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## Computerized Field System for Real-Time Monitoring and Analysis of Hydraulic Fracturing Operations

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### Summary

A new calibre of systems, generically denoted as RT-MACS, has been designed and developed for the monitoring, analysis and potential control of hydraulic fracturing treatments in real-time during the field operation. A number of prototypes have been built, based on state-of-the-art computer hardware, ranging from super mini-computers to entirely portable systems. They perform the complete spectrum of functions: data-acquisition from calibrated sensors, data-processing and storage in the central facility, display of processed data on scrolling windows, simulation of the overall process, using realistic engineering models for analysis, and display of overall status, including model results. The models used are unique in many respects: they use real-time data as input; they employ a novel history-matching scheme to determine elusive reservoir and fluid parameters in real-time; and they use the most advanced three-dimensional analysis to make calculations for pressures, height, width and length of fractures. Both trailer-transported and portable system prototypes have been successfully implemented in a number of commercial field operations, running without disruption in standard jobs on cooperative wells provided by interested producing companies; their presence had sufficient practical impact that the portable systems are now being offered on a broader scale throughout the industry.

### Introduction

Among the many operations of the petroleum producing process, hydraulic fracturing may be the most complex to conduct and the most evasive to verify in a scientific engineering manner: the success of the best-designed treatment can often be a victim of the vagaries of nature and there is very little direct information as to exactly how effective was

the treatment, or what went wrong when production shows poorly. As a consequence, the technology of hydrafrac has developed in an understandably conservative fashion (e.g. Ref. 1): well owner-operators wish to avoid risks involved in blind experimentation and, subject to technology/cost limitations, service companies have not been able to muster the many components needed to develop, verify or control the procedures which might have resolved some of the difficulties. In a sense, the necessarily competitive nature of the industry may have militated against the coordinated effort needed to upgrade the technology.

Recognizing this shortcoming, especially on the critical future supply end of gas from low-permeability reservoirs in the U.S., a more concerted effort is now being conducted by the Gas Research Institute to resolve some of the major problems obstructing progress in this area. This GRI project covers the whole range of data-gathering, analysis, design and actual implementation in the engineering operation; this involves detailed work on logging, coring, completion techniques, pre-frac testing, detailed fracture treatment design and real-time analysis, and post-fracturing testing. A more comprehensive account of this GRI effort may be found in Ref. 2 and in a companion to this paper, Ref. 3.

The system described in this paper is a major part of the GRI project: its purpose is to be the nerve-center of the overall effort - by collecting and organizing the data, by design and real-time analysis of the job, and by overall evaluation for the operator at any instant in time, allowing feedback control to the equipment operation as confidence is gained in the verity of its predictions.

The motivation for this system grew from recognising a number of shortcomings in present capabilities:

- The operator has presently very little, if any, capability to explore alternatives if problems begin to appear as the job is being pumped.
- The operator does not get a clear picture of current job status, e.g. schedule history, possible interpretations of data collected to date, etc.

References and illustrations at end of paper.

- The models used to design the fracture are not being called on to track the consequences of the design schedule, as the job progresses.
- The models used often seem to be very unrealistic – but there has not been any concrete way to check their estimates: the created fracture cannot be scrutinised, until better fracture diagnostic techniques have been developed – another major thrust of the overall GRI project.
- Experience gained on other jobs is not actively available on the current job, except perhaps qualitatively in the minds of consultants, service-company and well-operating company personnel.

To remedy these deficiencies, the system described here has been designed to provide the following principal capabilities, at the operators disposal:

- A data-base of processed data obtained on previous jobs: any related job will be called up in an instant for comparison to the present pattern of events.
- The system operates in real-time during the job, so that all data-acquisition, retrieval, processing and display is instantaneous. This allows the operator to get an immediate overview of the job.
- The system runs models in real-time to calculate best estimates of job effectiveness and possible impending problems. The operator can thus make immediate decisions on procedural changes.
- The models are realistic descriptions of the flow and fracturing process; they run in real-time with actual flow data as input; and they will allow reservoir parameters to be determined by real-time history-matching. This will improve, or perhaps eliminate the need for data from expensive cores and logs.
- The user-friendly graphics displays improve quality-control and allow the operator to confidently give feedback on equipment operation. Eventually, when confidence is gained in the system, some control may be performed automatically by the computer.

A more detailed description of these capabilities and their application is provided in the following sections.

### Overview of Real-Time System

A typical layout of field operations is shown in Figure 1. The principal modifications to the conventional hydraulic fracturing treatment are the sensor attachments distributed throughout the system: flow, rheology and  $\Phi$  of the gel are measured by instruments mounted on the "suction skid", before the blender and pumps; a (nuclear) densitometer is mounted on the "discharge skid", where a flowmeter may also be added (e.g. based on Doppler shift, rather than turbine meter); pressure is measured at the well-head, both in the tubing and in the annulus or casing – the former typically serving as "reflected downhole pressure", whenever

fluid is pumped down the annulus. In addition, downhole pressure may be measured directly on some jobs (see Figure 4(c) later), using a wireline.

Other measurement systems are being planned for future field applications: measurement of pressure difference  $\Delta p$  in the tubular goods should give a much better indication of flow rheology in the pipe (casing, annulus or tubing), allowing better calculations of downhole pressure from up-hole measurements – thus avoiding running an extra string on future commercial operations. As well, data from fracture diagnostic techniques (such as fracture mapping by means of downhole instrumentation) may be added to the system if such techniques can be proved reliable. In short, the computer system (shown in Figure 1) will acquire and process any data that may be of value to perform real-time evaluations of the job represented in Figure 1.

A schematic of the hardware required to achieve this real-time evaluation is shown in Figure 2(a); this refers specifically to the equipment on board the GRI Main Computer Trailer (MCT), consisting of the following principal components:

- **Data-Acquisition Modules**; these are presently based on customized high-speed A/D boards mounted in expansion slots of an IBM PC-compatible portable microcomputer. This portable system also allows data to be acquired on many jobs where the MCT cannot be present: this can then be post-processed, evaluated and added to the data-base for future reference.
- **Central Processing Unit (CPU)**; the present choice is a DEC VAX 11/750, but other super-minicomputers may be installed soon to better perform the main functions; this technology is advancing very rapidly, toward the point where real-time execution of our most complex models will be possible on transportable systems.
- **Magnetic Storage Devices**; a removable hard disc provides virtual memory capabilities through the VMS operating system on the main CPU; VMS is extremely effective both for multiple task execution and for calculations with large simulation programs, as if on a larger RAM base. In addition, a tape drive unit provides back-up and data transfer capabilities.
- **Graphical Display Units**; a Megatek 7200 vector CRT graphics unit effectively provides very rapid display of such information as data in scrolling window format, line diagrams of processes, and scheduling; in addition, a Tektronix 4115B raster CRT graphics unit provides high resolution color displays of information such as overall job status, schedules pumped, history-matching of data with models, and model estimates of underground conditions such as fracture geometry.
- **Hard copy devices**; a DEC LA120 line printer provides direct CPU communications, while a Versatec V-80/121 printer-plotter allows the immediate preparation of hard-copy plots and print-out for a status report or overall evaluation.

The resulting computerized facility, integrating this hardware and the software described later, performs the following principal functions:

1. **High-quality data-acquisition** from sensors such as the pressure transducers, flow-meters, densitometers and rheometers shown in Figure 1. This requires a reliable but unobtrusive hook-up to service-company equipment in the field (Figure 1): special instrumentation has been mounted on transportable skids [for use in conjunction with the GRI Main Computer Trailer] but the actual sensor-equipment interface is still undergoing development, as may be seen by noting the dashed options in Figure 1. The resulting capability seems to be a substantial improvement over existing industry efforts in this area, in quality and reliability of sensor data acquired.
2. **Operator-friendly displays of data**, discussed in detail later in the section on system applications. This serves a twin purpose: **quality control** of materials pumped; and the ability to immediately examine any change in system response – such as pressure transients. This state-of-the-art vector graphics unit allows instantaneous blow-ups, segmenting and all other reasonable multi-window display of incoming data; its capabilities thus extend far beyond that existing in the industry at present.

In effect, current monitoring facilities cover just these two first functions; our new system greatly enhances these capabilities and then closes the engineering loop as follows.

3. **Real-time analysis**, using data as direct input to realistic models of the physical processes involved. This completely novel capability allows for immediate evaluation of job status and forecasting of potential problems; the pressure response serves as a principal check on model accuracy, but other diagnostic techniques are being developed in parallel with the RT-MACS system. In fact, the models may be **history-matched** with the early observed response in order to determine a number of reservoir parameters – which are then employed for ongoing calculations of current status or forecasting of future response.
4. **Real-time displays of model results and job status** showing the schedules pumped so far, the estimated resulting fracture geometry and predictions of future conditions. These enable the operator to make an informed decision on further schedules to be pumped.
5. **Overall evaluation and immediate report generation** to provide the operator with a complete picture of the job and estimates of anticipated return on investment (RoI) from production.

The software modules associated with the operation of those hardware components are indicated schematically in Figure 2(b). They are classified in four broad categories:

- Data acquisition, storage and retrieval software.
- Real-time operating software.
- Graphical display software, for CRT and hard-copy.
- Physical modelling software. The components of this category are described in detail in the next section.

## Physical Modelling of the Hydrafrac Process

An integrated comprehensive package, called FRACWELL, has been developed to realistically simulate the overall hydrafrac process. This consists of four major modules, suitably interfaced (Figure 3) and running in real-time within the RT-MACS framework; these modules contain the most up-to-date physical data, mathematical formulation and computer implementation of models describing the following component processes:

- **Frac fluid/slurry flow in tubular goods and the perforations**, including effects of cross-linking, foaming and proppant concentration in gelled fluid flow rheology. This incorporates both laboratory and field data on pipe flow, the latter based on simultaneous uphole and downhole pressure measurement – wherever such data has been collected: a major purpose is to eliminate the need for such downhole data collection, by being confidently able to calculate true downhole fracturing pressures from measured uphole pressures. A comprehensive new formula for pipe friction has been developed, which matches the industry data presently available and supercedes the less reliable descriptions presently used by service companies in the industry. The principal parameters of this model are:
  - fluid rheology, consistency  $K'$  and flow index  $n'$ ;
  - fluid density and compressibility;
  - proppant density and concentration;
  - pipe diameters, roughness and configurations.

This module principally calculates downhole from uphole pressure or *vica versa*, using downhole pressure from the next module.

- **Fracture creation, extension, shut-in and closure**: this module is based on a 3D simulation of stresses, pressure distribution and crack-opening induced by the injection of the complex frac fluid. It incorporates the rock mechanics of deformation and fracture, the coupled fluid flow within the fracture and the fluid and heat exchange with the surrounding reservoir.

The principal parameters required for this model are:

- Fluid rheology,  $K$  and  $n$ , for channel flow; [These will typically be different from  $K'$  and  $n'$ , because of cross-linking on the way, some shear degradation of the fluid and thermal activation.]
- Earth stress distribution before fracturing.
- Rock modulus in reservoir and adjacent strata.
- Rock fracture toughness, for breakdown analysis.

This model calculates fracture dimensions (height, width and length) and associated downhole pressure at the fracture entrance, outside the perforations.

- **Reservoir simulation:** this component represents, as accurately as needed for practical purposes, the fluid flow and heat transfer within the rock in the strata surrounding the fracture. It thus allows calculations of fluid loss from the fracture, heat-up of frac fluid, induced stresses, and, eventually, production of oil and gas through the propped fracture.

The principal parameters of this model are:

- Reservoir permeability and porosity.
- Reservoir thermal conductivity and specific heats.
- Reservoir fluid saturations, and pore-pressures.
- Fluid leak-off and filter cake parameters.

This model calculates efficiency of the fracture and thermorheology of the frac-fluid.

- **Proppant transport and placement:** this tracks the movement of proppant with the frac-fluid, the differential settling (or buoyant) motion, the formation of proppant banks or potential screen-outs, and the eventual closure of the fracture walls onto the proppant, to form a permeable channel.

The parameters of this model are:

- Proppant particle diameters, and concentrations.
- Proppant density and fluid density.
- Fluid rheology on the scale of particles.

This model calculates the propped fracture length and width, needed to compute fracture conductivity during later production from the reservoirs.

The overall modelling capability, FRACWELL, has many features which seem to make it superior to anything presently existing in the industry:

- \* It contains the most comprehensive and realistic description of the physical processes that can practically be applied to the operation in question.
- \* It allows for real-time execution of the models, using actual flow data as input, so that the process is tracked continuously throughout the job.
- \* It incorporates a history-matching capability to allow for real-time determination of certain critical parameters, such as reservoir permeability, stress and modulus distribution, which cannot easily be determined by other means; this typically uses prior minifrac and/or the early pad gel phases of the actual job to match pressures with those observed. After matching, these parameters are used to predict future response and track progress during the more critical later (proppant-laden) phases of the job.
- \* It will have a self-checking capability at times of surges or viscosity changes, during which a pressure transient occurs that depends on current fracture geometry, which may thus be determined: this has the potential to provide a cost-free simple fracture mapping technique which may prove practically superior to other expensive diagnostic techniques which have been or are presently being pursued.

- \* It can be applied and checked throughout the engineering of the job: it works easily as a user-friendly stand-alone program in the design phase before the job; it runs in real-time during the job, allowing any scheduling changes to be recommended and accounted for immediately; it thus gives the operator an immediate complete picture of the operation, in the field, while remedies are still possible.

### Field Application of the System

During the past year, the RT-MACS facility has been implemented in real-time on four full cooperative wells (Ref. 3), involving GRI contractors and a variety of operating companies. In addition, data has been acquired on a number of other wells, using the portable data-acquisition system or the mobile data-acquisition trailer (Ref. 3); this data was then post-processed to produce field reports of the same kind as if RT-MACS had been there for real-time analysis. In this way, a large data-base and broad experience is being gained with operation of the system.

To illustrate the use of the system, we have chosen a cooperative well from the GRI Tight Gas Sands Program: extensive logging, coring and other pre-fracture measurements (Ref. 3) were performed by various GRI contractors in cooperation with the well operator, Prairie Producing Company. The well was located near Nacogdoches, East Texas and targeted the Travis Peak/Hosston formations, which have also been a principal target of the GRI project.

The flow, rheology and proppant data acquired during the job is shown in Figure 4(a); the job went roughly according to schedule and quality control was good. The resulting uphole and downhole pressures are shown in Figures 4(b,c), where they are compared with predictions obtained by using the physical models. Unknown reservoir and friction parameters may be obtained by history-matching, a technique that involves comparing the observed pressures and model predictions in order to minimize the error between them. When history-matching is performed on the early response to pad injection, the parameter values obtained may then be used during the rest of the job to ensure the best model predictions possible. Use of our wellbore transport model may be seen to give an excellent fit to uphole pressure in Figure 4(b). Although the form and coefficients of the pipe friction component of the model have been chosen to best fit an average of all industry lab and field data available to us (e.g. as in Ref. 7), fine tuning of these coefficients by history-matching has improved the accuracy to within 5 % over the entire duration of the fracture treatment. Note that we avoid logarithmic plots, as they tend to mask many important effects.

Even more interesting is the comparison of downhole (fracture) pressures in Figure 4(c), remembering that the extent of fracture containment may be estimated from the pressure rise or fall-off as long as other influences on fracture pressure can be identified and separated out. After the initiation phase, which is still under study with the 3D model, we see that the reservoir parameters associated with

no containment produce an excellent fit during the early part of the job, including the period of the great rise in pressure which is due to the first appearance of 50 lb. cross-linked gel in the fracture. After this early phase of no containment, the fracture pressure continues rising: the best fit with model predictions during this second phase seems to indicate that the fracture has now encountered substantial confining barriers; however, some of the pressure rise could also have been caused by increased flow resistance due to the proppant staging. Late in the job, when the heaviest proppant loading was reached, the pressure response turned sharply upwards. A screen-out was clearly developing, as no amount of confinement in the models could have produced by itself such an increase in pressure.

Although we have been able to identify mechanisms such as sliding resistance, bank buildup, and screen-out as potentially dominant contributors to fracture pressure – accounting for the late pressure rise in Fig. 4(c) (Ref. 11) – these mechanisms have not yet been finalised in our models. Until they are, the confinement inferred from the pressure response will remain uncertain for many treatments. A Nolte-Smith type of analysis (Refs. 9,10) would also require detailed incorporation of such modelling and mechanistic interpretations, if proper explanations are to be made: although such analyses are now being conducted as a major focus of treatment monitoring vehicles in the field (e.g. Refs. 7,8), it has become clear that much more detailed modelling is required and RT-MACS, using the models in Fig. 3, finally provides the basis for that capability.

Given that this is the case, the range of possible fracture geometries corresponding to different levels of confinement is shown in Figure 4(d). Designing and analyzing such a fracture treatment would consist of bounding the fracture within the limits of acceptable best and worst case estimates. If the fracture pressure can be history-matched with greater certainty, it would be possible to determine the best estimate of final fracture dimensions. The dominant parameter determined by this history-match is the confining stress contrast: other parameters, such as fluid leak-off coefficients may be determined by applying established techniques (e.g. Ref. 8) to mini-frac or post-frac shut-in data. The corresponding length of proppant transport is shown in Figure 4(e), in which the limits of no containment and high containment are shown. An overview of fracture geometry and associated job schedule information is also shown in colour displays used in the field, which cannot be reproduced here.

The critical final estimates are those for fracture width, height and especially length, as shown in Figure 4(d,e). Once the propped length and width of fracture is known, calculations can be made for oil or gas production (Ref. 3); a further advantage of RT-MACS is that this can be done at any stage during the job, so that decisions could be made to stop pumping (or change schedules) at any point in time. This has been found useful in a number of situations: for example, an impending screen-out was avoided, without failing design objectives, and a risky restart after equipment repair was foregone on the basis of adequate production from fracture length already created.

## Conclusions and Future Work

A comprehensive system (RT-MACS) for real-time monitoring, analysis and eventual control of hydraulic fracturing operations, has been designed, prototypes have been developed and the system has been tested on a number of conventional treatments in the field, hooking up to standard equipment without interfering with the job operational logistics. The immediate effect has been a clearer view of the fracturing process, with resulting strong on-site interaction between operators, service company personnel and other contractors or consulting personnel. Although some existing facilities (e.g. Refs. 7,8) also help to stimulate such interaction, it seems that RT-MACS provides a much more comprehensive analysis and therefore more reliable overview of the whole operation.

The system is now accumulating a great deal of experience, through such exposure to field conditions and input from knowledgeable personnel in the field; it is also storing a vast array of data from the many jobs which it monitors and analyzes. This data-base of scientifically processed data will help to establish good explanations of observed phenomena and good solutions to the many difficult problems encountered in a typical job. It will thus greatly assist operators and effectively represent the expertise of the many specialists on fracture who are now required to assist in effective job execution.

This accumulation of experience will be greatly accelerated by our development of a portable version of the system. This portable system now allows easy access (by airplane or car travel) to a much broader variety of jobs than were accessible to the large GRI main computer trailer. This will both broaden the data-base and also make it attractive for operating companies to have the RT-MACS service on most wells at low cost. In this way, the technology will be transferred very quickly to the industry.

This technology transfer should bring about dramatic improvements in the way jobs are done: equipment will be modified, instrumentation will be greatly improved and quality-control will be much better. As well, the effectiveness of fracturing treatments should be increased: once techniques are available to make reliable real-time estimates of underground fracture growth – thus achieving in the field what has already been proved possible in the laboratory (Ref. 6) – it will be possible to dynamically adjust the job scheduling as new information is received from the process itself. This adjustment, in turn, will require more flexible job logistics, automation and feedback control – as against the present desire to simply put away all the materials which are carried to the site.

The final outcome of all this technology development should, of course, be the achievement of more consistent increases in production from tight reservoirs and thus a more reliable return on investment. We believe that the facility described in this paper will soon reach such an expert status as to help in achieving that goal consistently.

## Acknowledgements

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## Figures

1. Overall layout of field equipment and interfaces with RT-MACS.
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- 2(b). Schematic of software configuration, for RT-MACS.
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- 4(b). Uphole pressure data acquired for Prairie Mast A-1, showing comparison of model vs. actual pressures; time n minutes.
- 4(c). Downhole pressure data acquired for Prairie Mast A-1; basic models results, with corrections for viscosity changes and proppant drag, are shown for comparison.
- 4(d). Model estimates for final hydraulic length, width and height, showing dependence on confining stress contrast and optimum choice from Figure 4(c).
- 4(e). Model estimates of proppant extent, variation with time and confinement; time in minutes.
- 4(f). Sample real-time display of job scheduling and overall status; fracture growth is shown for low confinement not actual stress distribution.

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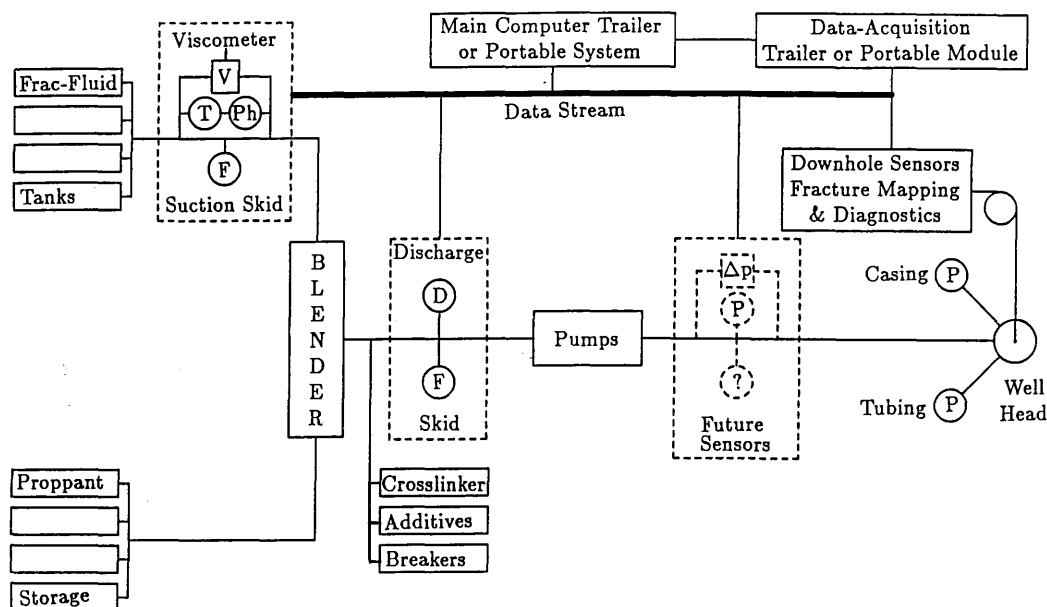


Fig. 1—Overall layout of field equipment and interfaces with RT-MACS.

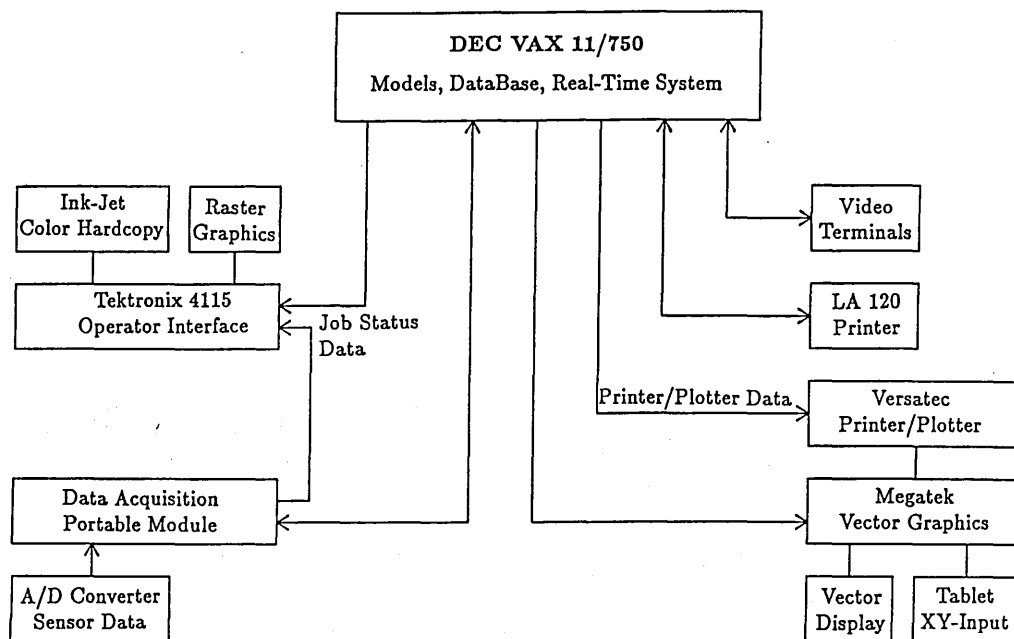


Fig. 2a—Schematic of hardware configuration, for RT-MACS.

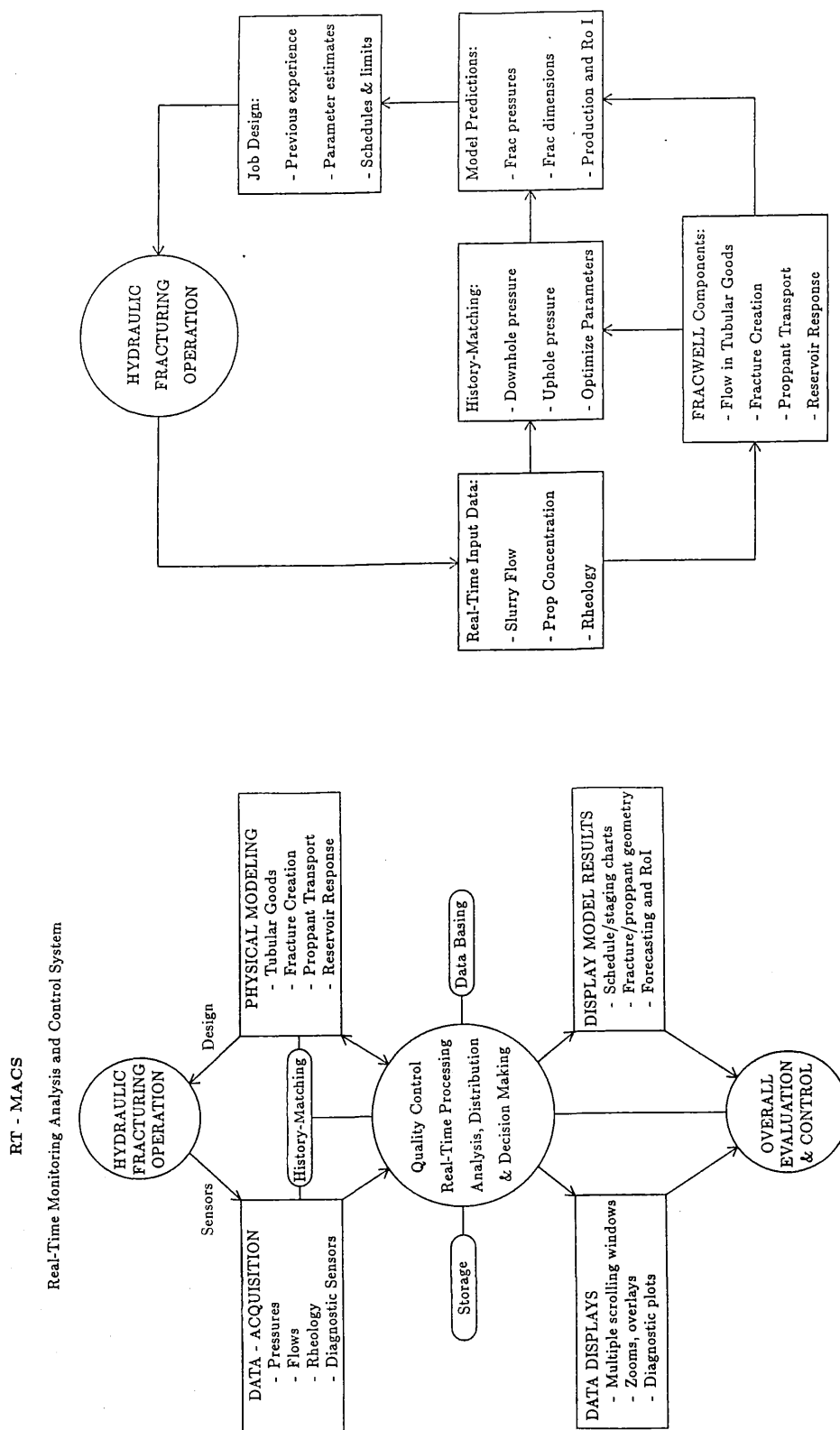


Fig. 3—Physical models of hydraulic process, flow diagram.

Fig. 2b—Schematic of software configuration, for RT-MACS.

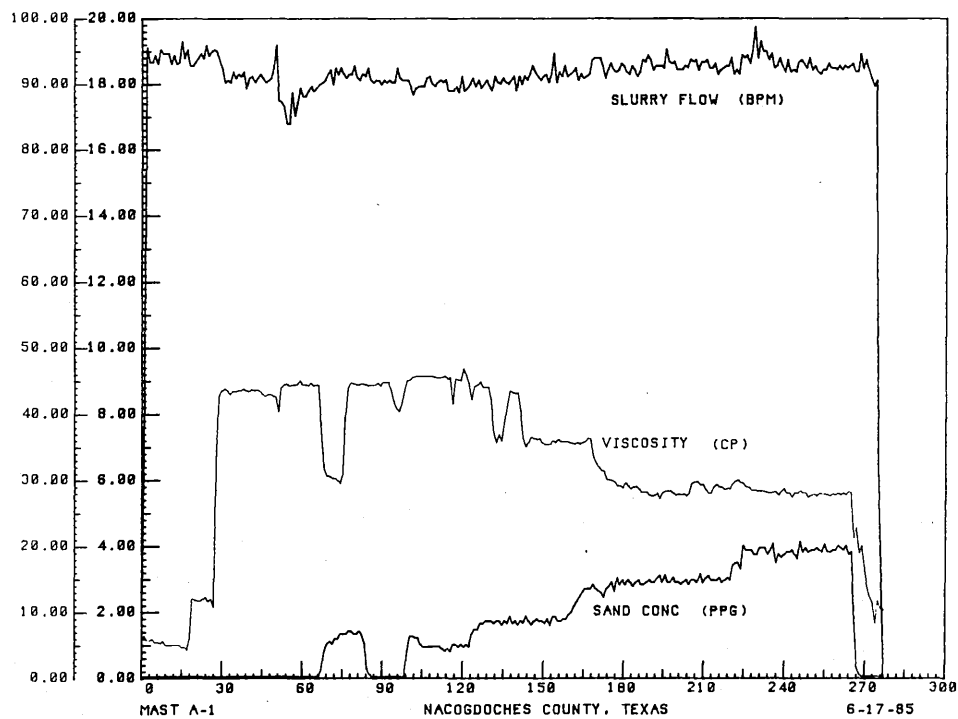


Fig. 4a—Flow, rheology, and proppant data for Prairie Mast A-1; time in minutes.

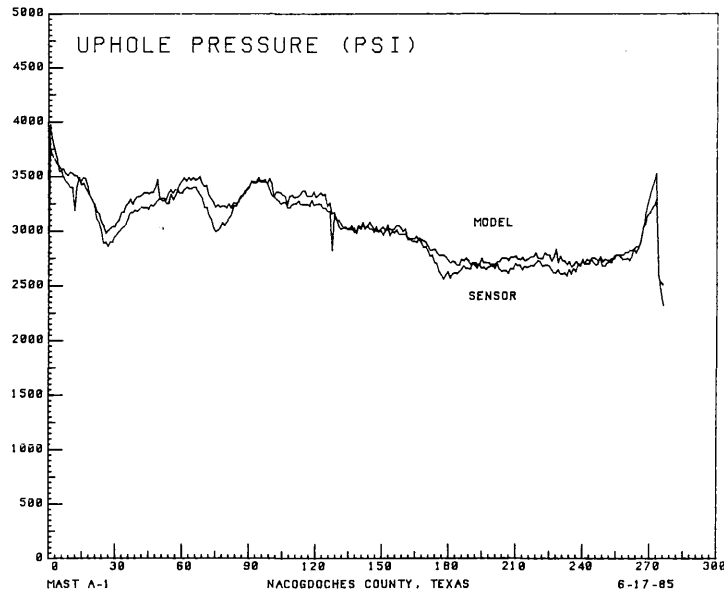


Fig. 4b—Uphole pressure data acquired for Prairie Mast A-1, showing comparison of models vs. actual pressures; time in minutes.

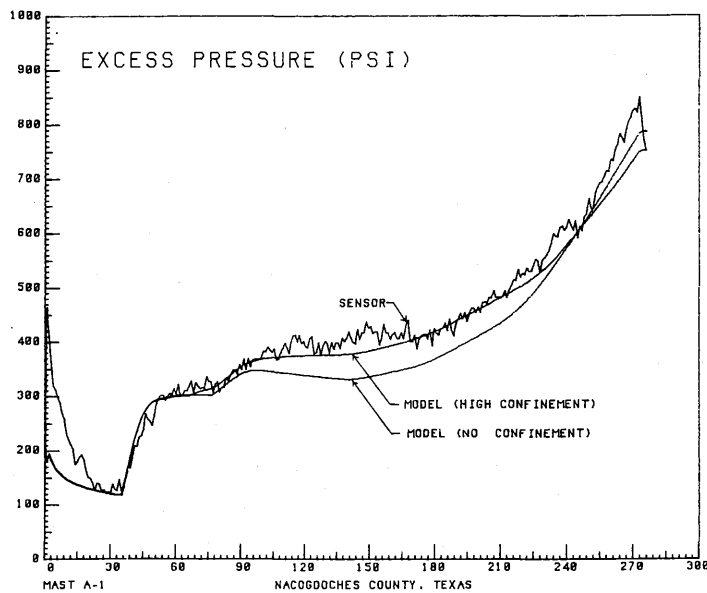


Fig. 4c—Downhole pressure data acquired for Prairie Mast A-1; basic models results with corrections for viscosity changes and proppant drag are shown for comparison.

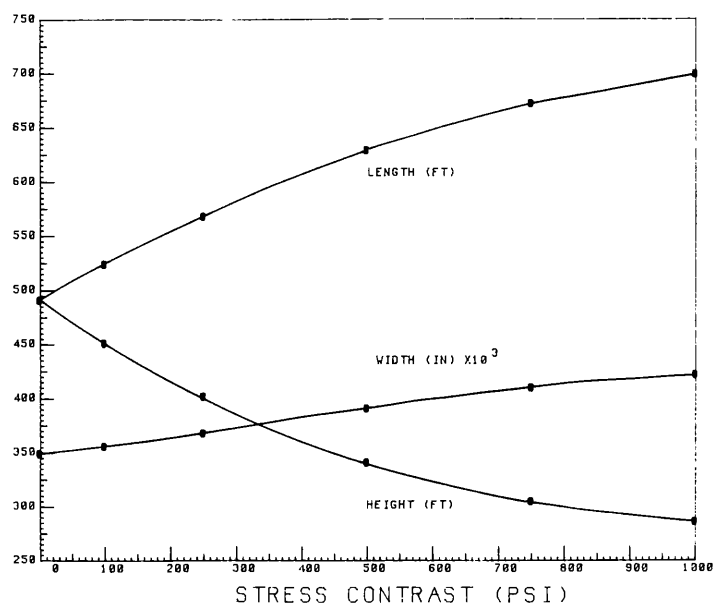


Fig. 4d—Model estimates for final hydraulic length, width and height, showing dependence on confining stress contrast and optimum choice from Fig. 4c.

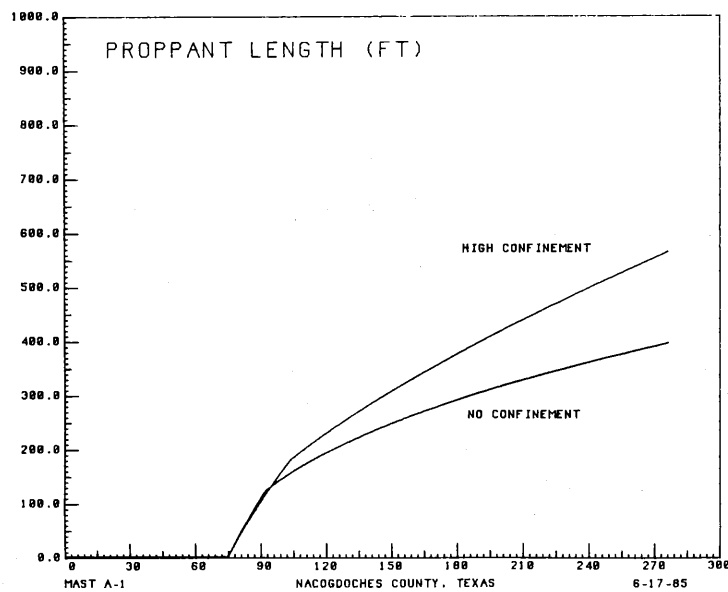


Fig. 4e—Model estimates of proppant extent, variation with time and confinement; time in minutes.

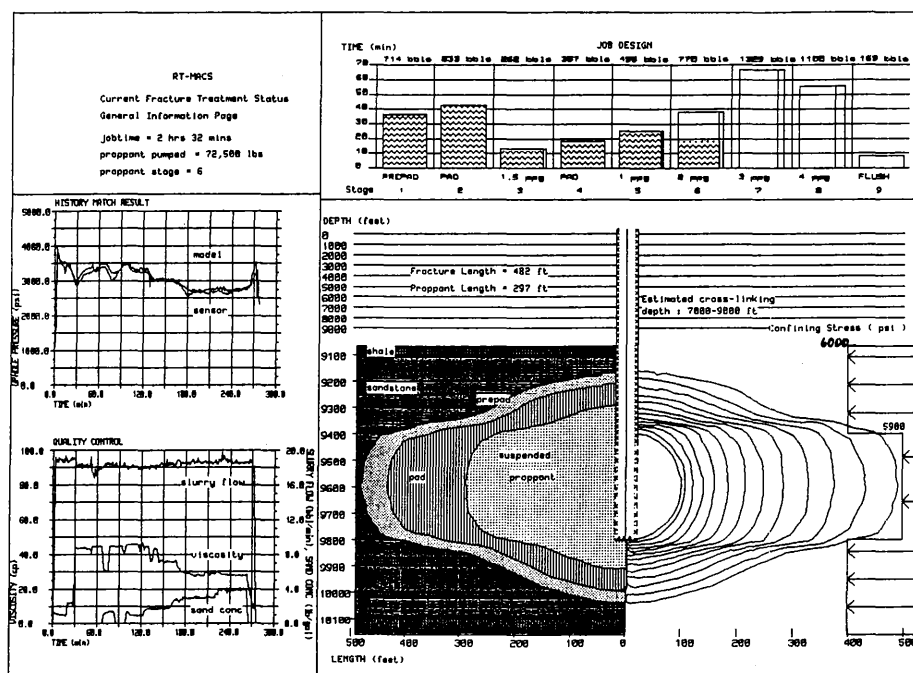


Fig. 4f—Sample real-time display of job scheduling and overall status; fracture growth is shown for low confinement not actual stress distribution.