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UNDERSTANDING THE EFFECT OF NATURAL FRACTURES ON THE HYDROFRACTURE STIMULATION OF NATURAL GAS RESERVOIRS.

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ABSTRACT

A finite element model for propagation of discrete fractures has been coupled to an implicit time-dependent fluid flow capability to be used as a predictive tool for hydraulic fracturing through sandstone lenses, as found in the Western Tight Gas Sands. Validation of the model is obtained by simulating controlled physical experiments. Our numerical model, FEFFLAP, was used to replicate the extension of a single-wing crack, driven through gypsum cement into a sandstone lens. Pressure-time records from the model and the experiments compare favorably.

INTRODUCTION

The Lawrence Livermore National Laboratory (LLNL) has pursued a program to further the understanding of the behavior of hydraulic fractures in the neighborhood of joints and interfaces in gas reservoirs [1]. These interfaces predominate in the Western Tight Gas Sands. Hydrofracture stimulation of the reservoirs often leads to shorter hydrofracs than are expected a priori. A common reason for this is expected to be the presence of natural fractures and geologic interfaces. Such discontinuities open up new flow paths for the injected fluids, create large frictional losses of potential, and prevent proppant intake over part of the wetted region. Our aim is to better understand the interplay between induced and natural fractures, so as to better estimate stimulation requirements.

To that end, a joint experimental and numerical modeling program has been pursued at LLNL. The numerical modeling efforts have resulted in the development and verification of the first transient model for fluid (gas and liquid) - driven fractures in jointed media under arbitrary stress fields. It is the implicit finite element program FEFFLAP (Finite Element Flow and Fracture Analysis Program), which can predict complex paths of fractures and the resulting flow in the network of natural and man-made channels.

The experimental work is performed in support of the numerical modeling, because without physical validation numerical models do not have credibility. We have completed scaled hydrofracture tests in blocks containing sandstone lenses, and tracked the fractures in a triaxial applied stress state. We will present the results of the physical experiments and the calculation of the tests with the numerical model.

Ultimately, we intend to provide forward modeling of the pressure-time records of hydrofractures in lenticular and jointed media, which can be used for stimulation diagnostics.

EXPERIMENTS

Three block tests (A,B,C) were performed to provide validation of the code. They involved sandstone tablets (lenses) embedded in gypsum cement (Figure 1). These experiments revealed the progression of fluid-driven fractures through the sandstone lenses [2]. The fractures were forced to initiate and propagate from a high pressure steel tube that was slotted on one side. Also, a wrap-around tape, extending out about 2 cm, kept the cement from entering the steel tube while pouring, and directed the crack into a sympathetic stress field. The fractures were constrained to travel unilaterally and fracture front was determined by resistance changes denoting the rupture of thin tungsten wires embedded perpendicular to the fracture plane. To maintain constant height, the fracture was contained in the vertical direction by wire mesh screens embedded near the top and bottom of the block, and perpendicular to the injection tube. The screens and sandstone tablet were anchored using piano wire stretched across the mold, and the gypsum cement was prepared carefully, according to pre-planned procedures of sifting, wetting, mixing, and pouring. To improve texture, the blocks were also vibrated for 20 minutes after pouring. After

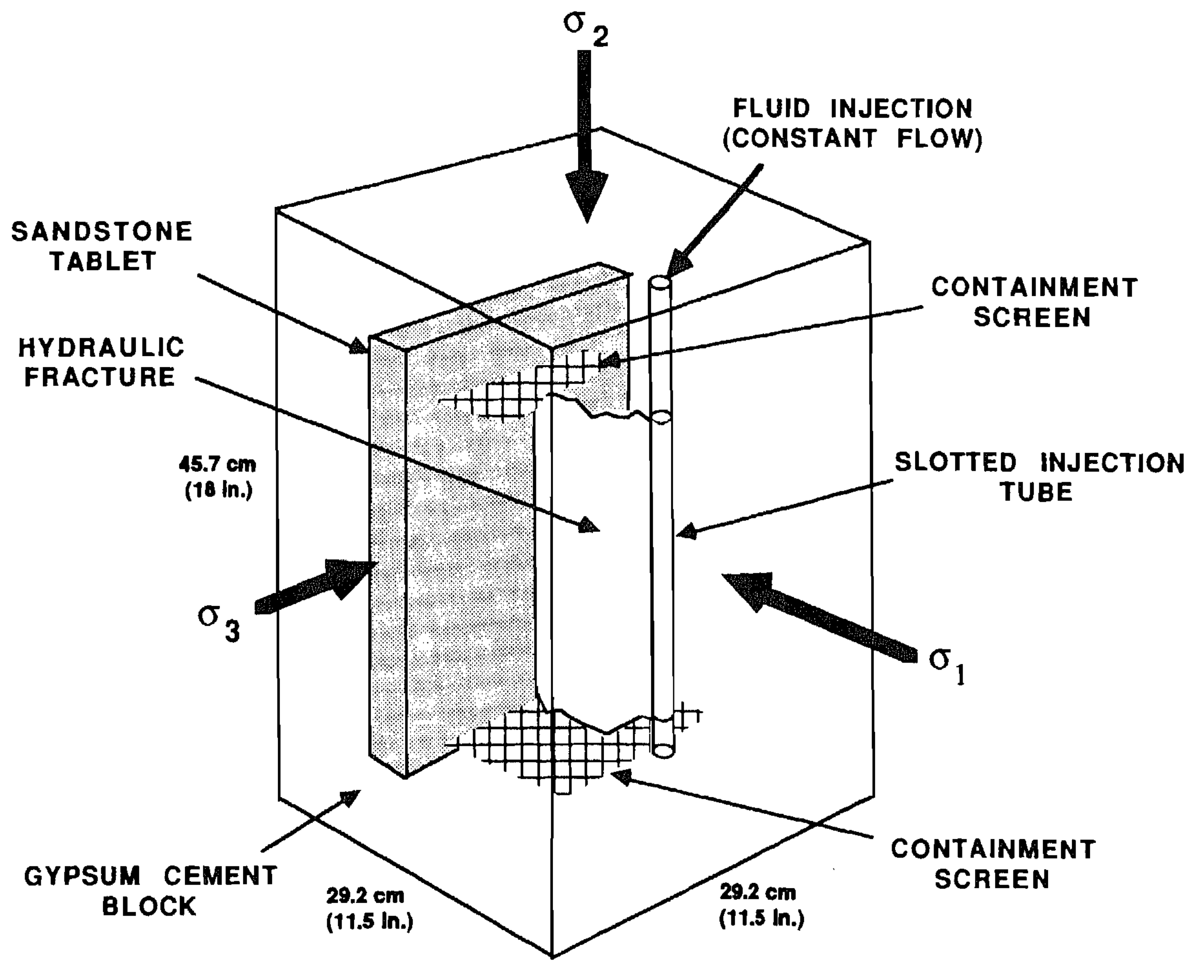

FIGURE 1. Schematic of block-fracturing experiments.

fracturing, the blocks were dissected to show the exact fracture outline as well as the extent of leakoff. Dissection of the blocks after testing showed them to be very homogeneous.

A light oil was used to propagate the fracture and was pumped at a steady rate with a ball-screw piston. The blocks were triaxially loaded for the duration of crack propagation. The injection pressure was closely monitored during the fracturing process. Figure 2, corresponding to test B, is given as an example to provide data for comparison with calculations. Crack velocity was estimated from the breakage times of the embedded wires (points A and B on Figure 2).

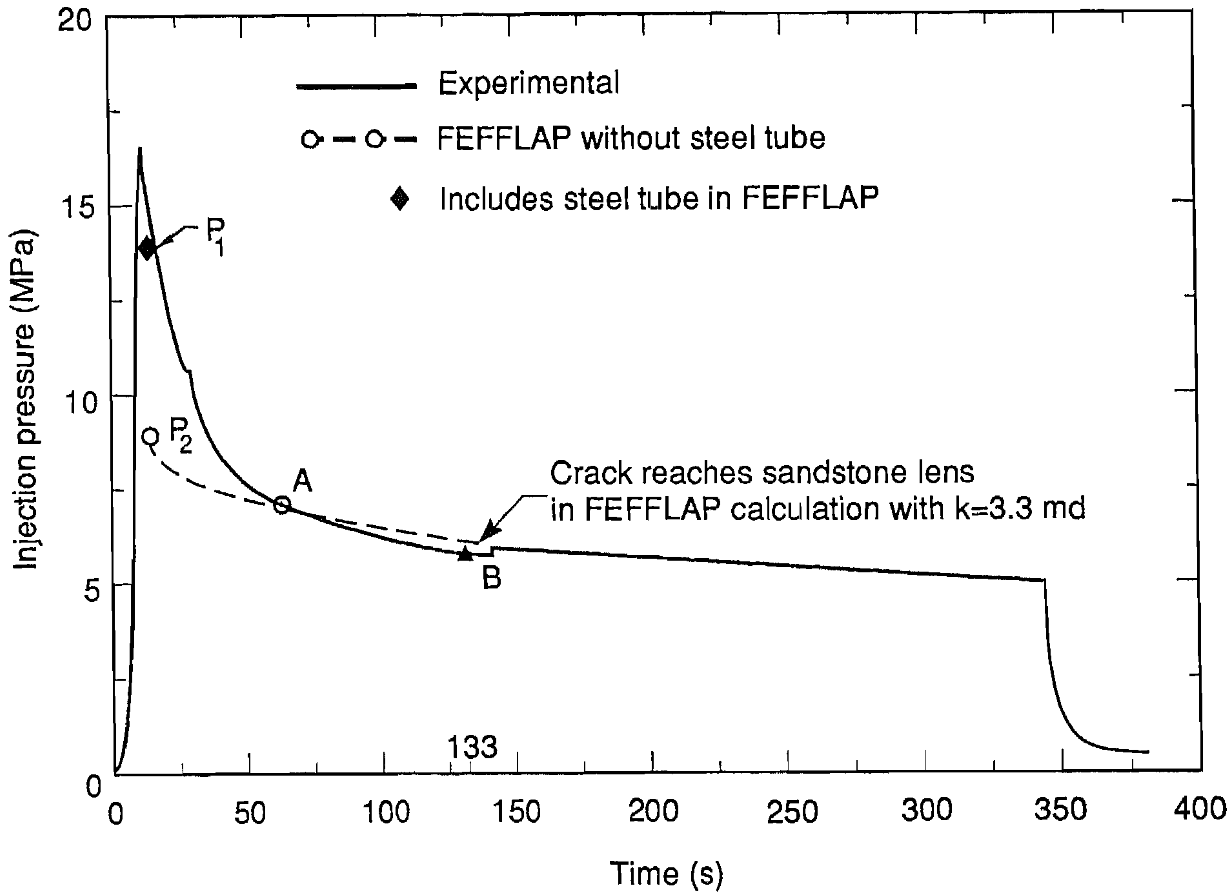

FIGURE 2. Pressure-time record for test B, and FEFFLAP calculated pressure-time history.

NUMERICAL MODEL

Central to our research is a finite element computer model called FEFFLAP which has been in a state of ongoing development and improvement [3,4}. Currently, we can model steady-state and/or time-dependent fluid flow in systems of natural and man-made fractures. The implicit time-dependent fluid flow algorithm in FEFFLAP is based on a model called FAST and includes fluid front and crack tip location, borehole pressure, pressure profile down the crack, heat loss, and leakoff [5]. It is coupled with a solid mechanics and fracture mechanics model for crack initiation and extension, and allows for nonlinear rock joint behavior. It contains logic to determine if fluid goes down an intersected joint and also whether the crack will penetrate through a geologic interface. The model can also be used for the analysis of gas fracturing [6].

The coupling between the elastic-fracture-joint model and the fluid flow model occurs in the following way: a crack is initiated or extended a given length. A time increment is estimated for the new crack length using the last crack tip velocity, or, in the case of initiation, initial velocity is estimated from the familiar Geertsma-DeKlerk solution [7].

Calculations then commence and iterations continue until stress intensity, crack shape, and joint evolution converge in the elastic model. In addition borehole pressure, pressure profile, and crack and fluid velocity converge in the flow model. The time increment is then iteratively recalculated using the average of the old and newly calculated crack velocities.

SEEPAGE MODEL FOR GYPSUM BLOCKS

The FAST model included in FEFFLAP was originally designed with leakoff in a saturated medium only. However, since the gypsum blocks were unsaturated, a liquid-into-gas flow model was added to FEFFLAP. We used a simple Darcy equation for flow velocity into the fracture wall:

$$v = \frac{dL}{dt} = \frac{k}{\mu}\frac{\Delta P}{L} \qquad (1)$$

where L = penetration depth
k = permeability
μ = fluid viscosity
t = time since exposure to fluid
ΔP = pressure gradient across L

Integrate to get the penetration depth,

$$L = \sqrt{2\ k\Delta P\ t/\mu} \qquad (2)$$

so that the velocity is known as a function of crack length. Leakoff velocity is then given by

$$v = \sqrt{k\Delta P/2\mu t} \qquad (3)$$

Because permeability (k) was not measured directly on the gypsum blocks, an initial value of k = 15 millidarcys was first adopted, based on reported values for hydrostone [8]. This gave a travel time to the tablet of 614 seconds, well outside of the values estimated from the experiments (75 s to 300 s). A second calculation was performed with a new k, chosen as 3.3 millidarcys; the travel time was then 133 s, well within the experimental range.

FEFFLAP ANALYSES

A cross section representing the gypsum block geometry was meshed for analysis with FEFFLAP and is shown in Figure 3. First, two calculations were performed without modeling the steel injection tube. The cracks were advanced to the times when they just reached the sandstone lens. Crack length at this point is 12.7 cm. Propagation was not continued through the lens in the calculation because the sandstone is more permeable and, in the experiment, we believe that the crack essentially stopped while fluid filled the lens and then the crack restarted. FEFFLAP has no flow storage capability at present to model such a phenomenon.

A pressure-time curve is generated from the successive crack tip locations during propagation. The curve is superimposed on the experiment record on Figure 2, for comparison purposes. Early pressures are not expected to compare well because of the steel tube and of the tape used to start and direct the fracture initially. In fact, the tip location next to the borehole where the crack initiates is not included in the curve because a pressure was not calculated due to coarseness of the finite element mesh there. Later pressures compare well with the experimental results.

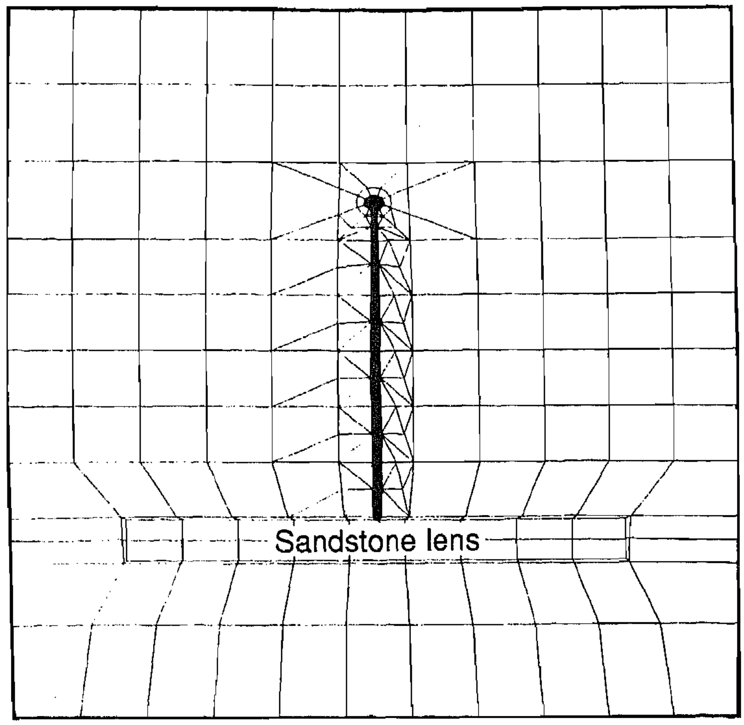

FIGURE 3. Finite element mesh of cross-section of crack propagating from borehole to sandstone lens in gypsum block.

The pressure profile down the crack, and the crack shape from the numerical results at 11.5 cm (largest crack length before interface is intersected) are shown on Figures 4 and 5, respectively; results are given for both permeabilities, k = 3.3 and 15 millidarcy. When the crack reaches 11.5 cm, the fluid front has just reached the tip of the propagating crack at the highest leakoff rate and was already there at the lower leakoff rate. However, at early times (not shown) the fluid did not reach the crack tip for either permeability. The pressure profile is slightly higher near the borehole for greater leakoff. For either value of k, pressure falls off rather quickly due to leakoff. Notice the ballooning of the crack, a feature of a single-wing crack in which the borehole constrains one end of the crack. This ballooning is not much influenced by the value of k.

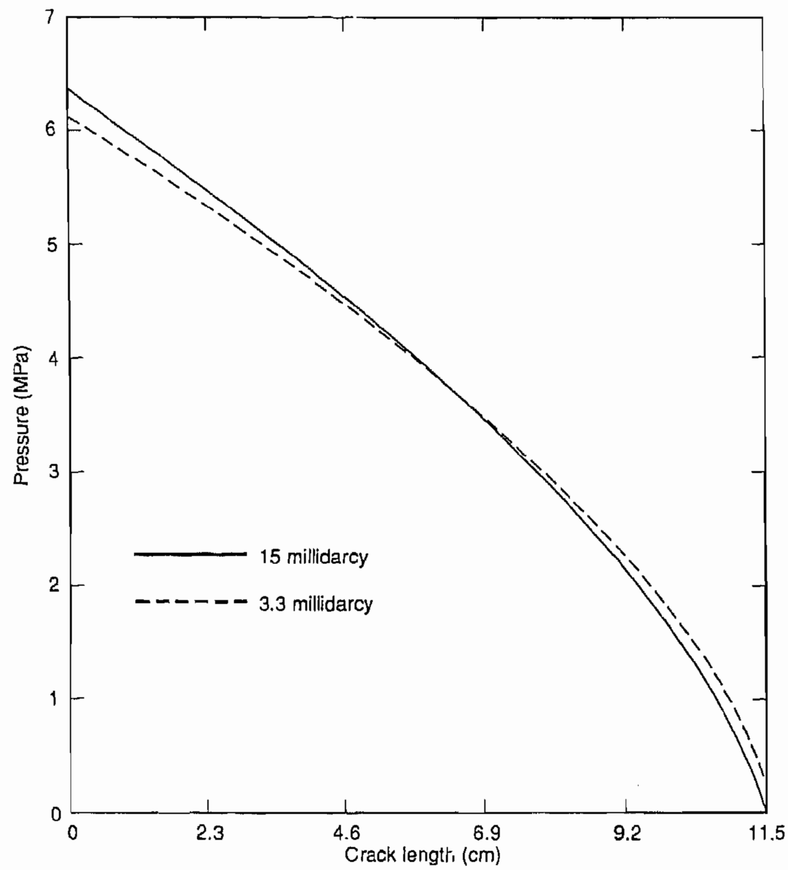

FIGURE 4. Pressure profiles as crack nears lens, for two values of permeability.

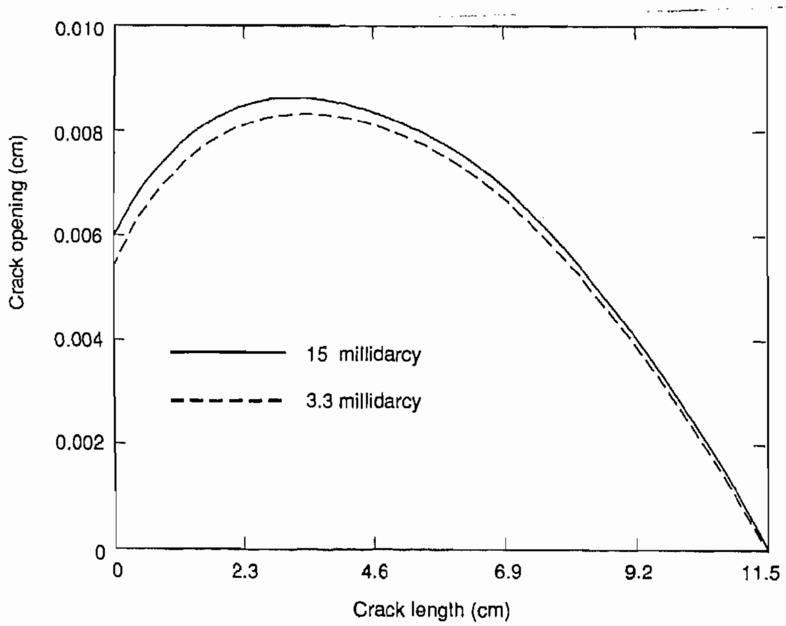

FIGURE 5. Crack shape as crack nears lens, for two values of permeability.

Figure 6 shows the calculated crack tip velocity as a function of crack length for k=3.3 millidarcys. Crack velocity decreases quickly as the crack extends and then decreases slowly. At later times the crack velocity agrees very well with the experimental value determined from points A and B on Figure 1 (where the wires broke). We noted that for k = 15 md the late-time crack tip velocity was slowed by a factor of 44, but fluid velocity at the inlet was slowed by only 3%.

Another calculation with k=3.3 md was performed, that included the elastic effects of the steel tube in the borehole In this case, the early crack extension required a higher pressure, Point P_1 on Figure 2, due to the higher stiffness of the tube. The pressure is in reasonable agreement with the experimental value. At late times the effects of the tube should be minimal.

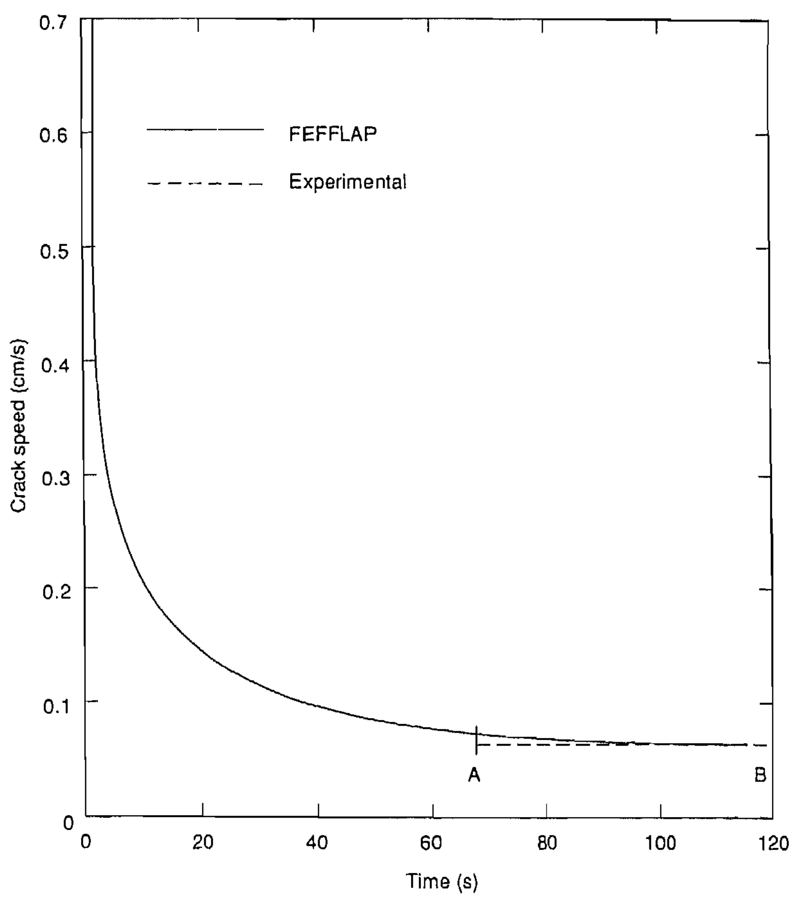

FIGURE 6. Decay of crack tip velocity as crack extends (k=3.3 md). The experimental value corresponds to an average value computed between points A and B on Figure 2.

Figure 7 contains the injection records for all three experiments. The circles indicate rupture of tungsten wires before the tablet, and triangles are for wires on the face of the tablet. A noticeable feature on at least two of the records is the pressure oscillations denoted as "irregular leak-off". We believe that they represent the lateral percolation of the fluid along the gypsum-sandstone contact, and the progressive debonding of that interface in small steps. A conspicuous feature is the jump in pressure when the crack front transects the first gypsum-sandstone interface. On Figures 7A and 7C this effect is quite pronounced, while on 7B it occurs also but to a lesser degree. This type of pattern on a pressure-time record is precisely that which could help a diagnostic of a field hydrofracture intersecting a gas lens.

SUMMARY AND CONCLUSIONS

A new finite element transient fracture propagation model was used to simulate a physical test of a hydraulically-induced fracture. The fracture originated from a small borehole in a gypsum block and intersected an embedded sandstone lens. Calculated pressure evolution and crack speed agreed well with the experiments. The numerical model also provided crack shape and the pressure profile down the crack at each crack length. This validation study is another step in our development of a model capable of describing fluid-driven fractures propagating through jointed rocks.

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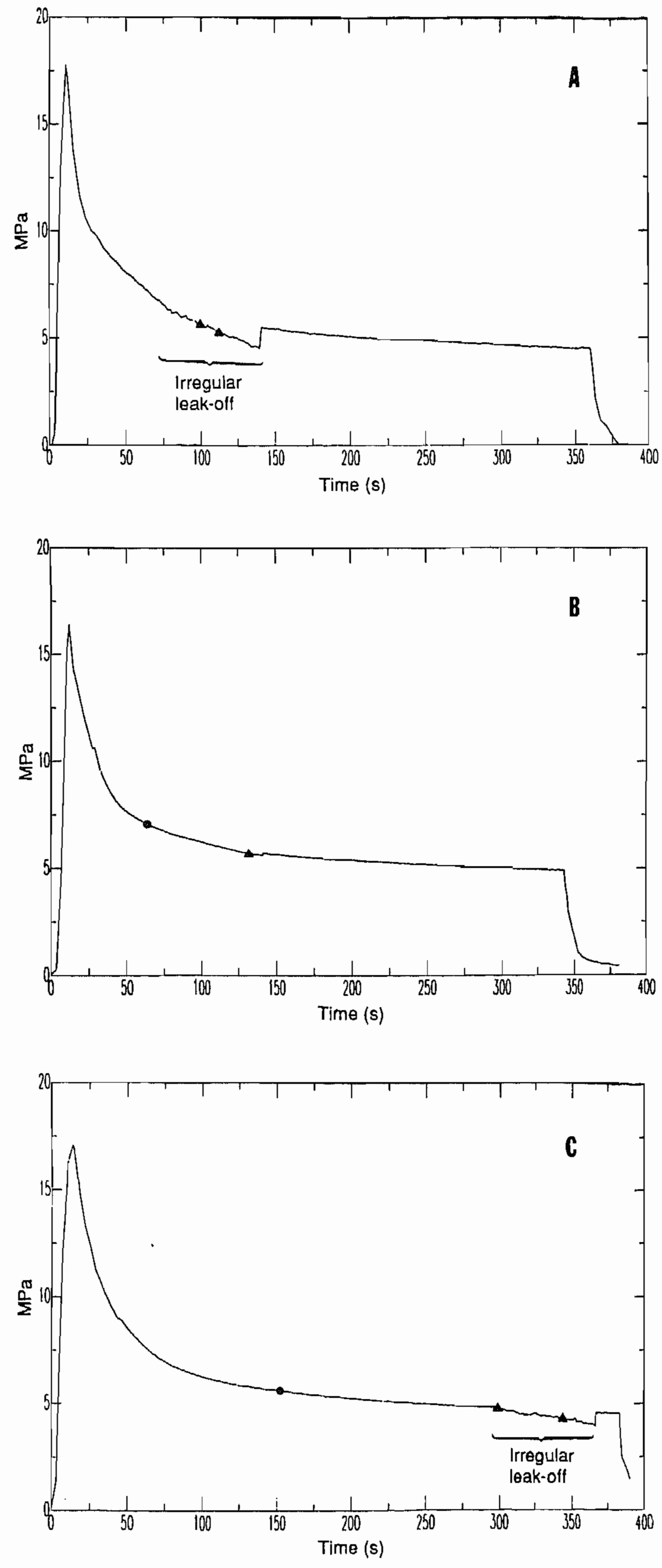

FIGURE 7. Pressure-time records for the three fracturing tests in gypsum blocks.

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