICK START

Q.1 Basics

If you don't have much time to devote to reading a user's manual, and are familiar with running computer software, this Quick Start shows you: (1) how to install PF-MODEL; and (2) where in this manual you can find a step-by-step tutorial.

Q.2 Installing PF-MODEL

You install PF-MODEL on your computer using the Setup program. The Setup program installs PF-MODEL, any OCX control files, and the default files from the installation disks to your hard drive.

Important: You cannot simply copy files from the installation disks to your hard drive and run PF-MODEL. You must use the Setup program first. This will decompress and install the files in the appropriate directories.

The following procedure will install PF-MODEL on your hard drive:

- Insert disk 1 into drive A.
- Use the appropriate setup command for your operating environment. For example, in Windows™ 98, you would go to Add/Remove Programs found in Control Panels. You may also run the Setup program by double-clicking on the Setup icon located on disk 1 in drive A.
- Follow the setup instructions on your screen.

Q.3 Running PF-MODEL

You are now ready to run the pneumatic fracturing computer model. Go to the Start button and select the PF-MODEL icon.

Q.4 Tutorial

Please refer to "Chapter 4 Step-by Step Example" to quickly get acquainted with PF-MODEL's intuitive interface.

PNEUMATIC FRACTURING COMPUTER MODEL

PF-MODEL

Version 3.0

An Integrated Modeling Environment and
Expert System for Pneumatic Fracturing

Developed and Written by

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May 1999

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CHAPTER 1

GETTING STARTED

1.1 PF-MODEL Versions

The enclosed disks contain the required files to setup the pneumatic fracturing computer model on your hard rive. PF-MODEL version 3.0 is currently being distributed on three disks. Any future upgrades may be obtained on disk or through e-mail. To set up PF-MODEL on your hard drive, read "Installing PF-MODEL" later in this chapter.

1.2 Required and Optional Hardware

To run PF-MODEL you need the following minimum system configuration:

- Microsoft Windows 95 or higher;
- A 80486 or higher microprocessor and math co-processor;
- 16MB of RAM, with approximately 400kb free in lower memory;
- A high density (1.44 MB) floppy drive (3.5" diskettes) for software installation;
- A hard drive, with at least 5 MB free;
- A VGA graphics card and suitable monitor;
- A Microsoft or compatible mouse.

The RAM, lower memory, and math co-processor requirements above are to ensure fast and efficient response times due to math intensive calculations and for drawing graphics. A smaller RAM and/or lower memory, or if your system does not have a math co-processor, will result in the user noticing a slower performance of PF-MODEL as drawing graphics and mathematical operations will take longer to complete. Out of memory errors may also result if insufficient RAM is available.

The following options give PF-MODEL more functional capabilities; however, they are not required:

- A printer with graphics capabilities.
- More than 16 MB of RAM.

If you have any problems with your particular system configuration, please make sure that you followed the installation instructions exactly (see Section 1.3 below). If the problem still exists, contact your system experts and then finally contact us at New Jersey Institute of Technology.

1.3 Installing PF-MODEL

PF-MODEL is distributed currently on three 3.5" 1.44 MB diskettes. The disks are formatted for standard IBM PCs and compatibles running MS-DOS or PC-DOS.

PF-MODEL must be installed on your hard disk in order to run. The files are compressed and will not run from the disk. The procedure below assumes that the installation will be from drive A: (the source drive) to drive C: (the destination drive). The default destination directory is C:\Program Files\PF-MODEL, but you may modify it.

Important:	It is good practice to write protect your installation disks. This will protect them from any possible viruses on your computer, ensuring that the disks are virus free. This means the "write protected tab," located at the back of the diskettes, must be open so that the square hole is **not** covered.

Insert the floppy disk titled disk 1 into drive A. Run your appropriate Setup program for your operating environment, or double-click the Setup icon located on Disk 1, then follow the setup instructions

1.4 User Agreement

Please note that PF-MODEL provides results that are based on academic efforts and research, and no claim is made about the reliability, or is any responsibility taken for the results obtained from the program. The computer program is proprietary. Specifically, you may not distribute, rent, sub-license, or lease the software or documentation; alter, modify, or adapt the software or documentation, including, but not limited to, translating, decompiling, disassembling, or creating derivative works without the prior written consent the New Jersey Institute of Technology.

1.5 Running PF-MODEL

You are now ready to run PF-MODEL. You can start PF-MODEL by using the Start button on the task bar in Windows. From the Start Menu, select the PF-MODEL application icon.

CHAPTER 2

THEORETICAL BACKGROUND

PF-MODEL makes extensive use of research on the pneumatic fracturing process performed at the Center for Environmental Engineering and Science (CEES) at New Jersey Institute of Technology (NJIT). For more information on model engines, deflection solvers, methods of solution, expert system design, etc., used in PF-MODEL, the following two references are helpful:

Sielski, B., *Development of a Computer Model and Expert System for Pneumatic Fracturing of Geologic Formations*. Ph.D. Dissertation, Department of Civil and Environmental Engineering, New Jersey Institute of Technology, Newark, NJ. May, 1999.

Puppala, S., *Fracture Propagation and Particulate Transport in Pneumatically Fractured Geologic Formations*. Ph.D. Dissertation, Department of Civil and Environmental Engineering, New Jersey Institute of Technology, Newark, NJ. August, 1998.

WARNING: Modifying the Probability, Flownet, or Default Libraries without fully understanding the corresponding theory behind their use could lead to unexpected behavior of PF-MODEL.

CHAPTER 3

USING PF-MODEL

3.0 General Overview

PF-MODEL fully exploits the graphical user interface (GUI) that is familiar to anyone that uses Windows type programs, such as Microsoft's Word or Excel. PF-MODEL uses the same pull down menus, buttons, scroll bars, etc., that are familiar to most users today. It should therefore be easy and intuitive to use PF-MODEL.

3.1 How to Run PF-MODEL

Refer to Chapter 1 (Getting Started) to run PF-MODEL. When the program starts, an introductory screen will appear. Select Go! to move to the Data Input screen.

3.2 Hot Keys and Mouse Functions

As outlined in Section 1.2, a mouse is required to use PF-MODEL. This is the easiest and most efficient way to move about in PF-MODEL. However, most menu items and buttons can be accessed using Hot Keys. The Hot Key which corresponds to any particular menu item or button is identified by an underscore under a letter. The Hot Key is activated by simultaneously pressing the <Alt> key and the Hot Key (*i.e.*, the underscored letter).

In most screens, the tab key can be used to move from one field or button to another field or button.

3.3 Screen Layout

The graphical user interface consists of two parts: the Main Screen and the Menu Bar.

3.3.1 The Top Menu Bar

The top menu bar gives access to the following six options:

[FILE]	...Select or create a data set, print, save, or exit PF-MODEL;
[COMPONENT]	...Select an active component to move to;
[LEAKOFF]	...Select the method of leakoff used by the model;
[DEFLECTION]	...Allows the user to select from four bending deflection solvers modeled in the program;
[ADVANCED]	...Allows access to the more advanced functions of PF-MODEL. Only the more experienced user should access these functions;
[BACKGROUND]	...Provides background and general information, including help.

The desired option is selected and executed by either clicking the left mouse button while positioned over the option, or by using the appropriate Hot Key. All of the above menus are drop-down menus, where more options are displayed. These option can be accessed by continuing to use the mouse, or the Hot Keys. The menus are described further in the following sections.

3.3.1.1 FILE Menu

When you choose the [FILE] option in the top menu bar, you are then transferred to the file drop-down menu:

[NEW]	...Generates a new PF-MODEL data set;
[OPEN]	...Opens an existing PF-MODEL data set;
[SAVE AS]	...Saves file under a user specified name;
[PRINT]	...Print the given screen to printer;
[EXIT]	...Ends the program.

3.3.1.2 COMPONENT Menu

When you choose the [COMPONENT] option you will see the active model components available to you. If a component is not active, you must go back to the data input screen and activate the component directly.

[SITE SCREENING] ...Move to the Site Screening component, where you can evaluate the applicability of pneumatic fracturing using PF-MODEL's expert system;

[SYSTEM DESIGN] ...Move to the System Design component where the estimated results for aperture and radius are found;

[CALIBRATION] ...The Calibration Mode can be used to determine a sites post-fracture modulus and conductivity (provided data from a pilot test is available). The modulus and conductivity values can then be used directly by the System Design component to better estimate the aperture and expected radius for the site;

[RETURN TO DATA INPUT] ...Returns back to the data input screen, allowing you to make changes in geology type, conductivity, etc.

3.3.1.3 LEAKOFF Menu

The [LEAKOFF] menu allows you to select from two approaches used to predict the complex pattern of leakoff that occurs in a fracture: an analytical method and graphical method. The analytical method calculates leakoff by summing the lost flow from successive annular rings of the fracture surface. The graphical method modifies Darcy's law to account for pressure variation with respect to radial distance in three dimensions.

[ANALYTICAL] ...Use the Analytical method to find the solution. This leakoff method uses an effective conductivity;

[GRAPHICAL] ...Use the Graphical (or flownet) method to find the solution. The graphical method expands to another drop down menu. It allows for the use of isotropic, as well as anisotropic conditions. The default leakoff method for PF-MODEL is $K_h = 5K_v$;

3.3.1.4 DEFLECTION Menu

It is assumed that pneumatic fractures cause deflection of the overburden in a manner similar to a thick plate in bending. The [DEFLECTION] menu provides four optional deflection models with different combinations of pressure distribution and formation geometry.

[LOG DISTRIBUTION/CIRCULAR PLAN] ...This is the default selection of PF-MODEL, which uses a logarithmic pressure distribution acting on a circular plate to predict a tapering fracture. It is always recommended that this Deflection Solver be used. The other three Deflection Solvers are included for research purposes;

[CONSTANT PRESSURE/CIRCULAR PLAN] ...Selects a constant pressure distribution acting on a circular plate to predict the fracture;

[CONSTANT PRESSURE/ANTICLINAL PLAN] ...Selects a constant pressure distribution acting on an anticlinal beam;

[LINEARLY TAPERING/CIRCULAR PLAN] ...Selects a linearly tapering pressure distribution acting on a circular plate.

3.3.1.5 ADVANCED Menu

The advanced functions of PF-MODEL should only be accessed by expert users of the program and the pneumatic fracturing technology. These options add greater functionality to the program, thereby increasing the versatility of any analysis performed by the model. It is also possible to tailor your version of PF-MODEL with proprietary information.

[MODEL ENGINE] ...Expands to another drop down menu. The engines models two different approaches to arrive at a solution: Bisection and Increasing. The default engine is Bisection, which decreases the processing time considerably by converging rapidly towards the solution, yet maintains the accuracy of the Increasing engine. The Increasing Engine is included for use during research;

[INPUT PARAMETERS] ...Accesses the Input Parameter screen, allowing you to change geotechnical properties or system properties for the current data set. Some of the properties include, Young's modulus, formation density, fracture toughness, density of the injection gas, etc. This is the preferred method to modify the default parameters since it does not permanently change your default libraries;

[EXPERT] ...Expands to another drop down menu. This option is only or an expert among the experts. The three default libraries are accessed through this option, and changes will become permanent, if saved. The libraries are:

- *Flownet* - contains the flownet shape factors used for the Graphical Leakoff Methods;
- *Knowledge Base* - Contains the heuristic probabilities, based on subjective probability theory (Bayes' theory) used by the inference engine of the Site Screening expert system.
- *Default* - Contains the geotechnical and system defaults for the 14 geologic formation supported by PF-MODEL.

It is not recommended that you permanently modify these libraries. If you make a change or mistake, and wish to return to the original libraries, you will need to either reinstall PF-MODEL from the original distribution disks, or contact NJIT/CEES for the master *.def files.

3.3.1.6 BACKGROUND Menu

From this menu item, you can access some of the history and background information of the pneumatic fracturing technology, and help for PF-MODEL.

[HISTORY] ...Since 1987, when research began on the pneumatic fracturing technology, a rich and colorful history has developed. This option will guide you through the journey;

[APPLICATIONS] ...Discusses some of the more traditional applications pneumatic fracturing is coupled with;

[CASE STUDIES] ...A presentation of various case studies;

[ABOUT PF-MODEL]	...About PF-MODEL;
[HELP]	...Describes how to access PF-MODEL's help and explanation facility, and if all else fails, how to contact NJIT/CEES for technical assistance.

CHAPTER 4

STEP-BY-STEP EXAMPLE

4.0 General Overview

The following example is deliberately simple to quickly get the first-time user comfortable with using PF-MODEL.

4.1 Description of Problem

Figure 4.1 shows a BTX plume that originated at the Little Bighorn Refinery, and is migrating towards a nearby creek. The contaminant originated from surface spills over an extended period of years.

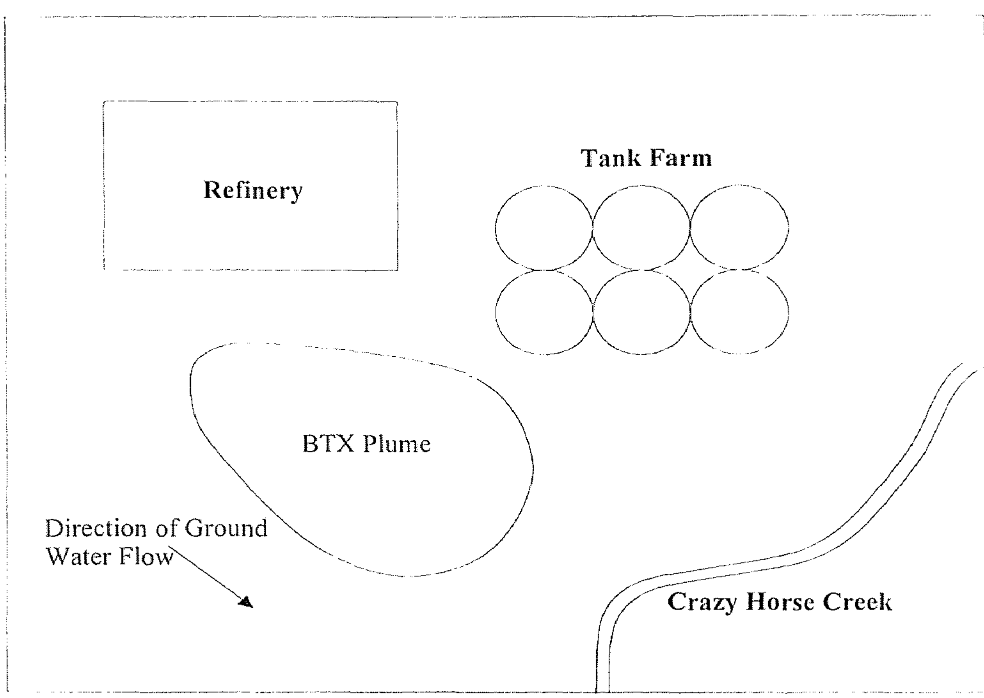

Figure 4.1 Map showing location of BTX plume at Little Bighorn Refinery.

In order to stop the plume migration, it has been determined that the contaminants should be removed from the subsurface. The subsurface profile consists of a 3 ft thick layer of miscellaneous granular fill and an underlying shale beginning at a depth of 19 ft. A medium-stiff clayey silt (UCS-CL) lies between the fill and shale. The water table varies seasonally from 6 to 15 ft. The maximum depth of the BTX plume is 15 ft. Figure 4.2 shows a profile view.

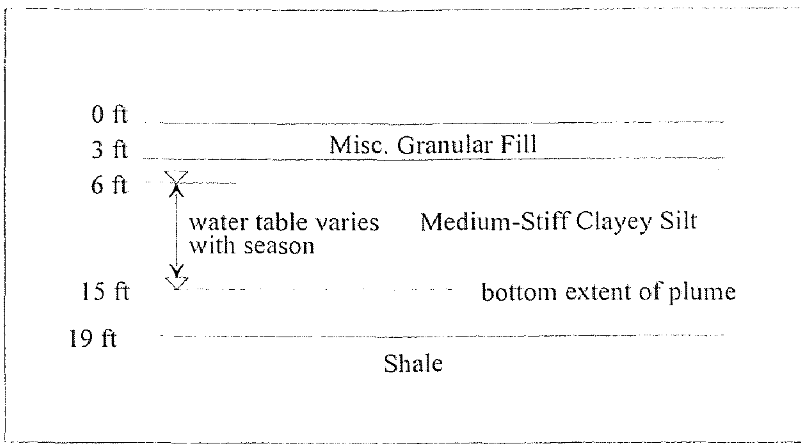

Figure 4.2 Cross sectional view of BTX plume.

A preliminary investigation is undertaken to develop a remedial plan in order to:

- determine if the pneumatic fracturing technology is applicable at the Little Bighorn Refinery, and
- if it is, increase the permeability of the clayey silt so that vapor extraction may be applied.

You are to use PF-MODEL to:

1. Determine if this site is applicable for the pneumatic fracturing technology.
2. If it is, estimate the maximum expected radius of fracture extent.
3. Determine system requirements (pressure and flow) to effect permeability enhancement to a design goal of wells spaced at 15 ft.

4.2 Generation of Data Set

Start PF-MODEL by clicking on the PF-MODEL icon located in your Start Menu of the Windows™ task bar. After the introductory screen, you are now viewing the Data Input screen (Figure 4.3). Take time to view this screen, and even explore some of the options available from the Menu Bar, such as the Background Menu (note that many of the options are not active yet). Take time to fill out the project name, date, and your name, if you haven't already.

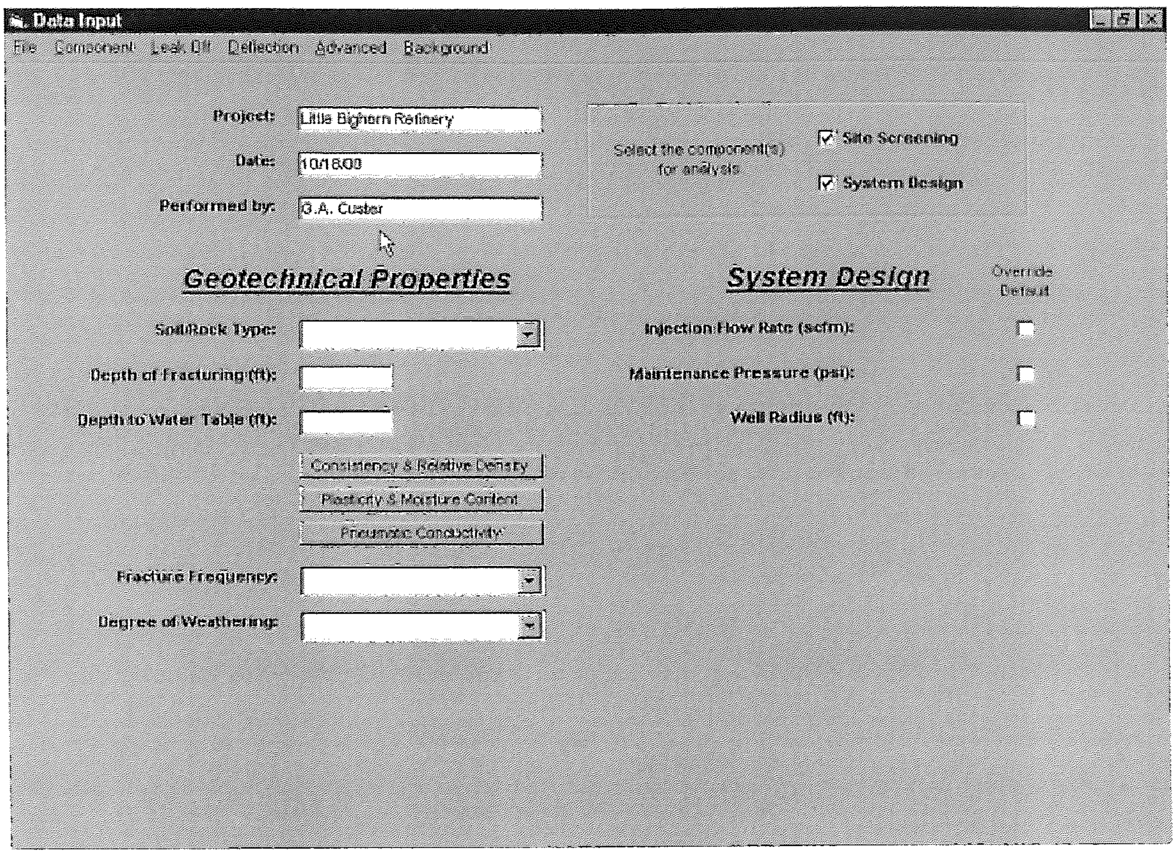

Figure 4.3 The Data Input Screen.

After becoming familiar with the Data Input screen, you are now ready to enter the known Little Bighorn Refinery site data. You first want to determine if pneumatic fracturing can be used for permeability enhancement at this site. On the top right of the main screen, find the frame that says, "Select component(s) for analysis," and

Select the <u>check box</u> for SITE SCREENING.

Note that some of the Geotechnical Properties are now activated and ready for data entry. If you have any questions, or need help on a particular item, you can get help by placing the pointer over the item, and RIGHT CLICK the mouse. For example, put the mouse pointer over the text "Soil/Rock Type."

Right Click the label SOIL/ROCK TYPE.

Now you can get a quick hint, or more help on the geologic types supported by PF-MODEL. Throughout PF-MODEL, you can obtain help by right clicking other buttons, labels, and graphs.

Click the button DONE.

You'll now select the soil type by scrolling down the Soil/Rock Type drop-down box.

Select CLAYEY SILT.

(Although not visible to you at this time, PF-MODEL has already selected geotechnical and system default values based on the soil type you have selected. If actual field data from the Little Bighorn Refinery was available, you would enter that data instead.)

For the depth of fracturing, we'll select an average depth for the plume,

Enter the value of 10. (ft)

Next, enter the depth of the water table. It is known that the water table varies from 6 to 15 ft. Assume that the work is to be done in August and therefore the water table is likely to be at its lowest level.

Enter the value of 15. (ft)

Other evidence is also available. The clayey silt is of medium-stiff consistency. Therefore,

Click the button CONSISTENCY & RELATIVE DENSITY,

Select the option MEDIUM TO STIFF,

Click the button DONE.

This is all the data and site evidence that is available. Now proceed to the Site Screening component and see if the pneumatic fracturing technology is going to be applicable.

Select COMPONENT from the Menu Bar,

Select SITE SCREENING from the Component Menu.

At this point the program begins to load the knowledge base library. When the library is loaded, the Site Screening screen appears (Figure 4.4).

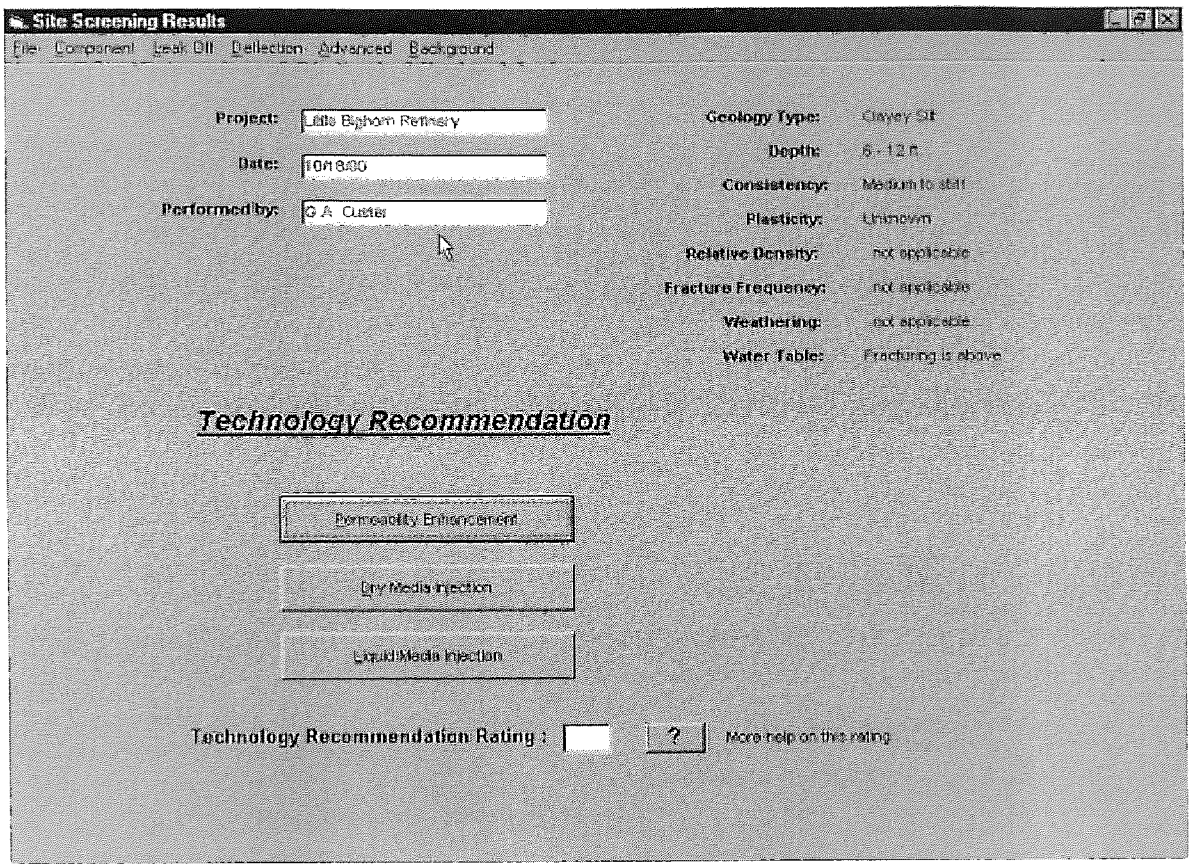

Figure 4.4 The Site Screening Screen.

Notice in the top right of the main screen, there are eight geotechnical properties. The site information that you entered in the Data Input screen should be reflected here. If everything looks right,

Click on the button PERMEABILITY ENHANCEMENT.

A technology recommendation rating of 76 is given. Right now, this value may not have any significant meaning. To better understand the rating,

Click the button "?"

Take time to read the recommendation ratings in the help box.

After reading the recommendation ratings, it is obvious that this site's value of 76 is a good candidate for permeability enhancement. Notice that there is still evidence that is not known. In this instance it is plasticity. Now check out if there can be any adverse effects due to plasticity.

The eight geotechnical labels on the upper right are also active objects. By clicking on any of them, a screen with qualifiers pops up. To see the effects of plasticity,

Click on the label PLASTICITY,

Select the option $w < PL$.

By this selection, you are assuming that the clayey silt is in a brittle condition ($w < PL$). Now check to see what effect this has on the technology recommendation.

Click on the button PERMEABILITY ENHANCEMENT.

A rating of 83 is given. This is an excellent condition for pneumatic fracturing. However, let's look at one more condition where the plasticity is liquid ($w > LL$).

Click on the label PLASTICITY,

Select the option $w > LL$,

Click on the button PERMEABILITY ENHANCEMENT.

A rating of 27 is given! In this instance, pneumatic fracturing is not likely to be effective for permeability enhancement (without use of system variants, *e.g.*, proppants). What this indicates is that more evidence is always desirable in order to have confidence in the recommendation.

However, the original recommendation rating of 76 is an indication that the site can support the technology. Therefore, you shall continue to develop the remedial plan and determine the expected maximum radius.

Select COMPONENT from the Menu Bar,

Select the RETURN TO DATA INPUT from the Component Menu.

At this point the program begins to load the Flownet and Default libraries (this will take a few seconds). When completed, the Data Input screen appears.

On the top right of the main screen, in the frame titled "Select component(s) for analysis,"

Select the <u>check box</u> for SYSTEM DESIGN.

Note that more of the properties are now active. But before proceeding, just check the default values to make sure they're appropriate for your application.

Select the button PNEUMATIC CONDUCTIVITY.

Notice that the default value for the post-fracture pneumatic conductivity is 0.00035 (cm/sec). The default values for post-fracture pneumatic conductivity have been carefully regressed from actual field measurements. You should note that the value of this parameter will have a significant influence on the propagation radius of pneumatic fractures.

For this reason, if you are using PF-MODEL in the Fracture Prediction Mode as you are now, ***<u>it is strongly advised that you use the default value.</u>*** However, if a pilot test of pneumatic fracturing was performed at the site and the actual value of post-fracture pneumatic conductivity has been determined, then it should be entered here. Please refer to the help screen for further discussion about pneumatic conductivity.

Click the button DONE.

Now look at some of the other default values. This will require using PF-MODEL's Advanced functions.

Select ADVANCED from the Menu Bar,

Select INPUT PARAMETERS from the Advanced Menu.

The Input Parameter screen is shown in Figure 4.5 on the following page. It lists the system and geotechnical parameters used by the System Design algorithm. Take time to examine the values and become familiar with the terms. Some of these should be obvious (*e.g.*, density of gas, Young's modulus, and formation density). Others, such as the Head Loss Factor, require expert knowledge in the development and subsequent analysis of the Flownet Library.

Click the button DONE.

The previous two screens, Pneumatic Conductivity and Input Parameters, are where most experts will make adjustments to "fine tune" a site, changing conductivity, modulus, density, etc., as required.

Since everything looks in order, it's time to find out the expected radius.

Select COMPONENTS from the Menu Bar,

Select SYSTEM DESIGN from the Components Menu.

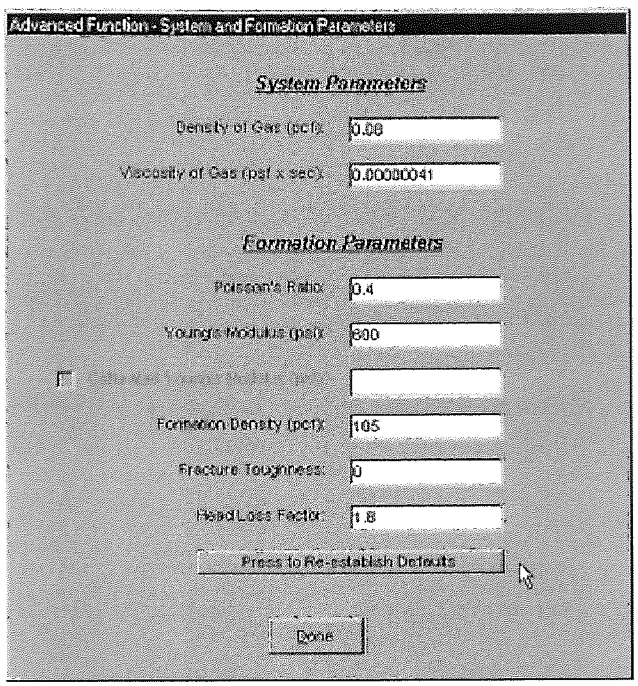

Figure 4.5 The Input Parameters Screen.

You should now see the System Design screen as shown in Figure 4.6 below.

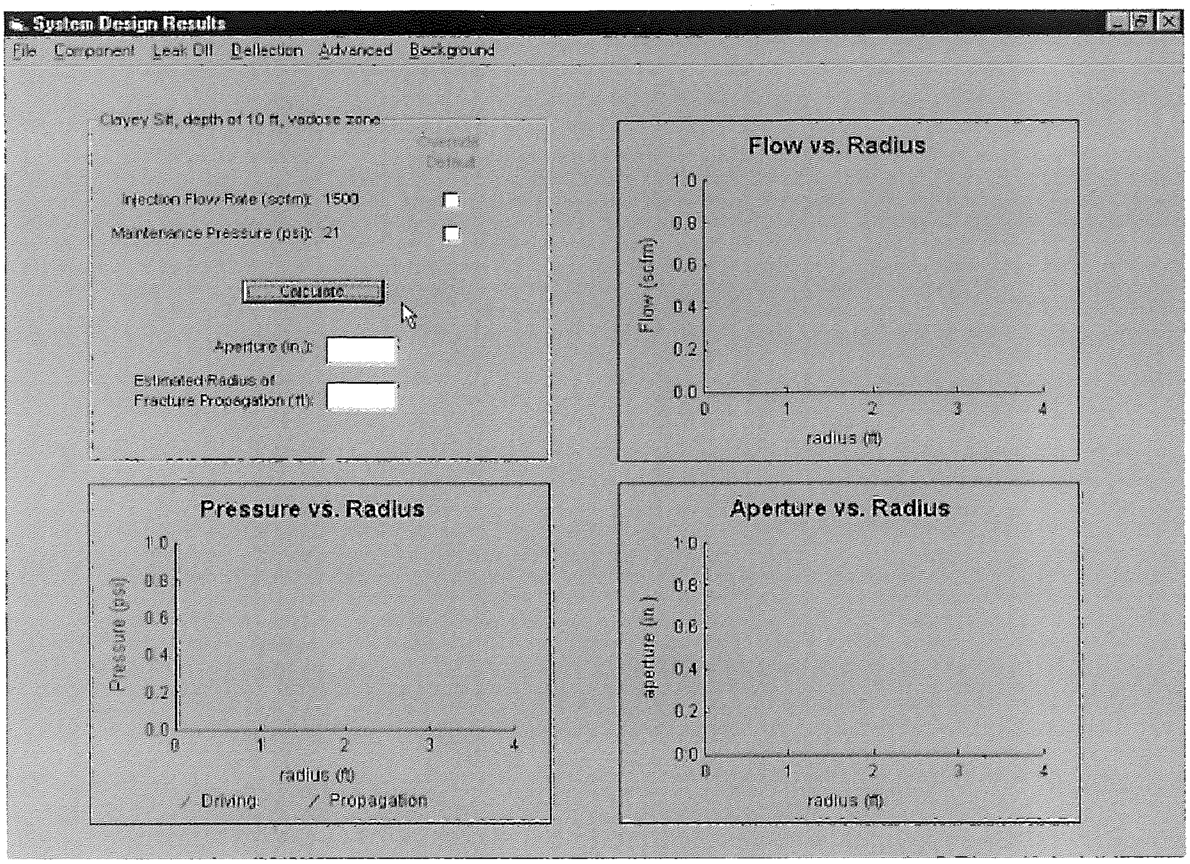

Figure 4.6 The System Design Screen.

Let's just verify the model solution algorithm's defaults. First check leakoff.

Select LEAKOFF from the Menu Bar,

Select GRAPHICAL from the Leakoff Menu.

A check should appear next to the leakoff model default, which is $K_h = 5K_v$ (this is also your only choice when using PF-MODEL's conductivity default). If not,

Select $K_h = 5K_v$ from the Graphical Sub-menu.

This choice reflects the fact that many natural geologic formations display some degree of anisotropy, with higher conductivity in the longitudinal direction. This anisotropy is normally due to stratification and bedding effects.

Next, check on the Deflection Solver used by PF-MODEL.

Select DEFLECTION from the Menu Bar.

The default is Log Distribution/Circular Plan and should already be selected. If not,

Select LOG DISTRIBUTION/CIRCULAR PLAN from the Deflection Menu.

Since everything is now set,

Click the button CALCULATE.

After a few seconds, PF-MODEL will present the estimated aperture and radius below the Calculate button.

The estimated aperture is 0.416 in. <<<

The estimated radius is 14.04 ft. <<<

If your answers are different than above, go back to the beginning of the step-by-step example and repeat the procedure until you arrive at the above solutions.

Now you're going to perform some "fine tuning" with the System Design component for preliminary layout of the fracture wells. Assume that a 25 ft well spacing is desired, and that a 20% "overlay" of fracture influence radius will be implemented. The required fracture radius is then:

$$\frac{25}{2} \times 1.20 = 15\,\text{ft}$$

Therefore, the system parameters must now be be modified to extend the fracture radius from 14.04 ft (the previous result) to 15.0 ft. The default flow rate of 1500 scfm must now be increased to accomplish this.

Click on the OVERRIDE DEFAULT check box for Flow Rate,

A text field has now appeared next to each system parameter. For the system flow rate,

Enter the value 2500, (scfm)

Click the button CALCULATE.

The estimated aperture is 0.864 in. <<<
The estimated radius is 15.7 ft. <<<

(Note: you could also adjust Maintenance Pressure to obtain a larger fracture radius. However, we will retain the default Maintenance Pressure which is associated with the selected flow rate.)

The chosen value of flow rate is apparently too high. Now try a lower value.

Enter the value 2000, (scfm)

Click the button CALCULATE.

The estimated aperture is 0.676 in. <<<
The estimated radius is 15.16 ft. <<<

You can continue with new values for system design, but these are close enough. That's because you've used default values for conductivity and modulus. It is estimated that the accuracy of the model when using the defaults is ±25%. More accurate results could be obtained by performing a pilot test since this would allow direct measurement of the post-fracture pneumatic conductivity and Young's modulus at the Little Bighorn Refinery.

Congratulations! You've completed your first preliminary design of a pneumatic fracturing system!

In summary, you found that:

- Pneumatic fracturing at the Little Bighorn Refinery is likely to be effective,
- A fracture well spacing of 25 ft was preliminarily selected.
- To obtain 15 ft well spacings:
  injection flow rate = 2000 scfm, and
  maintenance pressure = 24 psi.

The user is encouraged now to explore and create new sites for analysis. To quit PF-MODEL, go to the File Menu and select Exit.

APPENDIX I

SELECTIONS OF PROGRAM CODE USED IN PF-MODEL

I.1 Introduction

This appendix contains selected portions of code for copyright purposes. As programming style varies from individual to individual, this section will also allow for the reader to acclimate himself with this programmer's style of coding.

The following three selections were chosen:

- selected code from the System Design Subroutine, including coded subroutine calls for the Model Engine and PDF Subroutines,
- selected code for the Site Screening component's expert system, showing equations of subjective probability, and access to the knowledge base, and,
- coding for the Data Input screen showing mostly its object activation code.

Please note that PF-Model, documentation, and the code herein are part of academic efforts and research and are proprietary to the author and NJIT. Specifically, you may not distribute, rent, sub-license, or lease the software, documentation, and code; alter, modify, or adapt the software, documentation, or code, including, but not limited to, translating, decompiling, disassembling, or creating derivative works without the prior written consent of the author and the New Jersey Institute of Technology.

I.2 Selected Code for the System Design Subroutine

```
Option Explicit

Private Sub cmdCalculate_MouseUp(Button As Integer, Shift As Integer, _
                        X As Single, Y As Single)

ProcName = "cmdCalculate_MouseUp"
On Error GoTo ErrorHandler

If Button = vbLeftButton Then

Screen.MousePointer = vbHourglass
Screen.MousePointer = 11

   Dim ApertureFlag As Integer
   Dim D As Single
   Dim Density As Single
   Dim DENSITYGas As Single
   Dim depth As Single
   Dim FractureToughness As Single
   Dim HeadLossDistance As Single
   Dim HeadLossFactor As Single
   Dim K As Single
   Dim Kh As Single
   Dim Kv As Single
   Dim MaintPres As Single
   Dim Modulus As Single
   Dim Poisson As Single
   Dim PRESdriv As Single
   Dim RADIUSwell As Single
   Dim R_next As Single
   Dim VISCOSITYGas As Single
   Dim XX As Single

Abort = "No"      ' Set the Abort Error Flag to No.

   Density = Val(frmInputParameters.txtFormationDensity)   ' Formation density
   DENSITYGas = Val(frmInputParameters.txtDensityGas)
   depth = Val(frmDataInput.txtFractureDepth)      ' Depth of fracture
   FractureToughness = Val(frmInputParameters.txtFractureToughness)
   HeadLossFactor = Val(frmInputParameters.txtHeadLossFactor)
   Modulus = Val(frmInputParameters.txtYoungsModulus)
```

```
Poisson = Val(frmInputParameters.txtPoissonsRatio)

' Determine which well radius to use, either default or user provided.
If frmDataInput.chkOverrideWellRadius.Value = 1 Then       ' Checked (or on)
   RADIUSwell = Val(frmDataInput.txtWellRadius)
ElseIf frmDataInput.chkOverrideWellRadius.Value = 0 Then   ' Unchecked (or off)
   RADIUSwell = Val(frmDataInput.lblDefaultWellRadius.Caption)
End If

VISCOSITYGas = Val(frmInputParameters.txtViscosityGas)


ApertureFlag = 0       ' Turns off aperture at well calculation

' Determine which hydraulic conductivities to use.

' If anisotropic conductivity is selected.
If frmPneumaticConductivity.optKhKv = True Then
   Kh = Val(frmPneumaticConductivity.txtHorizontalConductivity)
   Kv = Val(frmPneumaticConductivity.txtVerticalConductivity)
' If isotropic conductivity is selected.
ElseIf frmPneumaticConductivity.optTotalConductivity = True Then
   Kh = Val(frmPneumaticConductivity.txtTotalConductivity)
   Kv = Kh
' Else use the default as an isotropic.
Else
   Kh = Val(frmPneumaticConductivity.txtPneumaticDefault)
   Kv = Kh
End If

' Calculation of driving pressure.
' Determine which pressure to use, either the default or user provided.
If frmDataInput.chkOverridePressure.Value = 1 Then      ' Checked (or on)
   MaintPres = Val(frmDataInput.txtMaintenancePressure)
ElseIf frmDataInput.chkOverridePressure.Value = 0 Then  ' Unchekced (or off)
   MaintPres = Val(frmDataInput.lblDefaultPressure.Caption)
End If
PRESdriv = MaintPres - ((Density * depth) / 144) ' units in psi


' Calculation of head loss distance
HeadLossDistance = HeadLossFactor * depth      ' units in feet

' Determines the value of "D" which is used for the circular
' plate log distribution.
If mnuSolverLogDistribution.Checked = True Then
   D = (Modulus * (depth ^ 3)) / (12 * (1 - (Poisson ^ 2)))
End If

If mnuAdvancedEngineIncreasing.Checked = True Then
   Call Increasing(Abort, ApertureFlag, D, Density, DENSITYGas, depth, _
         FractureToughness, HeadLossDistance, K, Kh, Kv, MaintPres, Modulus, _
         Poisson, PRESdriv, RADIUSwell, R_next, VISCOSITYGas, XX)
Else
```

```
        Call Bisection(Abort, ApertureFlag, D, Density, DENSITYGas, depth, _
                FractureToughness, HeadLossDistance, K, Kh, Kv, MaintPres, Modulus, _
                Poisson, PRESdriv, RADIUSwell, R_next, VISCOSITYGas, XX)
    End If
    Screen.MousePointer = 0 '  Sets mouse pointer back to default.
End If

If Button = vbRightButton Then
    HELP_ITEM = "System Design Calculation"
    Call Help(HELP_ITEM)
End If


'  Error Code.
Exit Sub
ErrorHandler:
    Msg = "An untrapped error has occured.  Please make a " & Chr$(13)
    Msg = Msg & "note of the following information." & Chr$(13) & Chr$(13)
    Msg = Msg & "Error number: " & Err.Number & Chr$(13)
    Msg = Msg & "Description: " & Err.Description & Chr$(13)
    Msg = Msg & "Location: " & Screen.ActiveForm.Name & Chr$(13)
    Msg = Msg & "Procedure: " & ProcName
    MsgBox (Msg)

End Sub



Public Sub Increasing(Abort, ApertureFlag, D, Density, DENSITYGas, depth, _
                FractureToughness, HeadLossDistance, K, Kh, Kv, MaintPres, Modulus, _
                Poisson, PRESdriv, RADIUSwell, R_next, VISCOSITYGas, XX)

    Dim RADIUS As Single
    Dim RADincr As Single
    Dim Qtip As Single

ProcName = "Increasing"
On Error GoTo ErrorHandler


    ' Initialize the variables
    RADIUS = 1
    RADincr = 0.01
    Qtip = 1

    Do While Qtip > 0
        RADIUS = RADIUS + RADincr
        Qtip = StarTrek(Abort, ApertureFlag, D, Density, DENSITYGas, depth, _
                FractureToughness, HeadLossDistance, K, Kh, Kv, MaintPres, Modulus, _
                Poisson, PRESdriv, RADIUS, RADIUSwell, R_next, VISCOSITYGas, XX)
            If Abort = "Yes" Then Exit Sub
        If RADIUS > 100 Then   ' infinite loops check
            txtEstimatedRadius.Text = "ERROR"
            Exit Do
```

```
    End If
  Loop
  ApertureFlag = 1        ' Turns on aperture at well calculation
  Call ShowResults(Abort, ApertureFlag, D, Density, DENSITYGas, depth, FractureToughness, _
            HeadLossDistance, K, Kh, Kv, MaintPres, Modulus, Poisson, PRESdriv, _
            RADIUS, RADIUSwell, R_next, VISCOSITYGas, XX)

' Error Code.
Exit Sub
ErrorHandler:
  Msg = "An untrapped error has occured.  Please make a " & Chr$(13)
  Msg = Msg & "note of the following information." & Chr$(13) & Chr$(13)
  Msg = Msg & "Error number: " & Err.Number & Chr$(13)
  Msg = Msg & "Description: " & Err.Description & Chr$(13)
  Msg = Msg & "Location: " & Screen.ActiveForm.Name & Chr$(13)
  Msg = Msg & "Procedure: " & ProcName
  MsgBox (Msg)

End Sub



Public Sub Bisection(Abort, ApertureFlag, D, Density, DENSITYGas, depth, _
            FractureToughness, HeadLossDistance, K, Kh, Kv, MaintPres, Modulus, _
            Poisson, PRESdriv, RADIUSwell, R_next, VISCOSITYGas, XX)

  Dim FlowFlag As Integer
  Dim QError As Single
  Dim Qlow As Single
  Dim Qmiddle As Single
  Dim RADIUS As Single
  Dim RADIUSlow As Single
  Dim RADIUSmiddle As Single
  Dim RADIUSup As Single

ProcName = "Bisection"
On Error GoTo ErrorHandler

  RADIUSlow = 1
  RADIUSmiddle = 100
  RADIUSup = 200
  QError = 100
  FlowFlag = 1

  Do While QError > 0.1

    RADIUSmiddle = ((RADIUSlow + RADIUSup) / 2)

    If FlowFlag = 1 Then

      RADIUS = RADIUSlow
      Qlow = StarTrek(Abort, ApertureFlag, D, Density, DENSITYGas, depth, _
          FractureToughness, HeadLossDistance, K, Kh, Kv, MaintPres, Modulus, _
          Poisson, PRESdriv, RADIUS, RADIUSwell, R_next, VISCOSITYGas, XX)
```

```
      If Abort = "Yes" Then Exit Sub
    RADIUS = RADIUSmiddle
    Qmiddle = StarTrek(Abort, ApertureFlag, D, Density, DENSITYGas, depth, _
            FractureToughness, HeadLossDistance, K, Kh, Kv, MaintPres, Modulus, _
            Poisson, PRESdriv, RADIUS, RADIUSwell, R_next, VISCOSITYGas, XX)
      If Abort = "Yes" Then Exit Sub
  Else
    RADIUS = RADIUSmiddle
    Qmiddle = StarTrek(Abort, ApertureFlag, D, Density, DENSITYGas, depth, _
            FractureToughness, HeadLossDistance, K, Kh, Kv, MaintPres, Modulus, _
            Poisson, PRESdriv, RADIUS, RADIUSwell, R_next, VISCOSITYGas, XX)
      If Abort = "Yes" Then Exit Sub
  End If

  If (Qlow * Qmiddle) < 0 Then
    RADIUSup = RADIUSmiddle
    FlowFlag = 0
  ElseIf (Qlow * Qmiddle) > 0 Then
    RADIUSlow = RADIUSmiddle
    FlowFlag = 1
  Else      ' RADIUSlow * RADIUSmiddle = 0
    Exit Do
  End If

  QError = Abs((RADIUSup - RADIUSlow) / (RADIUSup + RADIUSlow)) * 100
 Loop

 ApertureFlag = 1

 Call ShowResults(Abort, ApertureFlag, D, Density, DENSITYGas, depth, FractureToughness, _
          HeadLossDistance, K, Kh, Kv, MaintPres, Modulus, Poisson, PRESdriv, _
          RADIUS, RADIUSwell, R_next, VISCOSITYGas, XX)

 Error Code.
Exit Sub
ErrorHandler:
  Msg = "An untrapped error has occured.  Please make a " & Chr$(13)
  Msg = Msg & "note of the following information." & Chr$(13) & Chr$(13)
  Msg = Msg & "Error number: " & Err.Number & Chr$(13)
  Msg = Msg & "Description: " & Err.Description & Chr$(13)
  Msg = Msg & "Location: " & Screen.ActiveForm.Name & Chr$(13)
  Msg = Msg & "Procedure: " & ProcName
  MsgBox (Msg)

End Sub
```

Private **Function StarTrek**(Abort, ApertureFlag, D, Density, DENSITYGas, depth, _
FractureToughness, HeadLossDistance, K, Kh, Kv, MaintPres, Modulus, _
Poisson, PRESdriv, RADIUS, RADIUSwell, R_next, VISCOSITYGas, _
XX) As Single

```
   Dim Aperture As Single
   Dim PneumaticConductivity As Single
   Dim PHI As Single
   Dim PRES_n As Single
   Dim PRES_next As Double
   Dim PRES_prop As Single
   Dim Qleak As Single
   Dim Qres As Single
   Dim R_incr As Single
   Dim R_n As Single

ProcName = "StarTrek"  ' Assign the procedure name for error handling.
On Error GoTo FileError

   R_next = RADIUSwell
   R_n = RADIUSwell

   ' Determine to use either the default flow or user entered flow.
   If frmDataInput.chkOverrideFlow.Value = 1 Then     ' Checked (or on)
      Qres = Val(frmDataInput.txtFlowRate)
   ElseIf frmDataInput.chkOverrideFlow.Value = 0 Then  ' Unchecked (or off)
      Qres = Val(frmDataInput.lblDefaultFlow.Caption)
   End If

   ' Determines the value of the hydraulic conductivity that is used for the
   ' graphical flownet method.
   If (mnuLeakOffGraphicalKh_Kv.Checked = True) Or _
        (mnuLeakOffGraphicalKh_5Kv.Checked = True) Or _
        (mnuLeakOffGraphicalKh_10Kv.Checked = True) Then
      PneumaticConductivity = (Kv * Kh) ^ 0.5
   End If

   ' Determines the value of "K" which is used for the circular
   ' plate log distribution.
   If mnuSolverLogDistribution.Checked = True Then
      K = PRESdriv / (Log(RADIUS / RADIUSwell))
   End If

   PRES_n = (MaintPres * 144) / DENSITYGas     ' converts psi to ft
   PRES_prop = PRESprop(Abort, Density, DENSITYGas, depth, FractureToughness, R_n) ' units = ft

   Do While (Qres > 0) And (R_next < RADIUS) And (PRES_n > PRES_prop)

      R_incr = 0.1

      If (RADIUS - R_n) < 1 Then
         R_incr = 0.001
      End If

      R_next = R_n + R_incr

      XX = (R_next + R_n) / 2

      ' Determine the aperture.
```

```
    Aperture = ApertureCalculation(Abort, ApertureFlag, D, depth, K, Modulus, Poisson, _
                    PRESdriv, RADIUS, RADIUSwell, R_next, XX)


    ' This block checks to see if the square root is negative, and if
    ' it is, it jumps out of the subroutine.  The number '60' is to
    ' convert scfm to scf-sec.
    If (PRES_n ^ 2) < _
       (((12 * (Qres / 60)) * (VISCOSITYGas) * (PRES_n) * (Log(R_next / R_n))) / _
       ((Pi * DENSITYGas) * (Aperture ^ 3))) Then
       StarTrek = Qres
       Exit Do
    End If

    PRES_next = ((PRES_n ^ 2) - _
       (12 * (Qres / 60) * VISCOSITYGas * PRES_n * Log(R_next / R_n)) / _
       (Pi * DENSITYGas * (Aperture ^ 3))) ^ 0.5

    PRES_prop = PRESprop(Abort, Density, DENSITYGas, depth, FractureToughness, R_n)


    '  Calculate the Flow by the Flownet method.
    If (mnuLeakOffGraphicalKh_Kv.Checked = True) Or _
       (mnuLeakOffGraphicalKh_5Kv.Checked = True) Or _
       (mnuLeakOffGraphicalKh_10Kv.Checked = True) Then

       Call Flownet(Abort, depth, PHI, R_incr, RADIUS, XX)

       ' The value 1.9686 converts conductivity of cm/sec to ft/min.
       Qleak = 1.9686 * PneumaticConductivity * PRES_n * PHI * Pi * _
            ((R_next) + (R_n))
       Qres = Qres - Qleak

    Else
    '  Else it calulates by the analytical method.

       ' The value 1.9686 converts conductivity of cm/sec to ft/min.
       Qleak = (((Kh * Kv) ^ 0.5) * 1.9686) * _
          (((PRES_next + PRES_n) / 2) / (HeadLossDistance)) * _
          Pi * (R_next ^ 2 - R_n ^ 2)

       Qres = Qres - (2 * Qleak)

    End If

    StarTrek = Qres
    R_n = R_next
    PRES_n = PRES_next
  Loop

Exit Function

FileError:
'  Divide by zero
```

```
If Err.Number = 11 Then
   Msg = "The algorithm is dividing by zero.  This is most " & Chr$(13)
   Msg = Msg & "likely due to an incorrectly entered system, input, " & Chr$(13)
   Msg = Msg & "or geologic parameter.  Go back and check your " & Chr$(13)
   Msg = Msg & "entered data." & Chr$(13) & Chr$(13)
   Msg = Msg & "If the problem persists, please make a " & Chr$(13)
   Msg = Msg & "note of the following information." & Chr$(13) & Chr$(13)
   Msg = Msg & "Error number: " & Err.Number & Chr$(13)
   Msg = Msg & "Description: " & Err.Description & Chr$(13)
   Msg = Msg & "Location: " & Screen.ActiveForm.Name & Chr$(13)
   Msg = Msg & "Procedure: " & ProcName
   MsgBox (Msg)
   Resume ErrorAbort
Else
   Msg = "An untrapped error has occured.  Please make a " & Chr$(13)
   Msg = Msg & "note of the following information." & Chr$(13) & Chr$(13)
   Msg = Msg & "Error number: " & Err.Number & Chr$(13)
   Msg = Msg & "Description: " & Err.Description & Chr$(13)
   Msg = Msg & "Location: " & Screen.ActiveForm.Name & Chr$(13)
   Msg = Msg & "Procedure: " & ProcName
   MsgBox (Msg)
   Resume ErrorAbort
End If

ErrorAbort:
   Abort = "Yes"

End Function



Public Function PRESprop(Abort, Density, DENSITYGas, depth, FractureToughness, R_n) As Single

ProcName = "PRESprop"
On Error GoTo FileError

   PRESprop = (Density * depth + (FractureToughness / ((Pi * R_n) ^ 0.5))) / DENSITYGas


Exit Function

FileError:
' Divide by zero
If Err.Number = 11 Then
   Msg = "The algorithm is dividing by zero.  This is most " & Chr$(13)
   Msg = Msg & "likely due to an incorrectly entered system, input, " & Chr$(13)
   Msg = Msg & "or geologic parameter.  Go back and check your " & Chr$(13)
   Msg = Msg & "entered data." & Chr$(13) & Chr$(13)
   Msg = Msg & "If the problem persists, please make a " & Chr$(13)
   Msg = Msg & "note of the following information." & Chr$(13) & Chr$(13)
   Msg = Msg & "Error number: " & Err.Number & Chr$(13)
   Msg = Msg & "Description: " & Err.Description & Chr$(13)
   Msg = Msg & "Location: " & Screen.ActiveForm.Name & Chr$(13)
   Msg = Msg & "Procedure: " & ProcName
```

```
    MsgBox (Msg)
    Resume ErrorAbort
Else
    Msg = "An untrapped error has occured.  Please make a " & Chr$(13)
    Msg = Msg & "note of the following information." & Chr$(13) & Chr$(13)
    Msg = Msg & "Error number: " & Err.Number & Chr$(13)
    Msg = Msg & "Description: " & Err.Description & Chr$(13)
    Msg = Msg & "Location: " & Screen.ActiveForm.Name & Chr$(13)
    Msg = Msg & "Procedure: " & ProcName
    MsgBox (Msg)
    Resume ErrorAbort
End If

ErrorAbort:
    Abort = "Yes"
End Function
```

```
Private Function ApertureCalculation(Abort, ApertureFlag, D, depth, K, Modulus, Poisson, _
                        PRESdriv, RADIUS, RADIUSwell, R_next, XX) As Single

    Dim aperture_well As Single

ProcName = "ApertureCalculation"
On Error GoTo FileError

    ' If ApertureFlag = 1, then the well aperture is calculated for
    ' the final RADIUS.
    If ApertureFlag = 1 Then
        XX = RADIUSwell
        R_next = RADIUSwell
    End If

        If mnuSolverLogDistribution.Checked = True Then
            ApertureCalculation = (XX ^ 4 / (128 * D)) * ((2 * PRESdriv) + (3 * K) - _
            (2 * K * Log(XX / RADIUSwell))) + (XX ^ 2 / (256 * D)) * _
            ((-10 * K * (RADIUS ^ 2)) + ((RADIUSwell ^ 2) * ((8 * K) + (16 * PRESdriv) - _
            (16 * K * Log(XX / RADIUSwell))))) + _
            ((K * (RADIUS ^ 4)) / (64 * D)) - _
            ((K * (RADIUSwell ^ 2) * (RADIUS ^ 2)) / (32 * D))
        ElseIf mnuSolverConstantPressure.Checked = True Then
            ApertureCalculation = (3 * PRESdriv * (1 - (Poisson ^ 2)) * ((XX ^ 4) - _
            (2 * (RADIUS ^ 2) * (XX ^ 2)) + (RADIUS ^ 4))) / _
            (16 * Modulus * (depth ^ 3))
        ElseIf mnuSolverAnticlinalPlan.Checked = True Then
            ApertureCalculation = ((PRESdriv * (1 - (Poisson ^ 2))) * ((XX ^ 4) - _
            (2 * (RADIUS ^ 2) * (XX ^ 2)) + (RADIUS ^ 4))) / _
            (2 * Modulus * (depth ^ 3))
        Else        ' Lineraly tapering
            aperture_well = (3 * PRESdriv * (1 - (Poisson ^ 2)) * RADIUS ^ 4) / _
                    (16 * Modulus * (depth ^ 3))
            ApertureCalculation = aperture_well - (aperture_well * R_next / RADIUS)
        End If
```

```
Exit Function

FileError:
' Divide by zero
If Err.Number = 11 Then
   Msg = "The algorithm is dividing by zero. This is most " & Chr$(13)
   Msg = Msg & "likely due to an incorrectly entered system, input, " & Chr$(13)
   Msg = Msg & "or geologic parameter. Go back and check your " & Chr$(13)
   Msg = Msg & "entered data." & Chr$(13) & Chr$(13)
   Msg = Msg & "If the problem persists, please make a " & Chr$(13)
   Msg = Msg & "note of the following information." & Chr$(13) & Chr$(13)
   Msg = Msg & "Error number: " & Err.Number & Chr$(13)
   Msg = Msg & "Description: " & Err.Description & Chr$(13)
   Msg = Msg & "Location: " & Screen.ActiveForm.Name & Chr$(13)
   Msg = Msg & "Procedure: " & ProcName
   MsgBox (Msg)
   Resume ErrorAbort
Else
   Msg = "An untrapped error has occured. Please make a " & Chr$(13)
   Msg = Msg & "note of the following information." & Chr$(13) & Chr$(13)
   Msg = Msg & "Error number: " & Err.Number & Chr$(13)
   Msg = Msg & "Description: " & Err.Description & Chr$(13)
   Msg = Msg & "Location: " & Screen.ActiveForm.Name & Chr$(13)
   Msg = Msg & "Procedure: " & ProcName
   MsgBox (Msg)
   Resume ErrorAbort
End If

ErrorAbort:
   Abort = "Yes"
End Function
```

I.3 Selected Code from the Site Screening Component

```
Option Explicit

' Evidence variables.
Dim E1 As Single
Dim E2 As Single
Dim E3 As Single
Dim E4 As Single
Dim E5 As Single

Dim EvidenceCounter As Integer

' Flag to select between 3 different technologys.
Dim TechnologyFlag As Integer
```

```
Private Sub cmdPermeabilityEnhancement_MouseUp(Button As Integer, Shift As Integer, _
                        X As Single, Y As Single)

If Button = vbLeftButton Then

  ' Put an hourglass up to indicate the program is calculating.
  Screen.MousePointer = vbHourglass
  Screen.MousePointer = 11

  ' Set Flag = 1 for Permeability Enhancement Probability Recommedations.
  TechnologyFlag = 1
  Call AssignEvidence(TechnologyFlag, E1, E2, E3, E4, E5)

  Screen.MousePointer = 0 ' sets the pointer back to the default.

End If

If Button = vbRightButton Then
  HELP_ITEM = "Permeability Enhancement"
  Call Help(HELP_ITEM)
End If

End Sub



Public Sub AssignEvidence(TechnologyFlag, E1, E2, E3, E4, E5)

Dim EvidenceCounter As Integer

ProcName = "AssignEvidence"
On Error GoTo ErrorHandler


EvidenceCounter = 1

   Call GetGeologyTypeEvidence(TechnologyFlag, EvidenceCounter, E1, E2, E3, E4, E5)

   If Not (frmSiteScreening.lblDepth.Caption = "Unknown") Then
     Call GetDepthEvidence(TechnologyFlag, EvidenceCounter, E1, E2, E3, E4, E5)
   End If

   If Not (frmSiteScreening.lblPlasticity.Caption = "Unknown" Or _
        frmSiteScreening.lblPlasticity.Caption = "  not applicable") Then
     Call GetPlasticityEvidence(TechnologyFlag, EvidenceCounter, E1, E2, E3, E4, E5)
   End If

   If Not (frmSiteScreening.lblConsistency.Caption = "Unknown" Or _
        frmSiteScreening.lblConsistency.Caption = "  not applicable") Then
     Call GetConsistencyEvidence(TechnologyFlag, EvidenceCounter, E1, E2, E3, E4, E5)
   End If

   If Not (frmSiteScreening.lblRelativeDensity.Caption = "Unknown" Or _
```

```
        frmSiteScreening.lblRelativeDensity.Caption = "  not applicable") Then
     Call GetRelativeDensityEvidence(TechnologyFlag, EvidenceCounter, E1, E2, E3, E4, E5)
  End If

  If Not (frmSiteScreening.lblWeathering.Caption = "Unknown" Or _
        frmSiteScreening.lblWeathering.Caption = "  not applicable") Then
     Call GetWeatheringEvidence(TechnologyFlag, EvidenceCounter, E1, E2, E3, E4, E5)
  End If

  If Not (frmSiteScreening.lblFractureFrequency.Caption = "Unknown" Or _
        frmSiteScreening.lblFractureFrequency.Caption = "  not applicable") Then
     Call GetFractureFrequencyEvidence(TechnologyFlag, EvidenceCounter, E1, E2, E3, E4, E5)
  End If

  If Not (frmSiteScreening.lblWaterTable.Caption = "Unknown") Then
     Call GetWaterTableEvidence(TechnologyFlag, EvidenceCounter, E1, E2, E3, E4, E5)
  End If


' Go to Subjective Probability Calculator.
Call SubjectiveProbability(EvidenceCounter, E1, E2, E3, E4, E5)

' Error code.
Exit Sub
ErrorHandler:
   Msg = "An untrapped error has occured.  Please make a " & Chr$(13)
   Msg = Msg & "note of the following information." & Chr$(13) & Chr$(13)
   Msg = Msg & "Error number: " & Err.Number & Chr$(13)
   Msg = Msg & "Description: " & Err.Description & Chr$(13)
   Msg = Msg & "Location: " & Screen.ActiveForm.Name & Chr$(13)
   Msg = Msg & "Procedure: " & ProcName
   MsgBox (Msg)

End Sub



Private Sub GetGeologyTypeEvidence(TechnologyFlag, EvidenceCounter, E1, E2, E3, E4, E5)

Dim Formation As String
Dim Evidence As Single
Formation = frmSiteScreening.lblGeologyType.Caption

ProcName = "GetGeologyTypeEvidence"
On Error GoTo ErrorHandler

Select Case Formation
   Case "Clay"
      Select Case TechnologyFlag
         Case 1     ' Permeability Enhancement
            Evidence = Val(frmKnowledgeBase.txtK_Formation_Clay.Text)
         Case 2     ' Dry Media Injection
            Evidence = Val(frmKnowledgeBase.txtDryMI_Formation_Clay.Text)
         Case 3     ' Liquid Media Injection
```

```
        Evidence = Val(frmKnowledgeBase.txtLiquidMI_Formation_Clay.Text)
    End Select
Case "Clayey Sand"
    Select Case TechnologyFlag
        Case 1      ' Permeability Enhancement
            Evidence = Val(frmKnowledgeBase.txtK_Formation_ClayeySand.Text)
        Case 2      ' Dry Media Injection
            Evidence = Val(frmKnowledgeBase.txtDryMI_Formation_ClayeySand.Text)
        Case 3      ' Liquid Media Injection
            Evidence = Val(frmKnowledgeBase.txtLiquidMI_Formation_ClayeySand.Text)
    End Select
Case "Clayey Silt"
    Select Case TechnologyFlag
        Case 1      ' Permeability Enhancement
            Evidence = Val(frmKnowledgeBase.txtK_Formation_ClayeySilt.Text)
        Case 2      ' Dry Media Injection
            Evidence = Val(frmKnowledgeBase.txtDryMI_Formation_ClayeySilt.Text)
        Case 3      ' Liquid Media Injection
            Evidence = Val(frmKnowledgeBase.txtLiquidMI_Formation_ClayeySilt.Text)
    End Select
Case "Silty Clay"
    Select Case TechnologyFlag
        Case 1      ' Permeability Enhancement
            Evidence = Val(frmKnowledgeBase.txtK_Formation_SiltyClay.Text)
        Case 2      ' Dry Media Injection
            Evidence = Val(frmKnowledgeBase.txtDryMI_Formation_SiltyClay.Text)
        Case 3      ' Liquid Media Injection
            Evidence = Val(frmKnowledgeBase.txtLiquidMI_Formation_SiltyClay.Text)
    End Select
Case "Silt"
    Select Case TechnologyFlag
        Case 1      ' Permeability Enhancement
            Evidence = Val(frmKnowledgeBase.txtK_Formation_Silt.Text)
        Case 2      ' Dry Media Injection
            Evidence = Val(frmKnowledgeBase.txtDryMI_Formation_Silt.Text)
        Case 3      ' Liquid Media Injection
            Evidence = Val(frmKnowledgeBase.txtLiquidMI_Formation_Silt.Text)
    End Select
Case "Silty Sand"
    Select Case TechnologyFlag
        Case 1      ' Permeability Enhancement
            Evidence = Val(frmKnowledgeBase.txtK_Formation_SiltySand.Text)
        Case 2      ' Dry Media Injection
            Evidence = Val(frmKnowledgeBase.txtDryMI_Formation_SiltySand.Text)
        Case 3      ' Liquid Media Injection
            Evidence = Val(frmKnowledgeBase.txtLiquidMI_Formation_SiltySand.Text)
    End Select
Case "Sand"
    Select Case TechnologyFlag
        Case 1      ' Permeability Enhancement
            Evidence = Val(frmKnowledgeBase.txtK_Formation_Sand.Text)
        Case 2      ' Dry Media Injection
            Evidence = Val(frmKnowledgeBase.txtDryMI_Formation_Sand.Text)
        Case 3      ' Liquid Media Injection
```

```
      Evidence = Val(frmKnowledgeBase.txtLiquidMI_Formation_Sand.Text)
  End Select
Case "Sand and Gravel"
  Select Case TechnologyFlag
    Case 1     ' Permeability Enhancement
      Evidence = Val(frmKnowledgeBase.txtK_Formation_SandGravel.Text)
    Case 2     ' Dry Media Injection
      Evidence = Val(frmKnowledgeBase.txtDryMI_Formation_SandGravel.Text)
    Case 3     ' Liquid Media Injection
      Evidence = Val(frmKnowledgeBase.txtLiquidMI_Formation_SandGravel.Text)
  End Select
Case "Gravel"
  Select Case TechnologyFlag
    Case 1     ' Permeability Enhancement
      Evidence = Val(frmKnowledgeBase.txtK_Formation_Gravel.Text)
    Case 2     ' Dry Media Injection
      Evidence = Val(frmKnowledgeBase.txtDryMI_Formation_Gravel.Text)
    Case 3     ' Liquid Media Injection
      Evidence = Val(frmKnowledgeBase.txtLiquidMI_Formation_Gravel.Text)
  End Select
Case "Shale/Siltstone"
  Select Case TechnologyFlag
    Case 1     ' Permeability Enhancement
      Evidence = Val(frmKnowledgeBase.txtK_Formation_Shale.Text)
    Case 2     ' Dry Media Injection
      Evidence = Val(frmKnowledgeBase.txtDryMI_Formation_Shale.Text)
    Case 3     ' Liquid Media Injection
      Evidence = Val(frmKnowledgeBase.txtLiquidMI_Formation_Shale.Text)
  End Select
Case "Sandstone"
  Select Case TechnologyFlag
    Case 1     ' Permeability Enhancement
      Evidence = Val(frmKnowledgeBase.txtK_Formation_Sandstone.Text)
    Case 2     ' Dry Media Injection
      Evidence = Val(frmKnowledgeBase.txtDryMI_Formation_Sandstone.Text)
    Case 3     ' Liquid Media Injection
      Evidence = Val(frmKnowledgeBase.txtLiquidMI_Formation_Sandstone.Text)
  End Select
Case "Limestone/Dolomite"
  Select Case TechnologyFlag
    Case 1     ' Permeability Enhancement
      Evidence = Val(frmKnowledgeBase.txtK_Formation_Limestone.Text)
    Case 2     ' Dry Media Injection
      Evidence = Val(frmKnowledgeBase.txtDryMI_Formation_Limestone.Text)
    Case 3     ' Liquid Media Injection
      Evidence = Val(frmKnowledgeBase.txtLiquidMI_Formation_Limestone.Text)
  End Select
Case "Granite/Gneiss/Schist"
  Select Case TechnologyFlag
    Case 1     ' Permeability Enhancement
      Evidence = Val(frmKnowledgeBase.txtK_Formation_Igneous.Text)
    Case 2     ' Dry Media Injection
      Evidence = Val(frmKnowledgeBase.txtDryMI_Formation_Igneous.Text)
    Case 3     ' Liquid Media Injection
```

```
            Evidence = Val(frmKnowledgeBase.txtLiquidMI_Formation_Igneous.Text)
        End Select
    Case "Basalt"
        Select Case TechnologyFlag
            Case 1      ' Permeability Enhancement
                Evidence = Val(frmKnowledgeBase.txtK_Formation_Basalt.Text)
            Case 2      ' Dry Media Injection
                Evidence = Val(frmKnowledgeBase.txtDryMI_Formation_Basalt.Text)
            Case 3      ' Liquid Media Injection
                Evidence = Val(frmKnowledgeBase.txtLiquidMI_Formation_Basalt.Text)
        End Select
    End Select


' Sets the Evidence to variable E(x) based on how many peices of evidence have been
' entered/selected.  For example, if the EvidenceCounter = 2 for this block of code,
' then E2 is assigned the probability which is used in the Subjective Probability
' Equations later.
Select Case EvidenceCounter
    Case 1
        E1 = Evidence
    Case 2
        E2 = Evidence
    Case 3
        E3 = Evidence
    Case 4
        E4 = Evidence
    Case 5
        E5 = Evidence
End Select

EvidenceCounter = EvidenceCounter + 1

' Error code.
Exit Sub
ErrorHandler:
    Msg = "An untrapped error has occured.  Please make a " & Chr$(13)
    Msg = Msg & "note of the following information." & Chr$(13) & Chr$(13)
    Msg = Msg & "Error number: " & Err.Number & Chr$(13)
    Msg = Msg & "Description: " & Err.Description & Chr$(13)
    Msg = Msg & "Location: " & Screen.ActiveForm.Name & Chr$(13)
    Msg = Msg & "Procedure: " & ProcName
    MsgBox (Msg)

End Sub



Public Sub SubjectiveProbability(EvidenceCounter, E1, E2, E3, E4, E5)

Dim Ceaser As Single        ' Temporary variable to hold multiplied values of E.
Dim Belief As Single

ProcName = "SubjectiveProbability"
```

```
On Error GoTo ErrorHandler

' Subtract one from the EvidenceCounter since the program will always have one
' EvidenceCounter+1 when it enters here.
EvidenceCounter = EvidenceCounter - 1

Select Case EvidenceCounter
   Case 1     ' 1 peice of evidence is known.
      Ceaser = E1 * 0.5
      Belief = (Ceaser / (Ceaser + ((1 - E1) * 0.5)))
   Case 2     ' 2 peices of evidence are known.
      Ceaser = E1 * E2 * 0.5
      Belief = (Ceaser / (Ceaser + ((1 - E1) * (1 - E2) * 0.5)))
   Case 3     ' 3 peices of evidence are known.
      Ceaser = E1 * E2 * E3 * 0.5
      Belief = (Ceaser / (Ceaser + ((1 - E1) * (1 - E2) * (1 - E3) * 0.5)))
   Case 4     ' 4 peices of evidence are known.
      Ceaser = E1 * E2 * E3 * E4 * 0.5
      Belief = (Ceaser / (Ceaser + ((1 - E1) * (1 - E2) * (1 - E3) * (1 - E4) * 0.5)))
   Case 5     ' 5 peices of evidence are known.
      Ceaser = E1 * E2 * E3 * E4 * E5 * 0.5
      Belief = (Ceaser / (Ceaser + ((1 - E1) * (1 - E2) * (1 - E3) * (1 - E4) * (1 - E5) * 0.5)))
End Select

 ' Display the probability to 1 decimal place.
 Belief = CInt(Belief * 100)
 frmSiteScreening.txtTechRating = Belief

' Error code.
Exit Sub
ErrorHandler:
   Msg = "An untrapped error has occured.  Please make a " & Chr$(13)
   Msg = Msg & "note of the following information." & Chr$(13) & Chr$(13)
   Msg = Msg & "Error number: " & Err.Number & Chr$(13)
   Msg = Msg & "Description: " & Err.Description & Chr$(13)
   Msg = Msg & "Location: " & Screen.ActiveForm.Name & Chr$(13)
   Msg = Msg & "Procedure: " & ProcName
   MsgBox (Msg)

End Sub
```

I.4 Selected Code for the Data Input Screen

```
Option Explicit

' Delcare variables for various message boxes that appear in this form.
Dim FlagDepth As Integer
Dim FlagSoilRock As Integer
Dim FlagWaterTable As Integer
Dim FlagWeathering As Integer
```

```
Sub GeologicalPropertiesOnOff()

'This subroutine will turn on or turn off the various geological
'properties found on the Data Input form depending on the type
'of soil or rock that is selected by the user.

  'Enable/Disable the Degree of Weathering and Fracture
  'Frequency boxes depending on if a soil or rock type
  'is selected.
  If cboType.Text = "Clay" Or _
  cboType.Text = "Clayey Sand" Or _
  cboType.Text = "Clayey Silt" Or _
  cboType.Text = "Silty Clay" Or _
  cboType.Text = "Silt" Or _
  cboType.Text = "Silty Sand" Or _
  cboType.Text = "Sand" Or _
  cboType.Text = "Sand and Gravel" Or _
  cboType.Text = "Gravel" Then
    cboWeathering.Text = " "
    cboWeathering.Enabled = False
    lblWeathering.Enabled = False
    cboFracFrequency.Text = " "
    cboFracFrequency.Enabled = False
    lblFracFrequency.Enabled = False


  ElseIf cboType.Text = "Shale/Siltstone" Or _
  cboType.Text = "Sandstone" Or _
  cboType.Text = "Shale" Or _
  cboType.Text = "Limestone/Dolomite" Or _
  cboType.Text = "Granite/Gneiss/Schist" Or _
  cboType.Text = "Basalt" Then
    cboWeathering.Text = " "
    cboWeathering.Enabled = True
    lblWeathering.Enabled = True
    cboWeathering.ListIndex = 0    ' makes weathering unknown upon
                                   ' selection or change in rock formation
    cboFracFrequency.Text = " "
    cboFracFrequency.Enabled = True
    lblFracFrequency.Enabled = True
    cboFracFrequency.ListIndex = 0     ' makes fracture frequency unknown upon
                                       ' selection or change in rock formation
  End If

  ' Disable Plasticity button if a silt/sand/rock are selected.
  If cboType.Text = "Silt" Or _
  cboType.Text = "Silty Sand" Or _
  cboType.Text = "Sand" Or _
  cboType.Text = "Sand and Gravel" Or _
  cboType.Text = "Gravel" Or _
  cboType.Text = "Shale/Siltstone" Or _
```

```
  cboType.Text = "Sandstone" Or _
  cboType.Text = "Shale" Or _
  cboType.Text = "Limestone/Dolomite" Or _
  cboType.Text = "Granite/Gneiss/Schist" Or _
  cboType.Text = "Basalt" Then
     cmdPlasticityMoisture.Enabled = False
  Else   ' Plasticity isinstead true (i.e., a Clayey soil)
     cmdPlasticityMoisture.Enabled = True
  End If

  ' Disable OCR if a rock type is selected.
  If cboType.Text = "Shale/Siltstone" Or _
  cboType.Text = "Sandstone" Or _
  cboType.Text = "Shale" Or _
  cboType.Text = "Limestone/Dolomite" Or _
  cboType.Text = "Granite/Gneiss/Schist" Or _
  cboType.Text = "Basalt" Then
     cmdConsDense.Enabled = False
  Else   ' OCR is instead true (i.e., a soil type)
     cmdConsDense.Enabled = True
  End If
End Sub

Sub SystemPropertiesFalse()

   ' This procedure is used to make all the objects in
   ' system design disabled, i.e., false.

   lblSystemProperties.Enabled = False
   lblFlowRate.Enabled = False
   txtFlowRate.Enabled = False
   lblMaintenancePressure.Enabled = False
   txtMaintenancePressure.Enabled = False
   lblWellRadius.Enabled = False
   txtWellRadius.Enabled = False
   cmdPneumaticConductivity.Enabled = False
   lblOverride.Enabled = False
   chkOverrideFlow.Enabled = False
   chkOverridePressure.Enabled = False
   chkOverrideWellRadius.Enabled = False
   lblDefaultFlow.Enabled = False
   lblDefaultPressure.Enabled = False
   lblDefaultWellRadius.Enabled = False
End Sub

Sub SystemPropertiesTrue()

   ' This procedure is used to make all the objects in
   ' system design enabled, i.e., true

   lblSystemProperties.Enabled = True
   lblFlowRate.Enabled = True
   txtFlowRate.Enabled = True
   lblMaintenancePressure.Enabled = True
```

```
    txtMaintenancePressure.Enabled = True
    lblWellRadius.Enabled = True
    txtWellRadius.Enabled = True
    cmdPneumaticConductivity.Enabled = True
    lblOverride.Enabled = True
    chkOverrideFlow.Enabled = True
    chkOverridePressure.Enabled = True
    chkOverrideWellRadius.Enabled = True
    lblDefaultFlow.Enabled = True
    lblDefaultPressure.Enabled = True
    lblDefaultWellRadius.Enabled = True
End Sub

Sub GeologicalPropertiesTrue()

    ' This procedure is used to make all the objects in
    ' geological properties enabled, i.e., true.

    lblGeotechnicalProperties.Enabled = True
    lblType.Enabled = True
    cboType.Enabled = True
    lblFractureDepth.Enabled = True
    txtFractureDepth.Enabled = True
    lblWaterDepth.Enabled = True
    txtWaterDepth.Enabled = True
    cmdPlasticityMoisture.Enabled = True
    cmdConsDense.Enabled = True
    lblWeathering.Enabled = True
    cboWeathering.Enabled = True
    lblFracFrequency.Enabled = True
    cboFracFrequency.Enabled = True


    Call GeologicalPropertiesOnOff
End Sub



Sub GeologicalPropertiesFalse()

    ' This procedure is used to make all the objects in
    ' geological properties disable, i.e., false.

    lblGeotechnicalProperties.Enabled = False
    lblType.Enabled = False
    cboType.Enabled = False
    lblFractureDepth.Enabled = False
    txtFractureDepth.Enabled = False
    lblWaterDepth.Enabled = False
    txtWaterDepth.Enabled = False
    cmdPlasticityMoisture.Enabled = False
    cmdConsDense.Enabled = False
    lblWeathering.Enabled = False
    cboWeathering.Enabled = False
```

```
    lblFracFrequency.Enabled = False
    cboFracFrequency.Enabled = False

End Sub
```

Sub Form_Load()

```
    ' Puts a date in the date field if this is a new file.

    txtDate = Date

    ' Puts blanks in system properties labels until defaults or overrides selected.
    lblDefaultFlow.Caption = " "
    lblDefaultPressure.Caption = " "
    lblDefaultWellRadius.Caption = " "

    ' Initialize the Soil/Rock Type combo box with the soils and rocks.
    cboType.AddItem "Clay"
    cboType.AddItem "Clayey Sand"
    cboType.AddItem "Clayey Silt"
    cboType.AddItem "Silty Clay"
    cboType.AddItem "Silt"
    cboType.AddItem "Silty Sand"
    cboType.AddItem "Sand"
    cboType.AddItem "Sand and Gravel"
    cboType.AddItem "Gravel"
    cboType.AddItem " "
    cboType.AddItem "Shale/Siltstone"
    cboType.AddItem "Sandstone"
    cboType.AddItem "Limestone/Dolomite"
    cboType.AddItem "Granite/Gneiss/Schist"
    cboType.AddItem "Basalt"

    ' Initialize the Weathering combo box.
    cboWeathering.AddItem "Unknown"
    cboWeathering.AddItem "Slightly weathered"
    cboWeathering.AddItem "Moderately weathered"
    cboWeathering.AddItem "Highly weathered"

    ' Initialize the Fracture Frequency combo box.
    cboFracFrequency.AddItem "Unknown"
    cboFracFrequency.AddItem "Closely jointed"
    cboFracFrequency.AddItem "Medium jointed"
    cboFracFrequency.AddItem "Widely jointed"

    ' Disable all the geologic/system/media property
    ' objects, which will be enabled when the
    ' proper checkbox(s) is selected.

    Call GeologicalPropertiesFalse

    Call SystemPropertiesFalse
```

```
  End Sub

Sub cboType_Click()

  ' Call the subroutine that turns on/off the approriate
  ' data input parameters which are/are not needed depending
  ' on the soil or rock type selected.
  Call GeologicalPropertiesOnOff

  ' When a first time or new formation type is selected, the Con/Den
  ' should be unknown.
  frmConDen.optUnknown.Value = True

  Call EstablishFormationDefaults
  Call CalculatePressure
  Call EstablishWellRadiusDefaults
End Sub
```

APPENDIX J

TABLES USED IN VALIDATION AND CALIBRATION OF PF-MODEL

Both the Site Screening and System Design components of PF-Model underwent extensive validation and calibration procedures. This appendix contains the remaining tables of this evaluation, as discussed previously in Chapter 4, "Validation and Calibration."

Table J.1 System Validation of Dry Media Injection Variant.

								Evaluator Results †					System	
Formation Type	Depth (ft)	Depth to W.T. (ft)	Consistency	Plasticity	Relative Density	Fracture Frequency	Weathering	A	B	C	D	E	Result	Rating
Silty Clay	18	10	medium	???	n/a	n/a	n/a	M	Y	M	M	Y	M	55
Clayey Silt	10	18	medium	brittle	n/a	n/a	n/a	Y	Y	Y	Y_M	Y	Y	69
Clay	8	4	soft	plastic	n/a	n/a	n/a	M	N	M	M	M	M	53
Silty Clay	12	10	medium	liquid	n/a	n/a	n/a	M	M_Y	M	M	Y	M	50
Clay	10	???	???	???	n/a	n/a	n/a	M	M	M	M	M	M	55
Clay	4	10	very stiff	brittle	n/a	n/a	n/a	M	N	M	M	Y	M	57
Silty Sand	14	8	n/a	n/a	med. dense	n/a	n/a	Y	Y	Y	Y_M	Y	Y	75
Sand	24	10	n/a	n/a	dense	n/a	n/a	Y	Y	Y	M	Y	Y	71
Sand and Gravel	14	20	n/a	n/a	very dense	n/a	n/a	Y	Y	Y	Y_M	Y	Y	69
Siltstone	20	12	n/a	n/a	n/a	closely	slightly	Y	Y_M	Y	Y	N	Y	60
Shale	10	???	n/a	n/a	n/a	???	???	M	M	M	N	M	Y	65
Shale/Siltstone	12	18	n/a	n/a	n/a	widely	highly	M	M	N	N	N	N	41
Sandstone	10	16	n/a	n/a	n/a	widely	slightly	N	M	N	N	N	N	27
Basalt	15	???	n/a	n/a	n/a	medium	slightly	N	N_M	N	N	N	N	43
Sandstone	12	8	n/a	n/a	n/a	???	???	M	M	M	M	M	M	55

Notes: † - Evaluators are:
A) Dr. J. Schuring, Patent Holder of PF, NJIT
B) T. Boland, PF Design Engineer, NJIT
C) B. Sielski, PF Research Assistant, NJIT
D) J. Liskowitz, President, ARS Technologies, Inc.
E) T. King, Sr. Engineer, McLaren/Hart Environmental Engineering Corp.

Y = recommended, rating = 60 - 100
M = marginally recommended, rating = 45 - 60
N = not recommended, rating = 0 - 45
n/a = not applicable
??? = unknown (not provided to evaluator)

Table J.2 System Validation of Liquid Media Injection Variant.

Formation Type	Depth (ft)	Depth to W.T. (ft)	Consistency	Plasticity	Relative Density	Fracture Frequency	Weathering	Evaluator Results † A	B	C	D	E	System Result	System Rating
Silty Clay	18	10	medium	???	n/a	n/a	n/a	Y	Y	Y	Y_M	M	Y	70
Clayey Silt	10	18	medium	brittle	n/a	n/a	n/a	Y	Y	Y	Y_M	M	Y	78
Clay	8	4	soft	plastic	n/a	n/a	n/a	Y	Y	Y	Y_M	M	Y	64
Silty Clay	12	10	medium	liquid	n/a	n/a	n/a	Y	Y	Y	Y_M	Y	Y	66
Clay	10	???	???	???	n/a	n/a	n/a	Y	Y	Y	Y_M	N	Y	70
Clay	4	10	very stiff	brittle	n/a	n/a	n/a	M	Y	M	Y_M	M	Y	62
Silty Sand	14	8	n/a	n/a	med. dense	n/a	n/a	Y	Y	Y	Y_M	Y	Y	79
Sand	24	10	n/a	n/a	dense	n/a	n/a	Y	Y	Y	M	Y	Y	75
Sand and Gravel	14	20	n/a	n/a	very dense	n/a	n/a	Y	Y	Y	Y_M	Y	Y	74
Siltstone	20	12	n/a	n/a	n/a	closely	slightly	Y	Y	Y	Y	Y	Y	74
Shale	10	???	n/a	n/a	n/a	???	???	M	Y	Y	M	M	Y	74
Shale/Siltstone	12	18	n/a	n/a	n/a	widely	highly	M	Y	N	M	Y	M	56
Sandstone	10	16	n/a	n/a	n/a	widely	slightly	N	M	N	M	M	N	36
Basalt	15	???	n/a	n/a	n/a	medium	slightly	M	M	M	M	M	M	55
Sandstone	12	8	n/a	n/a	n/a	???	???	M	M	M	M	M	Y	65

Notes: † - Evaluators are: A) Dr. J. Schuring, Patent Holder of PF, NJIT
B) T. Boland, PF Design Engineer, NJIT
C) B. Sielski, PF Research Assistant, NJIT
D) J. Liskowitz, President, ARS Technologies, Inc.
E) T. King, Sr. Engineer, McLaren/Hart Environmental Engineering Corp.

Y = recommended, rating = 60 - 100
M = marginally recommended, rating = 45 - 60
N = not recommended, rating = 0 - 40
n/a = not applicable
??? = unknown (not provided to evaluator)

Table J.3 Validation of Graphical Leakoff Method ($K_h = K_v$) Using Bisection Model Engine.

Site Name	K_h	K_v	z	γ_{soil}	ν	Q	P_{in}	b	R	E	R/z	R/z	b	R	b	R	b	R
	(cm/sec)	(cm/sec)	fracture depth (ft)	(pcf)		Injected flow (scfm)	Maint. pres. (psi)	(measured) (ft)		Young's modulus (psi)	(actual)	(used in MCad)	(Mcad) (w/ single R/z useage) (ft)		(PF-Model) (w/ full R/z useage) (ft)		VB/Mcad	VB/Mcad
Frelinghuysen - 1	2.65E-04	2.65E-04	3.5	105	0.40	300	10	0.0792	4.2	38	1.20	1.14	0.0800	4.231	0.0790	4.213	0.99	1.00
	2.72E-04	2.72E-04	3.5	105	0.40	300	10	0.0533	4.2	56	1.20	1.14	0.0543	4.231	0.0548	4.237	1.01	1.00
	4.66E-04	4.66E-04	3.5	105	0.40	300	7	0.0208	4.2	86	1.20	1.14	0.0211	4.231	0.0211	4.225	1.00	1.00
	3.70E-04	3.70E-04	3.5	105	0.40	300	8	0.0317	4.2	69	1.20	1.14	0.0322	4.231	0.0322	4.225	1.00	1.00
Frelinghuysen - 2	2.72E-04	2.72E-04	6	105	0.40	715	13	0.0342	8.5	272	1.42	1.14	0.0345	8.531	0.0344	8.518	1.00	1.00
	4.41E-04	4.41E-04	6	105	0.40	1227	14	0.0367	8.5	283	1.42	1.14	0.0370	8.531	0.0369	8.518	1.00	1.00
	1.09E-03	1.09E-03	6	105	0.40	1157	15	0.0075	5.7	347	0.95	1.00	0.0075	5.713	0.0074	5.682	0.98	0.99
	3.36E-04	3.36E-04	8.3	105	0.40	1500	18	0.0233	11.7	688	1.41	1.14	0.0239	11.786	0.0235	11.725	0.98	0.99
	4.37E-04	4.37E-04	6	105	0.40	1500	17	0.0375	8.6	379	1.43	1.14	0.0378	8.628	0.0373	8.591	0.99	1.00
	2.93E-04	2.93E-04	8.6	105	0.40	1339	17	0.0390	11.3	291	1.31	1.14	0.0377	11.203	0.0388	11.288	1.03	1.01
Frelinghuysen - 3	8.47E-04	8.47E-04	6	105	0.40	857	15	0.0167	4.2	51	0.70	0.71	0.0169	4.231	0.0172	4.249	1.02	1.00
	2.12E-04	2.12E-04	6	105	0.40	964	11.4	0.0275	12.6	1197	2.10	2.00	0.0272	12.563	0.0274	12.587	1.01	1.00
	3.04E-04	3.04E-04	6	105	0.40	1000	11	0.0250	9.6	449	1.60	2.00	0.0249	9.599	0.0251	9.612	1.01	1.00
	1.98E-04	1.98E-04	9	105	0.40	943	16.5	0.0183	14.1	1149	1.57	1.14	0.0184	14.118	0.0185	14.142	1.00	1.00
	1.72E-04	1.72E-04	9	105	0.40	1114	14.7	0.0150	16.1	1890	1.79	2.00	0.0148	16.061	0.0153	16.183	1.03	1.01
	1.50E-04	1.50E-04	6	105	0.40	722	12.5	0.0275	11.7	1049	1.95	2.00	0.0282	11.786	0.0283	11.798	1.00	1.00
	2.54E-04	2.54E-04	8.3	105	0.40	984	17	0.0158	11.4	843	1.37	1.14	0.0168	11.591	0.0165	11.531	0.98	0.99
Tinker	8.23E-05	8.23E-05	8	105	0.40	1716	31	0.0417	19	5585	2.38	2.00	0.0415	18.976	0.0421	19.049	1.01	1.00
	1.44E-05	1.44E-05	19	105	0.40	1759	130	0.0125	30.8	39881	1.62	2.00	0.0124	30.733	0.0123	30.685	0.99	1.00
	6.95E-05	6.95E-05	8	105	0.40	1716	28	0.1000	23	4219	2.88	2.00	0.0993	22.960	0.1013	23.081	1.02	1.01
Marcus Hook	1.77E-04	1.77E-04	6	105	0.40	1200	12	0.0500	16.2	1835	2.70	2.00	0.0484	16.061	0.0498	16.183	1.03	1.01
	1.18E-04	1.18E-04	6	105	0.40	1276	19	0.0500	15.8	3204	2.63	2.00	0.0508	15.867	0.0505	15.842	0.99	1.00
	1.81E-04	1.81E-04	6	105	0.40	1400	14	0.0700	15.1	1270	2.52	2.00	0.0698	15.089	0.0694	15.065	0.99	1.00
Hillsborough-2	7.76E-05	7.76E-05	10	140	0.25	1500	21	0.0320	27.9	7960	2.79	2.00	0.0325	28.013	0.0323	27.964	0.99	1.00
	6.63E-05	6.63E-05	12	140	0.25	1607	25	0.0258	29.4	8238	2.45	2.00	0.0277	29.956	0.0275	29.908	0.99	1.00
	6.84E-05	6.84E-05	14	140	0.25	1886	30	0.0317	27.7	4141	1.98	2.00	0.0314	27.624	0.0316	27.673	1.01	1.00
Hillsborough-3	3.50E-05	3.50E-05	14	140	0.25	1029	28	0.0333	30	4683	2.14	2.00	0.0348	30.345	0.0346	30.296	0.99	1.00
Newark	2.72E-05	2.72E-05	10	140	0.25	771	37.5	0.0133	25	31135	2.50	2.00	0.0131	24.903	0.0134	25.049	1.02	1.01
	1.83E-05	1.83E-05	16	140	0.25	857	53	0.0108	30	25171	1.88	2.00	0.0113	30.345	0.0112	30.296	0.99	1.00
Flemington	1.20E-04	1.20E-04	16	140	0.25	2286	35	0.0260	24.5	2522	1.53	1.14	0.0260	24.515	0.0266	24.660	1.02	1.01
	4.02E-05	4.02E-05	27	140	0.25	1886	75	0.0104	33	10166	1.22	1.14	0.0110	33.454	0.0107	33.308	0.97	1.00

Table J.4 Validation of Graphical Leakoff Method ($K_h = 10K_v$) Using Bisection Model Engine.

Site Name	K_h (cm/sec)	K_v (cm/sec)	z fracture depth (ft)	γ_{soil} (pcf)	υ	Q Injected flow (scfm)	P_m Maint. pres. (psi)	b (measured) (ft)	R (measured) (ft)	E Young's modulus (psi)	R/z (actual)	R/z (used in MCad)	b (Mcad) (w/ single R/z useage) (ft)	R (Mcad) (w/ single R/z useage) (ft)	b (PF-Model) (w/ full R/z useage) (ft)	R (PF-Model) (w/ full R/z useage) (ft)	b VB/Mcad	R VB/Mcad
Frelinghuysen - 1	1.69E-03	1.69E-04	3.5	105	0.40	300	10	0.0792	4.2	38	1.20	1.14	0.0767	4.182	0.0774	4.188	1.01	1.00
	1.72E-03	1.72E-04	3.5	105	0.40	300	10	0.0533	4.2	56	1.20	1.14	0.0543	4.231	0.0554	4.249	1.02	1.00
	2.99E-03	2.99E-04	3.5	105	0.40	300	7	0.0208	4.2	86	1.20	1.14	0.0211	4.231	0.0213	4.237	1.01	1.00
	2.37E-03	2.37E-04	3.5	105	0.40	300	8	0.0317	4.2	69	1.20	1.14	0.0322	4.231	0.0322	4.225	1.00	1.00
Frelinghuysen - 2	1.75E-03	1.75E-04	6	105	0.40	715	13	0.0342	8.5	272	1.42	1.14	0.0345	8.531	0.0344	8.518	1.00	1.00
	2.85E-03	2.85E-04	6	105	0.40	1227	14	0.0367	8.5	283	1.42	1.14	0.0355	8.433	0.0361	8.470	1.02	1.00
	7.02E-03	7.02E-04	6	105	0.40	1157	15	0.0075	5.7	347	0.95	1.00	0.0071	5.616	0.0073	5.658	1.03	1.01
	2.19E-03	2.19E-04	8.3	105	0.40	1500	18	0.0233	11.7	688	1.41	1.14	0.0239	11.786	0.0233	11.701	0.97	0.99
	2.82E-03	2.82E-04	6	105	0.40	1500	17	0.0375	8.6	379	1.43	1.14	0.0363	8.531	0.0369	8.567	1.02	1.00
	1.88E-03	1.88E-04	8.6	105	0.40	1339	17	0.0390	11.3	291	1.31	1.14	0.0377	11.203	0.0388	11.288	1.03	1.01
Frelinghuysen - 3	5.38E-03	5.38E-04	6	105	0.40	857	15	0.0167	4.2	51	0.70	0.71	0.0162	4.182	0.0161	4.176	0.99	1.00
	1.69E-03	1.69E-04	6	105	0.40	964	11.4	0.0275	12.6	1197	2.10	2.00	0.0272	12.563	0.0266	12.490	0.98	0.99
	2.43E-03	2.43E-04	6	105	0.40	1000	11	0.0250	9.6	449	1.60	2.00	0.0240	9.502	0.0244	9.539	1.02	1.00
	1.30E-03	1.30E-04	9	105	0.40	943	16.5	0.0183	14.1	1149	1.57	1.14	0.0184	14.118	0.0185	14.142	1.01	1.00
	1.39E-03	1.39E-04	9	105	0.40	1114	14.7	0.0150	16.1	1890	1.79	2.00	0.0148	16.061	0.0149	16.085	1.01	1.00
	1.19E-03	1.19E-04	6	105	0.40	722	12.5	0.0275	11.7	1049	1.95	2.00	0.0282	11.786	0.0275	11.701	0.98	0.99
	1.69E-03	1.69E-04	8.3	105	0.40	984	17	0.0158	11.4	843	1.37	1.14	0.0158	11.397	0.0161	11.458	1.02	1.01
Tinker	6.39E-04	6.39E-05	8	105	0.40	1716	31	0.0417	19	5585	2.38	2.00	0.0415	18.976	0.0421	19.049	1.01	1.00
	1.10E-04	1.10E-05	19	105	0.40	1759	130	0.0125	30.8	39881	1.62	2.00	0.0130	31.122	0.0132	31.268	1.02	1.00
	5.29E-04	5.29E-05	8	105	0.40	1716	28	0.1000	23	4219	2.88	2.00	0.1058	23.349	0.1029	23.179	0.97	0.99
Marcus Hook	1.37E-03	1.37E-04	6	105	0.40	1200	12	0.0500	16.2	1835	2.70	2.00	0.0506	16.255	0.0498	16.183	0.98	1.00
	9.23E-04	9.23E-05	6	105	0.40	1276	19	0.0500	15.8	3204	2.63	2.00	0.0485	15.672	0.0493	15.745	1.02	1.00
	1.39E-03	1.39E-04	6	105	0.40	1400	14	0.0700	15.1	1270	2.52	2.00	0.0698	15.089	0.0711	15.162	1.02	1.00
Hillsborough-2	6.10E-04	6.10E-05	10	140	0.25	1500	21	0.0320	27.9	7960	2.79	2.00	0.0325	28.013	0.0319	27.867	0.98	0.99
	5.37E-04	5.37E-05	12	140	0.25	1607	25	0.0258	29.4	8238	2.45	2.00	0.0264	29.567	0.0265	29.616	1.00	1.00
	5.31E-04	5.31E-05	14	140	0.25	1886	30	0.0317	27.7	4141	1.98	2.00	0.0314	27.624	0.0324	27.867	1.03	1.01
Hillsborough-3	2.74E-04	2.74E-05	14	140	0.25	1029	28	0.0333	30	4683	2.14	2.00	0.0348	30.345	0.0341	30.199	0.98	1.00
Newark	2.17E-04	2.17E-05	10	140	0.25	771	37.5	0.0133	25	31135	2.50	2.00	0.0131	24.903	0.0134	25.049	1.02	1.01
	1.50E-04	1.50E-05	16	140	0.25	857	53	0.0108	30	25171	1.88	2.00	0.0107	29.956	0.0107	29.907	1.00	1.00
Flemington	7.75E-04	7.75E-05	16	140	0.25	2286	35	0.0260	24.5	2522	1.53	1.14	0.0260	24.515	0.0262	24.563	1.01	1.00
	2.62E-04	2.62E-05	27	140	0.25	1886	75	0.0104	33	10166	1.22	1.14	0.0110	33.454	0.0107	33.308	0.97	1.00

Table J.5 Validation of Analytical Leakoff Method Using Bisection Model Engine.

Site Name	K_h	K_v	z	γ_{soil}	υ	Q	P_m	b	R	E	b	R	b	R	b	R	b	R
	(cm/sec)	(cm/sec)	fracture depth (ft)	(pcf)		Injected flow (scfm)	Maint. pres. (psi)	(measured) (ft)		Young's modulus (psi)	(per S. Puppala) (dissertation)		(Mcad) (ft)		(PF-Model) (Analytical) (ft)		PF-M/Mcad	PF-M/Mcad
Frelinghuysen - 1	4.94E-04	4.94E-04	3.5	105	0.40	300	10	0.0792	4.2	38	0.070	4.2	0.0797	4.227	0.0799	4.225	1.00	1.00
	4.94E-04	4.94E-04	3.5	105	0.40	300	10	0.0533	4.2	56	0.050	4.2	0.0552	4.251	0.0554	4.249	1.00	1.00
	7.76E-04	7.76E-04	3.5	105	0.40	300	7	0.0208	4.2	86	0.019	4.1	0.0205	4.196	0.0206	4.200	1.00	1.00
	6.35E-04	6.35E-04	3.5	105	0.40	300	8	0.0317	4.2	69	0.034	4.3	0.0328	4.252	0.0329	4.249	1.00	1.00
Frelinghuysen - 2	3.95E-04	3.95E-04	6	105	0.40	715	13	0.0342	8.5	272	0.033	8.4	0.0349	8.556	0.0351	8.567	1.01	1.00
	6.35E-04	6.35E-04	6	105	0.40	1227	14	0.0367	8.5	283	0.034	8.3	0.0373	8.545	0.0373	8.543	1.00	1.00
	1.59E-03	1.59E-03	6	105	0.40	1157	15	0.0075	5.7	347	0.008	5.7	0.0080	5.817	0.0081	5.828	1.01	1.00
	4.59E-04	4.59E-04	8.3	105	0.40	1500	18	0.0233	11.7	688	0.024	11.8	0.0237	11.759	0.0238	11.774	1.00	1.00
	6.17E-04	6.17E-04	6	105	0.40	1500	17	0.0375	8.6	379	0.038	8.6	0.0388	8.685	0.0389	8.688	1.00	1.00
	4.59E-04	4.59E-04	8.6	105	0.40	1339	17	0.0390	11.3	291	0.040	11.4	0.0398	11.369	0.0398	11.361	1.00	1.00
Frelinghuysen - 3	1.83E-03	1.83E-03	6	105	0.40	857	15	0.0167	4.2	51	0.016	4.2	0.0165	4.205	0.0167	4.213	1.01	1.00
	2.84E-04	2.84E-04	6	105	0.40	964	11.4	0.0275	12.6	1197	0.027	12.6	0.0282	12.693	0.0282	12.684	1.00	1.00
	5.29E-04	5.29E-04	6	105	0.40	1000	11	0.0250	9.6	449	0.024	9.6	0.0259	9.694	0.0260	9.709	1.00	1.00
	2.41E-04	2.41E-04	9	105	0.40	943	16.5	0.0183	14.1	1149	0.019	14.3	0.0184	14.115	0.0185	14.142	1.01	1.00
	2.54E-04	2.54E-04	9	105	0.40	1114	14.7	0.0150	16.1	1890	0.015	16.0	0.0153	16.187	0.0153	16.183	1.00	1.00
	2.25E-04	2.25E-04	6	105	0.40	722	12.5	0.0275	11.7	1049	0.028	11.8	0.0277	11.724	0.0277	11.725	1.00	1.00
	3.44E-04	3.44E-04	8.3	105	0.40	984	17	0.0158	11.4	843	0.016	11.4	0.0163	11.507	0.0163	11.506	1.00	1.00
Tinker	1.06E-04	1.06E-04	8	105	0.40	1716	31	0.0417	19	5585	0.042	19.0	0.0420	19.038	0.0421	19.049	1.00	1.00
	2.47E-05	2.47E-05	19	105	0.40	1759	130	0.0125	30.8	39881	0.012	30.7	0.0127	30.937	0.0128	30.976	1.01	1.00
	7.76E-05	7.76E-05	8	105	0.40	1716	28	0.1000	23	4219	0.100	23.0	0.1000	23.004	0.1000	22.984	1.00	1.00
Marcus Hook	1.98E-04	1.98E-04	6	105	0.40	1200	12	0.0500	16.2	1835	0.050	16.2	0.0502	16.217	0.0503	16.231	1.00	1.00
	1.38E-04	1.38E-04	6	105	0.40	1276	19	0.0500	15.8	3204	0.042	15.8	0.0506	15.856	0.0505	15.842	1.00	1.00
	2.22E-04	2.22E-04	6	105	0.40	1400	14	0.0700	15.1	1270	0.049	15.8	0.0714	15.181	0.0711	15.162	1.00	1.00
Hillsborough-2	8.18E-05	8.18E-05	10	140	0.25	1500	21	0.0320	27.9	7960	0.032	27.9	0.0319	27.871	0.0319	27.867	1.00	1.00
	8.08E-05	8.08E-05	12	140	0.25	1607	25	0.0258	29.4	8238	0.028	29.5	0.0257	29.384	0.0259	29.422	1.01	1.00
	1.02E-04	1.02E-04	14	140	0.25	1886	30	0.0317	27.7	4141	0.033	27.6	0.0316	27.683	0.0316	27.673	1.00	1.00
Hillsborough-3	5.00E-05	5.00E-05	14	140	0.25	1029	28	0.0333	30	4683	0.036	29.9	0.0331	29.961	0.0333	30.005	1.01	1.00
Newark	3.05E-05	3.05E-05	10	140	0.25	771	37.5	0.0133	25	31135	0.013	25.0	0.0135	25.090	0.0134	25.049	0.99	1.00
	2.72E-05	2.72E-05	16	140	0.25	857	53	0.0108	30	25171	0.011	30.0	0.0108	30.021	0.0108	30.005	1.00	1.00
Flemington	1.55E-04	1.55E-04	16	140	0.25	2286	35	0.0260	24.5	2522	0.027	24.5	0.0267	24.668	0.0266	24.660	1.00	1.00
	6.10E-05	6.10E-05	27	140	0.25	1886	75	0.0104	33	10166	0.010	33.0	0.0104	32.971	0.0104	33.017	1.00	1.00

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