DOE/ID/13681-2

Advanced Geothermal Hydraulics Model

Phase I Final Report – Part II

**W. Zheng
J. Fu
W. C. Maurer**

July 1999

Work Performed Under Contract No. DE-FG07-98ID13681

**For
U.S. Department of Energy
Assistant Secretary for
Energy Efficiency and Renewable Energy
Washington, DC**

**By
Maurer Engineering Inc.
Houston, TX**

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, make any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

ADVANCED GEOTHERMAL HYDRAULICS MODEL
PHASE 1 FINAL REPORT – PART II

W. Zheng
J. Fu
W. C. Maurer

July 1999

Work Performed Under Contract No. DE-FG07-98ID13681

Prepared for the
U.S. Department of Energy
Assistant Secretary for
Energy Efficiency and Renewable Energy
Washington, DC

Prepared by
Maurer Engineering Inc.
Houston, TX

Advanced Geothermal Hydraulics Model

Phase I Final Report – Part II

TR99-22

Contract No. DE-FG07-98ID13681

Prepared for:

**Ms. Willettia D. Amos
U.S. DEPARTMENT OF ENERGY
850 Energy Drive
Mail Stop 1225
Idaho Falls, Idaho 83401-1563**

Prepared by:

**Dr. Wu Zheng
Mr. Jay Fu
Dr. William C. Maurer
MAURER ENGINEERING INC.
2916 West T. C. Jester Boulevard
Houston, Texas 77018-7098**

July 1999

Advanced Geothermal Hydraulics Model

The Advanced Geothermal Hydraulics project was also very successful. This project consists of modifying our Advanced Geothermal Hydraulics Model ("GEODRIL"), so that it can be connected to MARCONI's Intelligent Drilling Monitor (IDM), for real-time monitoring of geothermal wells. The advanced GEODRIL model, for the first time, takes into account phase changes and other thermal effects to allow more accurate calculation of bottom hole circulation pressures to reduce expensive and time consuming lost circulation problems in geothermal wells.

The Phase I project was very successful with real-time monitoring features being added to GEODRIL with input from MARCONI, so that the two programs are compatible with each other.

Maurer Engineering Inc. and MARCONI are currently preparing a Phase II proposal to integrate the GEODRIL model into MARCONI's IDM for more accurate real-time monitoring of geothermal wells. This proposal will be sent to you in the near future.

We greatly appreciate the DOE's support of these efforts and we look forward to continued support on these exciting and important geothermal projects.

Sincerely yours,

William C. Maurer

Enclosures (3 copies of each Final Report; 4 copies of Phase II Proposal))

p.c. Paul Grabowski, DOE-Washington
Janet K. Surrusco, DOE-Idaho, Falls
Joel Renner, Lockheed-Martin

Table of Contents

	Page
EXECUTIVE SUMMARY.....	v
1. INTRODUCTION.....	1-1
2. FEATURES OF GEODRIL	2-1
3. REAL-TIME MODULE FOR GEODRIL.....	3-1
4. IMPLEMENTATION OF REAL-TIME MODULE	4-1
5. INTERFACE OF REAL-TIME MONITORING MODULE	5-1
6. INTEGRATION OF GEODRIL AND IDM	6-1
7. CONCLUSIONS AND FUTURE WORK.....	7-1
APPENDIX A: MARCONI IDM SYSTEM ARCHITECTURE	
APPENDIX B: DESCRIPTION OF IDM PROCESSING	

Executive Summary

Lost circulation and "kicks" are major problems in drilling geothermal wells due to the driller's inability to accurately calculate bottom-hole fluid pressures in these hot wells. These calculations are more difficult than in oil wells due to phase changes (e.g., water/steam), high in-situ rock temperatures, thermal expansion of drilling fluids, and fluid rheological changes due to the high temperatures. As a result, tens of millions of dollars are spent annually fighting lost circulation and kick problems in geothermal wells.

To help overcome this problem, the DOE through Sandia funded Maurer Engineering Inc. (MEI) to develop an advanced geothermal well hydraulics model (GEODRIL) that for the first time takes into account all of the thermal effects that affect fluid pressures in hot, geothermal wells. GEODRIL is based on the conservation of mass, momentum, and energy and handles heat transfer for multi-phase flow (gas, liquid, solid). This program is now being tested with thermal data recently obtained by Sandia in a Salton Sea geothermal well in California.

Sandia funded Marconi (formerly Tracor Applied Services) to develop a PC Intelligent Drilling Monitor (IDM) that utilizes artificial intelligence to detect lost circulation, fluid influxes, and other circulation problems in geothermal wells. This model has proven helpful in detecting field drilling problems.

IDM utilizes real-time data, analytical models and a Bayesian network to detect problems by examining deviations from expected patterns. Improving the analytical models within IDM by adding GEODRIL will therefore improve the accuracy and usefulness of the IDM program.

The goal of this Phase I project was to add real-time monitoring and other features to GEODRIL in preparation for connecting GEODRIL to IDM. This was successfully accomplished during Phase I using technical input from Mr. Chip Mansure (Sandia) and Mr. Glenn Corser (Marconi).

In June, 1999 good agreement was obtained between GEODRIL predictions and wellbore temperature profiles obtained by Sandia in a Salton Sea geothermal well. These validation tests demonstrate that GEODRIL will be useful for predicting and avoiding lost circulation and fluid inflow problems in geothermal wells.

During Phase II, MEI will work with Marconi to integrate GEODRIL into IDM and the enhanced model will be tested in geothermal fields in the USA, Mexico or Hawaii. Sandia will provide technical input on how to structure the program for maximum usefulness in the field and will assist in field testing the integrated program.

The Phase II project has the potential for significantly reducing lost circulation and fluid influx problems and geothermal drilling costs.

1. Introduction

In geothermal well drilling, it is important to monitor bottom-hole temperatures and pressures to avoid kicks and lost circulation. Lost circulation constitutes about ten percent of total drilling time in geothermal wells while kicks can cause disastrous blowouts. Early detection of kicks and lost circulation would significantly reduce overall geothermal well costs.

The Intelligent Drilling Monitor (IDM) is a software product being developed by Marconi Inc. (previously called Tracor Applied Sciences) based on work funded by Sandia National Labs (Sandia), the Gas Research Institute (GRI), and Marconi. The initial project was funded by Sandia to provide intelligent monitoring of the flows and pressures in geothermal wells to detect circulation problems while drilling. This earlier product, called the Circulation Monitoring System (CMS), is designed to automatically detect and diagnose loss of circulation, fluid influxes, and other geothermal drilling problems.

CMS is based on the measurement of flow sensors (including the Sandia rolling float meter), pump stroke sensors and other monitoring systems. Data from these sensors are processed and examined for deviations from expected patterns. A Bayesian network (a probabilistic reasoning tool) is used to estimate the probability of each fault by examining these deviations. As work progressed on CMS, other key requirements were identified, including integrating other monitoring processes (e.g., drill-string dynamics) into the system.

Under support of Sandia, Maurer Engineering Inc. (MEI) developed GEODRIL, a comprehensive theoretical model to simulate multiphase flow in geothermal wells and heat transfer processes in the well and formations. This new model is applicable to drilling, completion, and injection/production operations. It treats hydraulic variables and well depth as transients and handles varying flow regimes, phase changes between liquid and gas, kicks, and lost circulation.

During Phase I, a real-time monitoring feature was added to GEODRIL so that it can be integrated into IDM during Phase II to improve its monitoring and analysis capabilities. GEODRIL, with the real-time monitoring feature, will be able to work in parallel with CMS so that both systems can supplement and calibrate each other. GEODRIL is designed to predict the occurrence, location, and influx of kicks and lost circulation to help drillers avoid and overcome these problems.

Meetings held with Mr. Chip Mansure from Sandia and Mr. Glenn Corser of Marconi showed that it was feasible to connect GEODRIL to IDM and that this would significantly improve the predictive capabilities of IDM in hot, geothermal wells.

This report presents work done during Phase I on adding a real-time monitoring module into GEODRIL and discusses future work needed to fully implement this model into Marconi's IDM system.

2. Features of GEODRIL

GEODRIL is a comprehensive model that provides an overall transient simulation of mass, momentum, and heat transfer for multiphase flow with multiple components in a geothermal wellbore. The theoretical model used in GEODRIL is based on the conservation of mass, momentum, and energy and handles multiphase flow of gas, liquid, and solids in the well, and heat transfer between the fluids and the formation. The mass and momentum equations are written for three-phase (gas, liquid, and solid) flow, but they also apply to single- and two-phase flow conditions.

There are differing flow patterns involved in multiphase flow. Available correlations of drag force between phases are used to calculate the friction force coefficient in the momentum equation. Therefore, the mass and momentum equations are equally applicable to the flow inside the drill string and in the wellbore annulus.

Energy equations are derived separately for fluids inside the drill string and in the wellbore annulus, as well as for heat transfer in the formation. Equilibrium is assumed between the coexisting phases. Therefore, the energy equations are written for the mixture of fluids rather than for each individual phase. Kick and lost circulation are controlled by pressure differences between the wellbore annulus and formation fluids.

GEODRIL is applicable to:

- Drilling, production, and injection operations
- Forward circulation and reverse circulation
- Conventional drilling and underbalanced drilling
- Onshore and offshore wells

GEODRIL can handle:

- Heat transfer inside the well and in the formation
- Phase change between liquid and gas phases
- Dynamic well depth during drilling simulation
- Inflow from and outflow to formation
- Cuttings transport
- Various flow regimes
- Different rheology models

GEODRIL is based on the mathematical models described above. The beta version of GEODRIL, which was developed in Phase I of the project funded by Sandia, applies to drilling operations including conventional, underbalanced, and coiled-tubing drilling.

Important features of the beta version of GEODRIL include:

- Models conventional drilling, underbalanced drilling, coiled-tubing drilling
- Simulates heat transfer inside the well and in the formation
- Provides dynamic well depth or constant well depth
- User specified drilling interval
- Automatically handles casing installation as wells deepen
- Models inflow from and outflow to formation
- Evaluates cuttings transportation
- Different fluids may be injected either by time or by well depth
- Models various flow regimes in multiphase flow
- Includes different rheology models including the Hershel-Bulkley model
- Includes databases for casing, drill string, and rock properties
- Allows rheology model selection and parameters estimation
- Provides a choice of units, including English or metric
- Outputs include distribution of temperature, pressure, velocities, and concentrations at any time step, and temperature, pressure, and pit gain as a function of time of well depth
- Output results stored in database and can be reviewed at any time

3. Real-Time Module for GEODRIL

Adding a real-time module (RTM) into GEODRIL will significantly enhance the capabilities of GEODRIL by allowing it to simulate multiphase flow in the wellbore and heat transfer processes in the well and formations, while providing real-time monitoring for detecting and predicting kicks and lost circulation.

An RTM has been developed by MEI, which is an ActiveX component and can be applied to a variety of applications for monitoring and analyzing drilling, completion, and injection/production. A diagram of how GEODRIL works with RTM is shown in Figure 3-1.

Figure 3-1. Real-Time Geothermal Hydraulics Model

The modified program performs the following functions via a data acquisition system:

- Data collection from a data acquisition system
- Data processing, filtering, and storage
- Display of real-time data
- Display of overall safety status

The components of the Real-Time Module are shown in Figure 3-2. The module consists of a real-time Data Server, Instrument Manager, Data Interface, Data Display, and Data Storage systems.

1. DATA SERVER

The Data Server is the central element of the RTM which integrates other parts of the real-time module, provides an interface between GEODRIL and RTM, and provides an interface between RTM and a database.

Figure 3-2. Components of the Real-Time Module

2. INSTRUMENT MANAGER

The Instrument Manager allows the user to add, edit, delete and save data definitions, such as data name, unit, maximum value, minimum value, and data description, which are associated with the data acquisition system.

3. DATA INTERFACE

The Data Interface allows the user to select input formats (WITS or original data string) and obtain historical data from the raw data database.

4. DATA DISPLAY

The Data Display allows the user to display and monitor data in digital and graphic formats and displays the results of real-time analysis and measured data instantaneously. This capability allows the driller to monitor the job status in real-time, to detect and predict potential problems early, and to take corrective actions to overcome well problems before they escalate into major catastrophies.

5. DATA STORAGE

The Data Storage component formats and allows the user to input a query to obtain and save data, and to open and display the historical data for a user-specified period. This component will be added during Phase II.

4. Implementation of Real-Time Module

The Real-Time Module (RTM) consists of three parts:

1. COM ARCHITECTURE

MEI Software Architecture consists of Application Class, Module Class, and MEI Foundation Class layers, as shown in Figure 4-1. The real-time module is in the Module Class layer and consists of individual components. The MEI Foundation Class (MFC) layer defines the drilling business objects, which are persistent. In other words, these objects can retain their values between different executions of the application.

Figure 4-1. MEI Software Architecture

2. DATA SERVER

The Data Server is a central part of the real-time module that allows users to obtain real-time data. Several client applications can share data from the real-time server, relieving the need for preparing a serial port for each client.

The Data Server has been implemented by the object oriented method. It was integrated through a parent class (data server class) and two child classes: data buffer class and instrument class. A hierarchy of the classes is shown in Figure 4-2.

Figure 4-2. Hierarchy of Classes

3. INSTRUMENT MANAGER

The Instrument Manager utilizes a back-end component that is responsible for manipulating predetermined data, and a front-end interface component that allows the user to create, open, and modify the predetermined data. Figure 4-3 shows the Instrument Information Window of the Instrument Manager that allows the RTM to automatically load the instrument that was used last time.

Channel	Data Name	Unit	Maximum	Minimum	Description
1	Time		0	0	
2	MD	ft	0	0	
3	Inlet Pressure	psi	0	0	
4	Outlet Pressure	psi	100	0	
5	Bottom Pressure	psi	5000	0	
6	Inlet Temperature	F	120	0	
7	Outlet Temperature	F	0	0	
8	Bottom Temperature	F	250	0	
9	FR Volume Total	bbl	100	0	

Figure 4-3. Instrument Information Window

The Instrument Configuration Window (Figure 4-4) allows users to define the specifications of the instrument sensors.

Channel	Data Name	Unit	Maximum	Minimum	Description
1	Time		0	0	
2	MD	ft	0	0	
3	Inlet Pressure	psi	0	0	
4	Outlet Pressure	psi	100	0	
5	Bottom Pressure	psi	5000	0	
6	Inlet Temperature	F	120	0	
7	Outlet Temperature	F	0	0	
8	Bottom Temperature	F	250	0	
9	FR Volume Total	bbl	100	0	

Figure 4-4. Instrument Configuration Window

The Instrument Channel Window (Figure 4-5) allows user to select variables of interest while the Port Setup Window (Figure 4-6) allows user to select a serial port.

Figure 4-5. Instrument Channel Window

Figure 4-6. Port Setup Window

5. Interface of Real-Time Monitoring Module

The RTM utilizes three types of interfaces:

1. DATA SOURCE INTERFACE

To meet the requirements for engineering models, this RTM interfaces with different data sources such as data acquisition hardware and history data from the vendor's raw database. With the aid of the instrument manager, the user can easily connect to a data acquisition system. This interface was completed on this Phase I project.

2. USER INTERFACE

The User Interface module is an independent and user-friendly component. As the user launches the RTM, the Instrument Information Window shown in Figure 4-3 will pop up if a predetermined instrument exists in the database, while the instrument configuration window shown in Figure 4-4 will pop up if no predetermined instrument exists. Clicking OK button on the instrument information window will load the digital display window.

The real-time monitoring module implemented in GEODRIL has been successfully tested with an external data acquisition system. While receiving real-time data from the external system, the Data Display Window (Figure 5-1) displays data every one or two seconds based on the user-specified interval of data transfer.

Figure 5-1. Data Display Window

3. GEODRIL INTERFACE

There are two ways to activate the real-time monitoring interface in GEODRIL. Clicking the “Monitoring” button on the data display window or the menu bar at the top of the GEODRIL Input Window (Figure 5-2) causes the GEODRIL Database Manager Window (Figure 5-3) to pop up that shows pre-calculated results for the geothermal well of interest.

Figure 5-2. GEODRIL Input Window

Figure 5-3. GEODRIL Database Manager

Calculated temperatures, pressures, pit gains, and other variables changing with MD and drilling time are stored in this database and can be retrieved at any time.

After the previous results are retrieved, the Monitoring Window shown in Figure 5-4 shows data on temperature, pressure, and pit gain variations.

Figure 5-4. Monitoring Window for Bottom-Hole Temperature, Pressure, and Pit Gain

Figure 5-5 shows the full-size Monitoring Window for measured and calculated bottom-hole, inlet, and outlet pressures plotted as a function of time.

Figure 5-5. Monitoring Window for Bottom-Hole and Inlet Pressure

Based on the comparison between measured data and calculated results, the user can easily detect and quantitatively analyze kicks and lost circulation as well as bottom hole temperature and pressure. For example, variations in pit gain will determine the time, location, and volume of kicks or lost circulation. Comparison between measured data and calculated results also allows real-time calibration of the model.

6. Integration of GEODRIL and IDM

There are at three main steps in integrating GEODRIL/IDM with Marconi's Intelligent Drilling Monitor (IDM):

1. INTEGRATE GEODRIL INTO IDM

IDM architecture allows straightforward integration of multiple processing modules using COM. GEODRIL could either be changed to a COM server or a wrapper could be put around it that would allow it to operate as a COM server.

Real-time data would be passed to GEODRIL from IDM at each time update through the COM interface. GEODRIL would process the data and pass the results of that processing back out through the COM interface. Data display could be handled either by the wrapper interface (using an ActiveX control as the wrapper) or by IDM.

2. COMBINE GEODRIL PROCESSING WITH OBSERVATIONS

GEODRIL contains a comprehensive hydraulics model of the wellbore that could be used to predict well states from time t to time $t+1$. This would allow GEODRIL to function as the plant model for a Kalman filter designed to model key aspects of the wellbore.

To do this, states would need to be identified that could be used as inputs to GEODRIL and related to rig measurements. For example, one possible state is bottom-hole pressure, which is related to the following measurements: standpipe pressure, pump rate, and average mud density.

GEODRIL could be used to predict bottom-hole pressure from one time step to the next and updated using a measurement equation relating bottom-hole pressure (BHP), standpipe pressure, pump rate, average mud density, and mud viscosity. When a new data point is received, the previous state estimates could be input back into GEODRIL to derive a new set of predictions for that time and then updated using observations from that time.

The key to this process is to determine a set of states that can be used to estimate variables of interest (e.g., wellbore pressure, temperature profiles) that are observable. Examples of possible states are bottom hole pressure, bottom hole temperature, liquid density, gas density, liquid phase velocity, gas phase velocity, and fluid friction factor. Possible measurements are mud weight in, mud weight out, temperature in, temperature out, standpipe pressure, pump rate, surface gas volume, and surface liquid volume. Combining observations and measurements could be done in the wrapper function described above that is used to convert GEODRIL to a COM server.

3. USE GEODRIL OUTPUT TO DETECT AND DIAGNOSE PROBLEMS

The outputs of the GEODRIL-based COM server could be monitored using a set of CuSum processes to look for deviations from expected behavior. The outputs could be fed in as evidence to an expanded Bayesian network that included additional hydraulics faults to those in IDM. The GEODRIL expanded Bayesian Inference Network would be developed based on input from Maurer drilling experts.

7. Conclusions and Future Work

During Phase I, a Real-Time Monitoring module (RTM) was added to GEODRIL to allow GEODRIL to be connected to Marconi's Intelligent Drilling Monitor (IDM) during Phase II. This will allow the IDM to more effectively detect kicks and lost circulation in high-temperature geothermal wells. A comparison between measured data and pre-calculated results allows the user to monitor variations of pressure, temperature, and pit gain in real time. The RTM module has been tested with an external data acquisition system.

Integrating GEODRIL and the IDM is seen by both MEI and Marconi as an exciting opportunity to expand the power and usefulness of both systems. GEODRIL can capitalize on IDM's real-time data acquisition and analysis capabilities while IDM can capitalize on the sophistication of the GEODRIL model to make more accurate predictions.

MEI brings GEODRIL and significant drilling expertise to the project while Marconi brings IDM and significant experience in developing practical real-time drilling monitoring and analysis systems to the project.

To practically integrate GEODRIL and IDM, significant work needs to be done in Phase II including:

- Improve the preliminary real-time monitoring module in GEODRIL to make it more user friendly
- Add the function of predicting occurrence, location, and influx of kicks and lost circulation in GEODRIL with real-time dynamic data, such as ROP and mud weight
- Practically integrate the real-time GEODRIL model into the IDM architecture
- Use the output of GEODRIL to detect and diagnose measuring problems
- Enhance the calculation speed of GEODRIL to keep pace with real-time monitoring in geothermal well drilling
- Develop GEODRIL for injection and production in geothermal wells

Integration of GEODRIL with IDM should significantly enhance IDM's capability for detecting lost circulation and kicks in geothermal wells and thereby significantly reduce geothermal drilling costs.

Appendix A: Marconi IDM System Architecture

Figure A-1 contains a diagram of the IDM system. Each block in the diagram is color-coded according to the following scheme:

- Blue box – functionality comes from FIX, the SCADA software that is the framework for the Circulation Monitoring System (CMS).
- Red box – functionality comes from third party data acquisition software.
- Green box – functionality is a C++ program implemented as a COM object. These blocks represent the core diagnostic and analytic modules for the system. Three modules are displayed: CMS – Circulation Monitoring System, Ann Press – Annular Pressure Estimation (DEA 125), and DS Dynamics – Drill-string Dynamics. CMS is currently under active development and projects are being formed in the other two areas.
- Yellow box – functionality is a C++ program implemented as an OPC server.

Figure A-1. IDM Architecture

The system framework is a Supervisory Control and Data Acquisition (SCADA) system called FIX, built by Intellution. About 70% of the PC-based SCADA applications now running are using FIX. FIX supplies a set of ready to use display widgets, maintains the real-time database, provides Web access, provides other network enabled clients that can be used as display only work stations, provides optional fail-over backup security, uses Visual Basic for Applications (VBA) as its scripting language, and provides drivers for many types of real-time devices and inputs.

Input to the system is done using OLE for Process Control (OPC). OPC is an industry standard, developed by the OPC Foundation working in collaboration with Microsoft, that extends OLE/COM to process control and factory automation applications. OLE is a set of

services provided by Win 95/Win 98/Win NT that span various aspects of commonly needed system functionality, including compound documents, customer controls, inter-application scripting, data transfer, and other software interactions. When used together, COM and OLE can allow applications to share 'objects' automatically. For example, COM and OLE allow spreadsheets to be embedded in word processing documents. When updates to the spreadsheet occur, OLE and COM ensure that the updates are automatically reflected in the embedded spreadsheet.

Conceptually, OPC can be thought of as an industry standard COM interface that allows data to be transferred from an OPC server to an OPC client. OPC provides a standard that allows any OPC client application to connect, always in the same way, to any vendor's OPC-compliant server and then be guaranteed the same behavior from that server. In essence, OPC provides the foundation for plug-and-play data acquisition. The intention is to bring the same benefits to industrial hardware and software that standard printer drivers brought to printing and ODBC (open database connectivity) brought to database access. FIX can be easily configured as an OPC client. To interface to third party data acquisition vendors, Marconi writes custom OPC servers that access data in a vendor specific manner and then input that data into IDM using OPC. In this manner, data acquisition is completely isolated from IDM and all that needs to be done to interface to a new data acquisition vendor is to write a new OPC server.

All system processing is exposed to the FIX framework through the use of COM and all processing modules are written as COM servers using C++. COM is an acronym for Component Object Model and is a protocol for connecting software objects. The connected objects can be either Dynamic Link Libraries (.dll's) or Executables (.exe's). In general, COM specifies how objects should be laid out in binary form in memory and also specifies how objects should communicate with one another. These specifications are independent of machine or language and are thus architecture-neutral.

To the programmer, COM objects consist of a collection of interfaces. An interface is the way an object exposes its functionality to the outside world. Physically an interface is a table of pointers to functions implemented by the object; a COM object can have as many interfaces (function tables) as it chooses. Interfaces require no statically or dynamically linked entry points and no hard-coded addresses other than those of a few general-purpose COM functions that get the communication process started.

COM objects may be either clients or servers. A COM *server* is an object that *provides* an interface (or interfaces) that someone else might want to use. A COM *client* is an object that *uses* an interface by calling one or more of its functions. COM clients and servers can be on the same machine or on separate machines on the same network.

As noted above, FIX uses VBA as its scripting language. Using VBA, it is very easy to interface to a COM server, making it a very simple matter to add additional processing modules to the FIX framework. Also, since all processing modules are implemented as COM servers, it is possible to distribute them across a network. This would allow a compute intensive process to run on a separate computer from the real-time machine that is managing data acquisition, display and storage. This also allows processes to run asynchronously so that if a program requires an extended period of time in which to perform its calculations, that resource can be provided in a natural way that does not interfere with any other system processing.

Appendix B: Description of IDM Processing

In general, for the modules shown in Figure A-1, processing under IDM is implemented using the following scheme:

- The process is dynamically modeled using one or more Kalman filters.
- The Kalman filters are monitored using CuSum or sequential hypothesis testing techniques.
- Outputs from the monitoring algorithms are used as evidence for Bayesian inference networks that can estimate the probability of a particular fault or problem occurring at each time update.

With respect to GEODRIL and IDM, an understanding of Kalman filters is very important because they provide a methodology that can be used to integrate GEODRIL simulation results with rig-site observations. A Kalman filter is a computational algorithm that processes measurements to obtain a minimum error estimate of the state of a system by using:

- Knowledge of system and measurement dynamics (system/plant model, measurement model),
- Statistics of system and measurement noises,
- Initial system information.

Kalman filters can be designed to handle both discrete and continuous measurements as well as linear and nonlinear system/measurement models. The parameters that the filter estimates are called the states of the filter. The state covariance matrix is used to estimate the uncertainty associated with each state as well as the uncertainties between states. Figure B-1 contains a block diagram showing the basic processing scheme for a Kalman filter. The oval represents initializing values for both the filter states and filter uncertainties. At time k , the system or plant model is used to predict the values of the states at time $k+1$. Measurements are taken at time $k+1$ and combined optimally with the predictions at time $k+1$ to give new state and uncertainty estimates at time $k+1$.

Kalman filters have traditionally been used in guidance and navigation systems. Marconi has been the first to apply them to down hole data analysis during drilling operations. There are several advantages to using Kalman filters for this purpose. They:

- Are adaptive. Kalman filters are adaptive, allowing them to adjust their state estimates as bottom-hole conditions change. This is a critical advantage for real-time monitoring in systems such as IDM. Traditional simulation or mathematical models provide predictions based strictly on initial conditions and are not able to adjust their predictions if conditions vary from the initializing input scenario.
- Work with simple models. Kalman filters can produce very accurate state estimates and predictions with relatively simple system models. The models used in a Kalman filter need only predict from time k to time $k+1$. Combining a model prediction at $k+1$ with a measurement at $k+1$ can dramatically increase the accuracy of the state estimate at $k+1$. The importance of this is that Kalman filters can be quite accurate in cases where the physics of the situation is very complicated or unknown, but where good approximate models exist and measurement data and models are available.

Figure B-1. Kalman Filter

- Provide a measure of information quality. A Kalman filter uses measurements to link the system model to observations on the actual evolution of the system being modeled. A filter is said to be observable if the n states of the filter can be estimated from n noise free measurements. Observability ensures that there is enough information in the measurements, and that the system model is an accurate enough representation of reality, to properly estimate the filter's state variables. This is in distinct contrast to many simulation models that have parameters, or that perform operations on those parameters, which cannot be directly tied to actual observations of the system.
- Are general in scope. Kalman filters can be used to model a wide variety of phenomena. Marconi has also developed methods for using simulation-generated data (e.g., power law fluid flow) in Kalman filter system and measurement models.
- Are computationally fast. In a wide variety of cases, Kalman filters can be implemented so that they operate very fast and use a minimum of computation power.
- Require small amounts of storage. Kalman filters do not need to store large amounts of data from one time update to the next. This makes them ideal for modeling real-time phenomena over long periods of time.
- Provide multiple ways to detect errors. There are several methods for monitoring a Kalman filter to detect problems in the system being modeled. These include: monitoring the states themselves for improper values, monitoring the state covariance matrix for unexpected behavior such as unlimited growth, and monitoring the differences between predicted measurements and observed measurements for trends or jumps. This allows a monitoring system to be built in which deviations from expected behavior can be detected and then combined to generate problem diagnoses.

Marconi has developed Kalman filters for a wide variety of dynamic systems and has also investigated methods for including simulation results in Kalman filters. Note that the plant model in a Kalman filter is similar in function to GEODRIL though usually it is considerably less sophisticated.

The CuSum test is used to detect significant deviations from expected behavior of the well. This is a well known statistical test used in quality control to detect processes that are "out of control", i.e., behaving differently than expected. Consider a process that generates time ordered

observations $x_1, x_2, x_3, \dots$ and suppose the observations have an expected or target value of θ . For n observations, the cumulative sum at n is defined by:

$$CS(n) = \sum_{i=1}^n (x_i - \theta)$$

If the process is in control, $CS(n)$ will be near zero since the x_i 's will tend to wander randomly about θ and the sum of these deviations will tend to zero. There are two ways that the process can become out of control: 1) the variance of the process can increase so that differences between each observation and the process target value become unacceptably large or 2) the process can become biased such that it begins to exhibit systematic differences between each observation and the process target. CuSum tests are constructed to handle both of these situations. Figure B-2 gives a conceptual illustration of the way a CuSum test works. A mask is created based on a truncated V shape. A line representing the target value passes through the center of the mask. The test works backward from the present, accumulating deviations from what is expected. The cumulative sums are compared to a mask, which determines the tolerance. If one of the sums is outside the mask, a significant event is detected. The slope of the mask's V determines the maximum bias we are willing to accept in the process. The difference between the target and the mask at the bottom or truncated portion of the V determines the amount of variance about the target value we are willing to accept in the process. This may also be thought of as the tolerance of the system.

Figure B-2. CuSum Testing

The value of the CuSum can be used in a Bayesian Inference Network (BIN) for problem detection and diagnosis. A BIN is a computationally efficient structure for probabilistic reasoning based on Bayes' theorem. Figure B-3 contains a simple example of a BIN that could be used for CMS. The topology of the network represents the dependence relationships that exist between the faults and the causes. In Figure B-3 the top row of nodes represents faults and includes (starting from the left): pump stroke counter error (also pump stroke calibration error), loss of pump efficiency, inflow sensor error (sensor problem or miscalibration), outflow sensor error, circulation loss, kick, washout, and plug. The bottom row of the network contains evidence nodes. Evidence nodes represent quantities that can be monitored or estimated and which will undergo a status change when there is a fault present that affects them. Starting from the left the evidence nodes are inflow sensor readings that differ from stroke count flow estimate, outflow sensor readings that differ from inflow sensor reading, and standpipe pressure changes. The

arrows link faults to evidence, and Bayes' theorem can be used to estimate fault probabilities based on evidence values.

Figure B-3. Bayesian Inference Network

As Figure B-3 illustrates, a BIN provides a clear and systematic way to model human causal reasoning without complicated rules or exceptions. A BIN can accept both evidence and absence of evidence and can estimate fault probabilities at each time update. From a theoretical standpoint, a BIN is very attractive because its performance can be quantified mathematically and its operation can be fully examined and understood. This is not always the case with a rule-based network. From an application standpoint, a BIN is very attractive because it is easily extendable, and new faults can be added with minimal effort. Also, it is computationally very fast and its performance can be measured and engineered to ensure it will run properly in a real-time system.

To understand the way a BIN works, suppose that the inflow measurement is significantly less than one would expect from the pump stroke counter readings. This can be caused by loss of pump efficiency or by a problem with the inflow meter. If the inflow measurement is indeed less than the true inflow, then (in the absence of other problems) the outflow measurement will be greater than the inflow measurement. If the flow measurements agree then the sensors are probably working correctly, so pump efficiency has been lost. Suppose instead that the inflow reading is less than the outflow reading. By itself, this could be caused by a well kick, an error in the inflow meter or an error in the outflow meter, but the discrepancy between inflow reading and pump stroke count would lead a human to suspect a problem with the inflow meter. In the Bayesian network, the symptoms not only increase belief in inflow meter error, but also combine to support a coherent diagnosis. Since the discrepancy with stroke count increases the likelihood of an inflow meter error, it helps to explain the flow discrepancy, and thus makes the beliefs in well kick and outflow meter error less than they would be with flow discrepancy alone. Similarly, the flow discrepancy helps to explain what would otherwise suggest a drop in pump efficiency, and reduces belief in that fault. The result is a high belief in inflow meter error and lower beliefs in the other faults. The probability calculations in the network automatically handle such considerations. Bayesian networks can be built using expert input, historical data, theoretical considerations, or any combination of the three.