ProTechnics

Expert's Corner

INTERVIEWS AND DISCUSSIONS WITH INDUSTRY EXPERTS

HYDRAULIC FRACTURING FROM MINE-BACK TO DIAGNOSTICS

Interview with Dr. Norman R. Warpinski

Expert's Corner is very fortunate to feature an exclusive interview with Dr. Norman Warpinski with Sandia National Laboratories in Albuquerque, New Mexico. He began his 27-plus year career at Sandia Laboratories studying hydraulic fracturing in "mine-back" tests conducted in tunnel complexes at the Nevada Test Site. From this early work Dr. Warpinski became a recognized expert in the fields of hydraulic fracturing, geomechanics, poroelasticity and in situ stresses.

Leveraging this expertise, Sandia National Laboratory partnered with the Department of Energy and the Gas Research Institute to exploit unconventional tight gas reservoirs through hydraulic fracturing. From these joint ventures, Dr. Warpinski has led many unique research projects, among them some of the first mine back examinations of actual hydraulically induced fractures at the Nevada Test Site in the late seventies and early eighties. He also helped lead the Multiwell Experiment (MWX) in Rifle, Colorado where actual fractures were created and then cored. More recently, he helped pioneer and develop much of the initial research and work on borehole micro-seismic and tilt technologies.

Dr. Warpinki's opinions and conclusions concerning hydraulic fracturing come from a true research perspective.

Q: ProTechnics
As the senior scientist at Sandia National Laboratories you have studied hydraulic fracturing from a very unique perspective. It is said that you have probably eyeballed more hydraulically created fractures than anyone in our industry. Would you describe for our readers some of the important work you have been involved with during your illustrious 27 year career?

A: Dr. Warpinski
I was lucky enough to have started working on hydraulic fracturing by doing "mine-back" experiments at the Nevada Test Site (NTS) back in the late 1970s. In those days, NTS was used for the testing of nuclear weapons and we had various tunnel complexes available for other types of work. We created fractures near interfaces, near faults and other discontinuities, near stress contrasts, in mostly unjointed rocks and in very jointed rocks, and under various other conditions. It was quite an eye opener to see how fractures really behave.

I was also fortunate to have worked on the DOE multiwell experiment in the Piceance basin. This was an eight-year experiment in the 1980s where we drilled three wells at very close spacing (a few hundred feet), took over 4,000 ft of core, conducted about 60 stress measurements in various sandstone, shale, and other lithologies, ran numerous drawdown, buildup and interference tests, conducted stimulations with various diagnostics, and basically worried those rocks to death. These experiments gave everyone involved a great appreciation for the complexity of the tight gas reservoirs in western US basins.

Thirdly, the GRI/DOE M-Site experimental work on fracture diagnostics in the mid-1990s helped pave the way for all of the fracture mapping that is being done today. That was probably the first place where we showed that fractures are often well contained, even in some cases where the stress contrasts are not that large.

In addition to this field work, I have built fracture models and various stress related models and also conducted assorted laboratory tests on fracture behavior, so I have a sincere appreciation of the difficulties with which modelers need to be concerned and some of the issues in lab testing. Currently I am working primarily on microseismic and tiltmeter fracture mapping and related issues.

Q: ProTechnics
Currently much research and debate surrounds the issue of predictive fracture modeling. Would you comment on where you think the industry stands today and where it needs to go on this issue?

A: Dr. Warpinski
Actually, I think that our models are pretty good, with one primary exception that I will discuss later. In general, I see the biggest problem with fracture models to be one of getting reliable input data – the garbage-in, garbage-out problem as noted previously by Bob Barree. (Read his interview online at www.corelab.com/protechnics) Companies do not want to spend any money getting the data necessary to do a good job and, as a result, the models may not look very good.

There are three primary formation parameters that we need to know to do an adequate job of modeling a fracture. These include the

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Young's modulus of the layers, the stresses in the layers, and the leakoff (permeability) characteristics of the formation.

I see very few cores being taken, so presumably engineers are relying on the dipole-sonic log to provide the rock property data. Given that we need a static Young's modulus that can be used for determining the width of a vertical crack (e.g., we need the horizontal compliance), it would be very surprising to me if the dynamic Young's modulus obtained from vertical velocities in highly transversely anisotropic materials like sedimentary rocks would be anywhere close to being correct. It is likely that one could use correlations to extract appropriate values for more well-behaved rocks, like sandstones, but such a process would be difficult for shales and other non-reservoir lithologies.

Worse yet, engineers are then using the same dipole log data to estimate stresses. Given the large number of the assumptions in the stress calculation and the minor issue that almost all of those assumptions are violated in major ways, it is hard to believe that we ever use the right stress data. Stresses in the reservoir interval can be calibrated with a diagnostic injection for closure stress, but there is no reason to believe that those results can be extrapolated to the non-reservoir rocks. Simply put, we do not know what the stresses are in the non-reservoir layers unless we measure them in at least a couple of wells in the field.

Finally, the size and performance of the fracture may be more dependent upon the leakoff than any other parameter. We have no way of accurately measuring the permeability of the formation without some kind of drawdown, buildup, injection, or interference test, but even those results are typically only representative of the permeability at one pressure. Since almost all rocks are naturally fractured and natural fractures are highly stress sensitive, it should be an expectation that the leakoff characteristics at fracturing pressures could be much different than those at the original reservoir pressure. Even analyses of falloff pressure after a minifrac are conducted at pressures lower than those at which the fracture is propagating. It is really necessary to analyze both the injection and the falloff behavior, use realistic stress and moduli, and then make it match.

Getting back to the models, if we had good modulus, stress and leakoff information, then the model predictions would likely be much more accurate. The one exception is in the reservoirs where we create non-planar fractures, such as the Barnett shale. We really have no good way to predict how that fracture is going to behave when we start injecting the fluid into a natural fracture network.

Of course, one way we get around all of these data and complexity issues is to use diagnostics to calibrate models. This is a reasonable approach that should work well in a given reservoir, but having accurate formation data improves this process significantly. The problem with the calibrated model is that we then need to do a few diagnostic tests in each reservoir, whereas we would rather be able to use the models directly.

Q: ProTechnics

Completion diagnostics is becoming a term of art in the science of hydraulic fracturing. What importance do you place on completion diagnostics and what level of importance do you believe it has played and will continue to play in fracturing optimization?

A: Dr. Warpinski

I think that diagnostics have a huge role to play in the following stimulation environments:

- Multiple zones where we need to know how many zones are being stimulated and/or how effectively they are stimulated
- Complex reservoirs where natural fractures, faulting and structure may result in unusual fracture behavior, anisotropy or orientations
- Tight rocks where well spacings are being constantly reduced and we need to optimize the spacing to maximize the resource
- Testing new stimulation concepts to see if they generate the effective fracture areas that we require
- New reservoirs where we would like to quickly assess stimulation results in order to best develop the reservoir

Since we continue to develop more and more marginal reservoirs in more and more difficult environments, I suspect that diagnostics will continue to increase in importance. Information on zones stimulated, fracture lengths, height growth and complex growth will always be important to the completion engineers.

Q: ProTechnics

In the course of the work performed at the M-Site in Colorado, which you directed, several hydraulically created fractures were actually imaged and cored. The resulting investigation of the cored fractures showed multiple parallel competing fractures at distance from the wellbore. Would you share the results of this work and relate it to the conventional wisdom of the single bi-wing fracture plane? How do these realities of complex geometries impact the mass balance equation of fracture geometry?

A: Dr. Warpinski

There have been several tests where fractures have been cored through or mined back and many parallel hydraulic fractures observed (the maximum so far is about 30 over a 4-ft interval at the Multiwell experiment), but we really do not know what exactly to do with multiple fractures yet. When I was doing mine-back experiments, we routinely saw multiple parallel fractures, but the biggest factor that I saw to account for this behavior was the presence of natural fractures in the rock. Those rocks with few natural fractures had few parallel hydraulic fracture planes. Those rocks that were highly naturally fractured had many parallel hydraulic fractures. The message that I took from those tests was: the more complicated the reservoir, the more complicated the hydraulic fracture. That made sense when you looked at the multiple fractures observed at the Multiwell experiment and the subsequent M-Site tests. Those rocks were naturally fractured (the only way they could possibly produce gas since the matrix permeabilities were submicrodarcy) and the natural fractures probably had a significant influence on the resultant hydraulic fracture complexity.

Ignoring the issue of how we generate so many fractures so close together, we can step back and ask what effect multiple fractures would have on a stimulation. First, having multiple fractures means having multiple walls, so friction would increase and the net pressure would need to be higher to accommodate the same rate in a single fracture. Second, there is potentially some additional storage in the multiple hydraulic fracture system, so our mass balance is altered in some uncertain way. Third, leakoff gets interesting with many sub-parallel fractures. Depending on the matrix permeability and reservoir fluid (gas, oil, or water), the initial leakoff could be many times higher than that of a single fracture because of the additional leakoff area, but may eventually decrease to rates that are very similar to a single fracture as the leakoff zones from individual fracture planes interact (leaving only the outermost fracture planes in contact with the reservoir as a whole). This behavior could produce a time-dependent leakoff that is difficult to assess or predict.

Our biggest problem is that we do not know how many of these multiple parallel fractures are actually effective, that is, actually take fluid. Many, if not most, of them may be some subsidiary fractures that really are not part of the fluid transport process and hence will have little impact on the behavior. Unfortunately, even a couple of effective fractures can alter the behavior significantly. At this time we have no way to predict if and how many effective multiple fractures are generated.

Q: **ProTechnics**

Radioactive tracers have been and are still the most widely used method to measure fracture height at the wellbore. Comparing tracer studies with fracture models, in some cases has led to differing opinions of the fracture height due to the premise that the fractures leave the wellbore in wells that are not perfectly vertical or have dipped beds. Please share with our readers your opinions regarding this debate. What has your extensive work with micro-seismic study proven in this area?

A: **Dr. Warpinski**

I really see very little downside to using tracers. Consider that tracers are

- inexpensive,
- easy to analyze, and
- provide useful diagnostic information when used with common sense.

The common sense part is the only issue. I would not consider tracers to be a reliable indicator of height growth if I was expecting a fracture height of 250 ft or greater in a wellbore that was deviated 5 degrees or greater, and initiated from a single group of perforations in the center of the interval. Likewise, if all fractures were 600 ft in height and initiated from single central points, then tracers might not be too reliable.

Most of the time, however, we are dealing with wellbore deviations of less than a degree and fracture heights that are on the order of 100 ft. Tracers should be perfectly adequate in such situations. Furthermore, the issue is not the total fracture height relative to the wellbore deviation. Rather, it is only the distance from the top perforation to the top of the fracture and the distance from the bottom perforation to the bottom of the fracture that are of concern. Fractures will initiate at each perforation that is open and then somehow join together (or maybe not join together) somewhere in the formation, so we can expect the fracture to be at the wellbore at the top and bottom open perforations. It is from that point that they will begin to migrate away from the wellbore if there is a wellbore deviation. Even in thick formations, tracers can be quite reliable if there are several sets of perforations and some of these are near the top and bottom of the reservoir.

This is not to say that interpretation problems will not develop with tracers in some cases. However, if the completion engineer (1) knows his reservoir and the behavior of wells drilled in that reservoir and (2) uses tracers routinely, he should be able to sort through the results and determine what information is reliable and what should be discarded.

Q: **ProTechnics**

I often hear from fracture analysis engineers, "I didn't build any or very little net pressure during my fracture treatment, therefore I had uncontrolled height growth." Would you comment on some of the more important issues surrounding net pressure analysis as it relates to fracture height growth? And, is little or no net pressure build a true indicator of height growth?

A: **Dr. Warpinski**

My first question is always "How does he even know whether or not he built pressure using surface pressure readings?" Net pressure is a very useful diagnostic if we take it seriously, but I really question how good a job we really do. Most likely, they did not have a downhole pressure gauge so we are basing such deductions on surface pressure readings. Do we really understand the changing rheological conditions in the wellbore sufficiently well to get meaningful estimates of downhole pressure? Do we know how many perforations are open initially and how many will open or erode as pumping progresses? Did they do any diagnostic or calibration injections prior to the stimulation? Do we know the stresses well enough to understand what the net pressure changes (or lack of change) means?

Perhaps a net pressure evaluation using surface pressure is most useful if all treatments are pumped the same way, in the same size wellbore, through the same set of perforations for each fracture in a field. Then we can make meaningful comparisons between wells.

Furthermore, constant net pressure can be an indication of any of the following:

- Height growth

- Fissure opening
- Slippage at interfaces or other decoupling
- Perforation erosion
- Viscosity reduction
- Tortuosity (ugh) reduction
- And probably many other things

I would like a lot more information and/or other comparative data before trying to interpret surface net pressure behavior.

Q: ProTechnics

In the last ProTechnology, Summer 2004, the Experts Corner interview was with Dr. Michael Conway. The interview addressed the issues concerning the "Myths and Realities of Created Fracture Length versus Effective Fracture Length". Would you weigh in with your comments on this very important subject?

A: Dr. Warpinski

I would not disagree with anything that Mike Conway said and from a production perspective his approach is correct. From a stimulation diagnostic perspective, however, I would like to talk about three fracture lengths:

- Total fracture length, from which we can deduce if our volumes, rates, viscosities, additives, pad volumes, etc. are correct
- Propped fracture length, from which we can assess proppant transport and infer intrinsic fracture conductivity
- Effective productive fracture length, from which we can infer something about damage in the fracture and damage/degradation of the reservoir

Knowing all three of these, I can begin to make some assessment of how to optimize the fracture design to improve the effective productive fracture length, which really is the only thing that counts.

Q: ProTechnics

Noted fracture experts in our industry are starting to indicate that, not 100% of the time but very often fracture height is overestimated in our pre-and post-treatment simulations and analysis. We have historically seen with radioactive tracer studies that measured fracture height at the wellbore is often less than the modeled height. From your work at Sandia, specifically your work with micro-seismic and tilt studies, you have probably been involved in more real research and actual field measurements than anyone in our industry. Would you bring this vast knowledge into a summation that would address the premise of this question concerning fracture height estimation?

A: Dr. Warpinski

I do not think that there is any question that fracture height is overestimated in our models. We seldom see evidence of excessive height growth in tests where diagnostics are used. I have seldom seen fractures that are penny-shaped, and most of those are in very thick formations (like the diatomites in California) where radial fractures would be expected.

From my perspective, it is likely that we have not incorporated all of the relevant physics in the models, particularly with respect to a fracture criterion in a layered medium (crossing all those interfaces). In addition, we never measure stresses anymore (except in the reservoir itself), so we use the dipole sonic data that typically gives relatively small stress contrasts and leads to predictions of large amounts of height growth. Put these together and it is pretty easy to see why we will often overpredict fracture height.

I think that we are headed in the right direction with all of the diagnostic tests that are being performed. The results of these tests are now beginning to redirect thinking relative to height growth, with most everyone coming to the conclusion that height growth is less severe than we think. Nevertheless, let's not get complacent. There are still plenty of reservoirs where height growth can be a major issue and it is probably prudent to design for the worst case and optimize from there as we begin to learn more about fracture behavior in our reservoirs.

Q: ProTechnics

In closing, I would like to sincerely thank you for taking time to participate in this interview. One final question, where is the effort from Sandia National Laboratories going to be focused in the future as it relates to hydraulic fracturing optimization?

A: Dr. Warpinski

Sandia National Laboratories is a research organization that performs work for both government and industry, but we can only work on topics for we which we are directly funded. Unfortunately, I see little interest in hydraulic fracture research, primarily I think, because so much energy was expended on fracturing in the 1980s that people became tired of it and did not want to hear any more arguments about fracture models and perforation schemes and flowback schemes and all of the other issues that were proposed but never verified in any concrete way. The main focus of research now appears to be related to diagnostics and that is where I hope to stay engaged. Maybe we can start to do some of that verification now.

FOR A COPY OF THIS MANUSCRIPT AND OTHER PAPERS ON COMPLETION DIAGNOSTICS, WRITE TO WADE.HUTCHINSON@CORELAB.COM

This interview was previewed in the Winter 2004 / December issue of the ProTechnology newsletter. To download a complete version of this and other interviews, as well as other information on completion diagnostics, please visit our website at **www.corelab.com/protechnics**