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PulsFrac™ Summary Technical Description

The PulsFrac™ computer program has been under development by John F. Schatz Research & Consulting, Inc. since 1990. It is an engineering and scientific software tool that simulates the dynamic response of a cased or uncased wellbore, its contents, and the porous rock formation around, including dynamic fracturing, to the energy released by gas-generating and stored pressure sources. Common applications are propellant tools, perforating guns, extreme overbalance events, dynamic underbalance, or combinations of these. Flow and fracturing, with durations in the range of a less than a millisecond to many tens of seconds, are simulated. Tools for importing and comparing with real-world data are provided. An illustration of the basic PulsFrac™ geometry is shown in Figure 1.

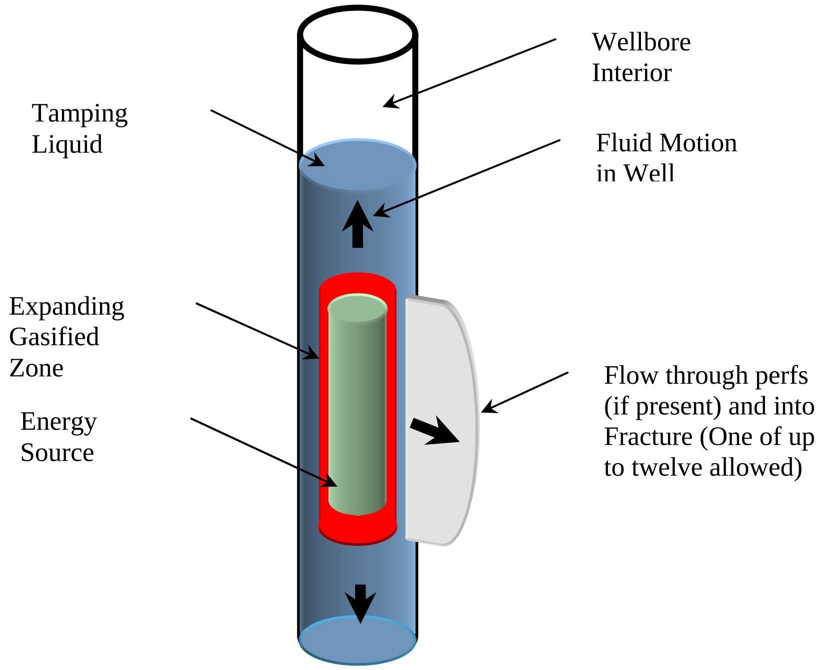


Figure 1. Basic wellbore and fracture geometry for PulsFrac calculations.

The PulsFrac™ program is based on energy release equations for the source, simultaneous coupled finite-difference solutions of the compressible Navier-Stokes equations for wellbore, perforation, and fracture flow, and solid rock mechanics equations for fracture initiation and propagation. No empirical curve fitting is used, although some approximations are used to solve lengthy equations where extreme accuracy is not necessary and computational speed is important. The underlying finite difference numerical scheme employs sophisticated gridding and stability schemes optimized for speed and accuracy. A full graphical user interface is incorporated to clarify results, enhance input and output, and allow for a wide variety of user-chosen options. Coding optimized for Windows 98 through XP and above is employed. Most of the actual operation of the PulsFrac™ software is apparent from the menus, toolbars, screen layouts, pop-up hints, and a full help system. Samples of typical screens are shown in Figures 2 and 3.

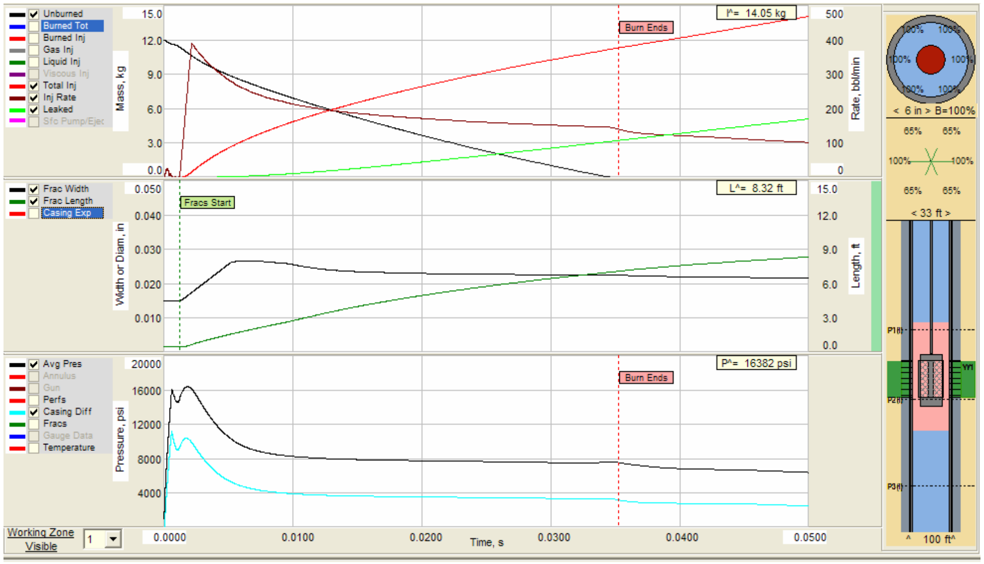
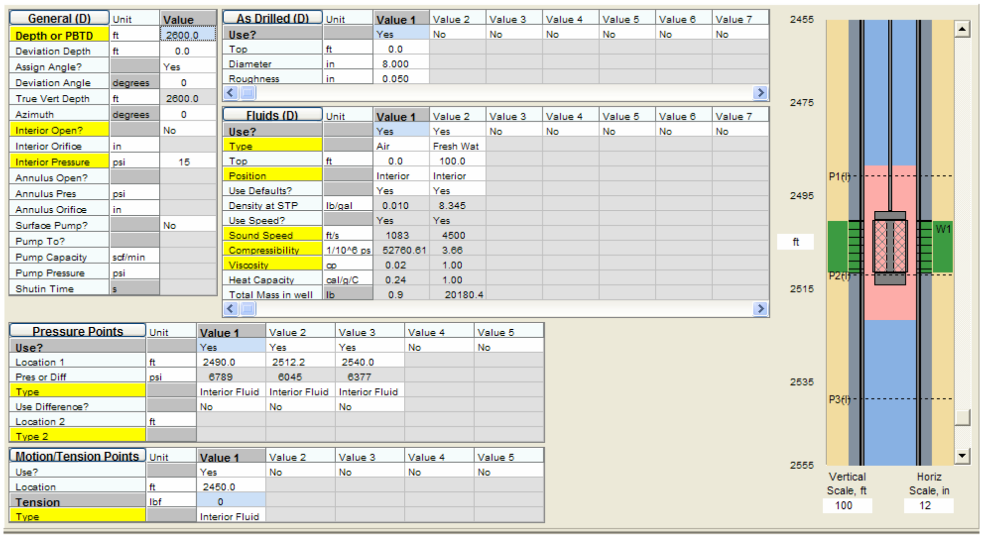


Figure 2. Typical PulsFrac™ graphical output screen. At top are mass plots. At middle are frac geometry plots. At bottom are pressure plots. All are vs. time. At right are perf breakdown and other geometric displays. This information is updated in real time as a run progresses.



General (D)	Unit	Value
Depth or PBTD	ft	2600.0
Deviation Depth	ft	0.0
Assign Angle?		Yes
Deviation Angle	degrees	0
True Vert Depth	ft	2600.0
Azimuth	degrees	0
Interior Open?		No
Interior Orifice	in	
Interior Pressure	psi	15
Annulus Open?		
Annulus Pres	psi	
Annulus Orifice	in	
Surface Pump?		No
Pump To?		
Pump Capacity	scf/min	
Pump Pressure	psi	
Shutin Time	s	

As Drilled (D)	Unit	Value 1	Value 2	Value 3	Value 4	Value 5	Value 6	Value 7
Use?		Yes	No	No	No	No	No	No
Top	ft	0.0						
Diameter	in	8.000						
Roughness	in	0.050						

Fluids (D)	Unit	Value 1	Value 2	Value 3	Value 4	Value 5	Value 6	Value 7
Use?		Yes	Yes	No	No	No	No	No
Type		Air	Fresh Wat					
Top	ft	0.0	100.0					
Position		Interior	Interior					
Use Defaults?		Yes	Yes					
Density at STP	lb/gal	0.010	8.345					
Use Speed?		Yes	Yes					
Sound Speed	ft/s	1083	4500					
Compressibility	1/10^6 ps	52760.61	3.66					
Viscosity	cp	0.02	1.00					
Heat Capacity	cal/g/C	0.24	1.00					
Total Mass in well	lb	0.9	20180.4					

Pressure Points	Unit	Value 1	Value 2	Value 3	Value 4	Value 5
Use?		Yes	Yes	Yes	No	No
Location 1	ft	2490.0	2512.2	2540.0		
Pres or Diff	psi	6789	6045	6377		
Type		Interior Fluid	Interior Fluid	Interior Fluid		
Use Difference?		No	No	No		
Location 2	ft					
Type 2						

Motion/Tension Points	Unit	Value 1	Value 2	Value 3	Value 4	Value 5
Use?		Yes	No	No	No	No
Location	ft	2450.0				
Tension	lbf	0				
Type		Interior Fluid				

Figure 3. Typical PulsFrac™ parameter input screen. Shown is the screen for wellbore parameters. Other input screens are available for full setup.

To properly represent dynamic behavior, coupled mathematical models of the following are included in PulsFrac™ coding.

- Multiple fluid types and phases (both in well and in fractures)
- Various energy sources, including propellants, perf guns, rapid gas expansion, and combinations of these
- Valves, orifices, and objects in the well, surface pressurization and ejection

- Flow into and breakdown of perforation tunnels
- Fracture initiation and propagation

Each of the models is briefly described below.

Multiple Fluid Types

The PulsFrac™ program allows for up to ten fluid types in the well and formation. These may be either liquid or gas, each with different properties. Fully compressible transient flow is calculated. A propellant or perforating gun is usually used to trigger compression and motion but is not required. All of the fluids may enter or exit the perforations and fractures. Thus, the fractures themselves may be driven by gas, liquid, or a combination of these. The multi-phase flow in the fractures is simplified by assuming that all phase velocities are equal (although they can vary along the length of the fracture) and is thus perhaps more properly termed “mixed-phase”.

Energy Sources

The energy source in PulsFrac™ computations can be a propellant tool, a perforating gun, a pressurized fluid, or a combination of these.

Propellant Tool

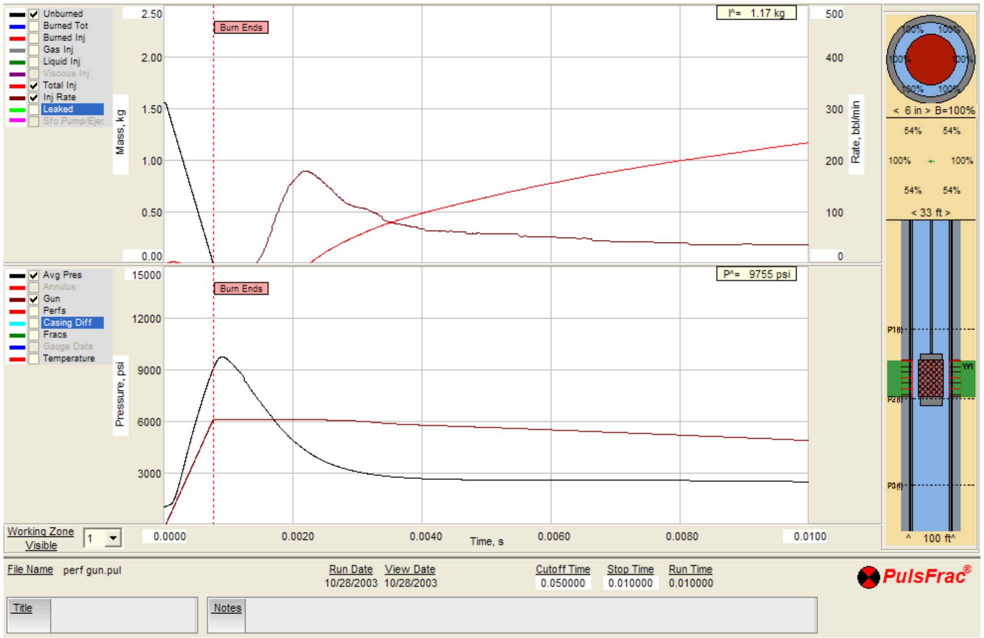
The PulsFrac™ program was originally developed for propellants. The propellant model uses accepted equations for the burn of a propellant and various parameters to allow for the energy content, burn rate, and geometric effects. Typically, the burn rate depends upon pressure. Some burn parameters can be obtained from the literature, as for gunpowders, but for the solid propellants in common field use, parameters are best established by comparing calculations with field data. The propellant ignition system is taken into account, as well as firing heads, carriers, and other inhole equipment.

Figure 2 (above) shows a hypothetical example of a 12 foot long by 2 inch diameter cylindrical propellant "stick" in a 5.5 inch pre-perforated cased hole with water tamp. Separate curves show the mass of tool remaining in the well, the mass entering the perfs and fractures, the dynamic leakoff, and the injection rate. Fracture width and length are shown. Pressure at the tool and the differential across the casing are shown. Peak pressure is about 16,000 psi and fracture length is about 8 feet in the longest of the 6 fractures, and about 5 feet in the others. Fractures are still growing at the end of the run at 50 ms. The tool burn itself takes about 35 ms. Many examples of this type have been calculated and matched to dynamic pressure records obtained in the field.

Perforating Gun

The perforating gun model allows the number, weight, and phasing of charges to be specified. Gun carrier dimensions, both external and internal, are adjustable. Burn/explosive parameters are set both for the detonating cord used to ignite the charges and the charges themselves. A gun efficiency is assigned to allow a choice of the amount of remnant gas expansion energy available after the jet has dissipated. Finally, the gun is allowed to ignite in the appropriate time sequence along its length.

Figure 4 shows an example of a PulsFrac™ run with a 12 ft perforating gun (3-3/8 in diameter, 6 spf in 5-1/2 casing) in water tamp. Since the gun response is very rapid, the run illustrated extends to 10 ms only. The gun ignition is over in less than 1 ms. During that time, peak pressure in the hole is about 10,000 psi. Of course, the actual peak pressure within the perforating jets can be in excess of 100,000 psi, but the software here is showing the average pressure in the working zone resulting from remnant gaseous energy, which has been distributed among the gas and liquid phases surrounding the gun.



Working Zone Visible 1

File Name perf gun.pul

Run Date 10/28/2003

View Date 10/28/2003

Cutoff Time 0.050000

Stop Time 0.010000

Run Time 0.010000

Figure 4. PulsFrac™ demonstration run with perforating gun.

This example shows that the PulsFrac™ program can calculate perforating gun ignition with very credible results. These pressures agree with recently obtained downhole high-speed field recorder observations. Such comparison with field data has shown that the model results vary with gun parameters (charge weight, etc.) as one actually observes.

Valves and Other Equipment

Some jobs require detailed calculations of pressure reflections and other effects caused by equipment or geometry variations in the hole. For example, extreme overbalance treatments are frequently executed with a pressure-actuated valve emplaced above the working zone. After the working zone is isolated, the well is pumped with gas, possibly through tubing, from the surface. When the valve actuation pressure is reached, the valve opens and surge flow begins. The valve may also be connected to or associated with a pressure-actuated firing head which ignites a perforating gun or other equipment, such as a combined perforating-propellant gun. PulsFrac™ can handle any of these situations.

Perforation Tunnels

PulsFrac allows gases and liquids to pass into perforation holes using dynamic choke flow equations. After that, an explicit model of tunnel behavior is used, as shown in Figure 5. Each tunnel is surrounded by a damaged zone with assigned thickness, Young's modulus reduction factor, and damaged Poisson's ratio. As dynamic pumping occurs into the perforation tunnel, the pressure builds up and the hoop stress around the perforation eventually becomes tensile. Fracturing, when it occurs, is assumed to occur at the damaged/intact zone interface. This model is a simplified equivalent of assuming a plastic zone out to the point of brittle failure initiation, assumed to be at the damaged zone boundary. When the tensile hoop effective stress at this boundary exceeds the prescribed rock tensile strength, breakdown is allowed to occur. Then flow begins into rock fractures and these fractures coalesce and grow as before. Furthermore, since the stress concentration caused by the wellbore expansion is accounted for in PulsFrac, this failure will occur first at the base of the perforation tunnels, as observed in published laboratory studies. For this model, flow and failure are treated independently for each perf, depending on its position and the oriented stress upon it. In this way, perfs nearer the top of pressure source will break down first, and perfs more nearly oriented in the stress-preferred direction will also break down first.

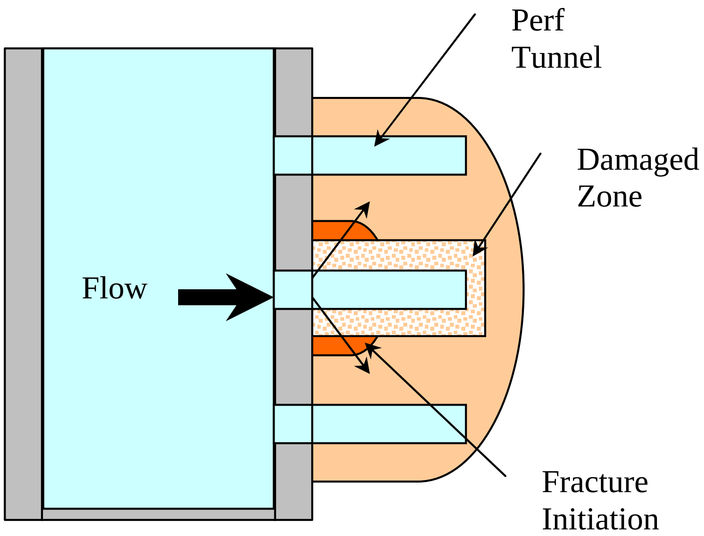


Figure 5. Perf damage model.

Fracture Propagation

PulsFrac propagates 1-12 fractures starting at the wellbore. For open holes, the fractures are aligned with the well and extend radially. For cased and perforated holes, the fractures are assumed to coalesce from the perf breakdown zones and then extend radially. Each fracture is affected by the oriented stress system as entered by the user, as well as the perf breakdown efficiency, for cased wells. Thus, even if a large number of fractures initiate, only those most preferred will propagate. This means that for very fast loading and relatively symmetric in-situ stresses, multiple fractures will propagate, while for slower loading and highly asymmetric stresses fewer (ordinarily only two) will propagate. A three dimensional model is not used, and upward and downward propagation are assumed to not exceed length. For example, a 12 foot high fracture wing that extends outward 6 feet will extend upward and downward at most 6 feet, with an approximately elliptical cross section. This approximation has been established with the help of laboratory work. Dynamic fractures cannot have unrestrained vertical growth as the time is not available.

Multiple fluid phases are injected into the fractures and move along radially according to the equations of compressible multi-phase fluid dynamics. Fracture width is calculated using the appropriate elastic equations. An effective stress model is used for the solid rock properties and leakoff is accounted for by a dynamic approximation. Fracture extension assumes "dynamic equilibrium" and uses mode I tensile failure within a classical fracture mechanics framework. Multiple fracture interacts to a set of simplified interaction rules. An illustration of fracturing concepts is shown if Figure 6.

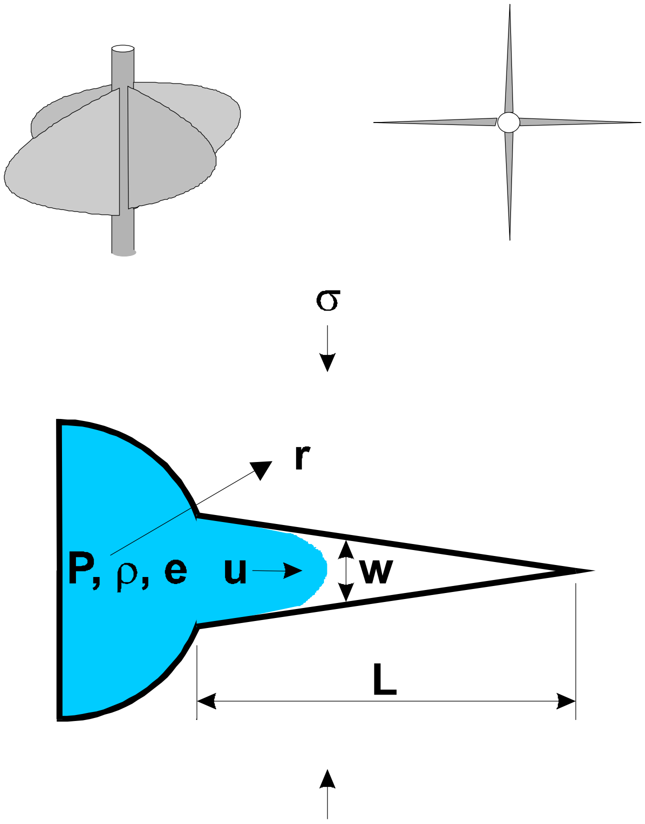


Figure 6. Fracture geometry and fracture mathematical parameters

Comparison of Software Results with Field Data using the StimGun™ Assembly

Most of PulsFrac's current features have been tested against actual field data, although many details have yet to be fully examined and confirmed. This is an ongoing process that will never cease as long as the technology is under development.

As an example of a field data test, a high-pressure dynamic recorder has been placed in a well with a combination perforating gun and propellant sleeve. This device is called the StimGun™ assembly. PulsFrac has been set up with the well parameters as obtained from the operator and the appropriate perforating gun and propellant dimensions.

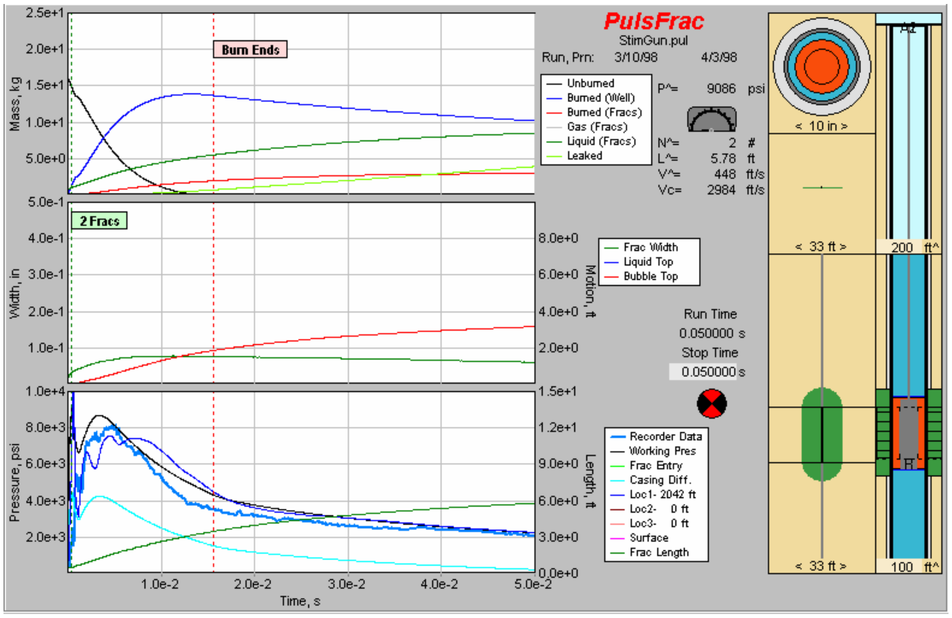


Figure 7. Comparison of PulsFrac run and field data for combined perforator-propellant tool, the Stim-Gun™ assembly.

Results to 50 ms are shown in Figure 7. The thicker line in the pressure graph is the high-speed recorder data. This tool was place just below the gun. Two calculated results are shown. The pressure curve with the higher peak is the average in the working zone. The curve with the lower peak is the simulation at the same depth as the recorder. The spike at about 1 ms is the perforating gun ignition. The subsequent broader peak is caused by the propellant burn. In this case, two fractures to 5.8 feet are calculated.

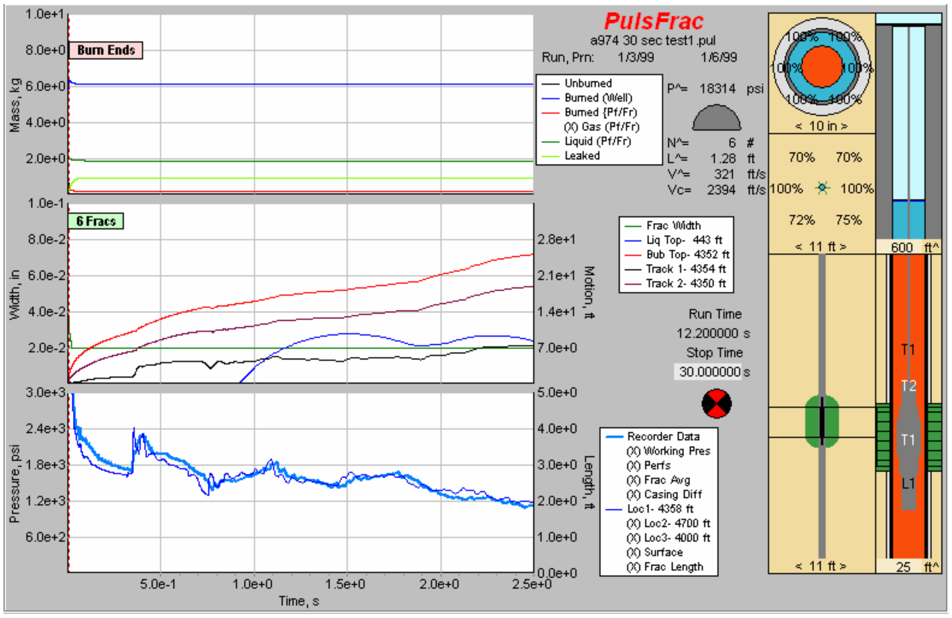


Figure 8. Comparison of PulsFrac run and field data to long time (2.5 s).

A second StimGun example is shown in figure 8. Here, we emphasize long-time results, which may be used to determine surface motion, ejection, packer responses, etc. The run shown is a short tool in a long carrier placed relatively near the bottom of the well. The run and data are shown to 2.5 s. Tamp was oil above working zone and water below. This situation sets up a fairly complex series of constructively and destructively interfering waves. The figure does not show the pressure within the tool burn, but only the subsequent response at the recorder. The PulsFrac calculation (thin blue line) follows the data (thick blue line) very well, even to most of the small fluctuations, showing that these features are real and not computational or instrument-related noise. In the full run (not shown), good agreement actually continues to 30 s. (the full duration of the data). To achieve this computational accuracy, the geometry of the hole and equipment must be entered into PulsFrac with great care.

Conclusion

The PulsFrac™ software is robust and can be used for a wide range of dynamic wellbore calculations. The sub-models contained within the program are physics-driven and rely on measured or estimated input parameters. Real-world data, when available after the fact, has been matched in most cases. However, because of the large number of parameters and variables represented by the real world, predictions made before data are available must always be made with care and tempered with professional engineering and scientific judgement.