RESULTS

Although spectacular advances in hydraulic fracturing, aka fracking, have taken place and many aspects are well understood by now, the topology, geometry and evolution of the crack system remains an enigma and mechanicians wonder: Why fracking works?

Fracture mechanics of individual pressurized cracks has been clarified but the vital problem of stability of interacting hydraulic cracks escaped attention. First, based on the known shale permeability, on the known percentage of gas extraction from shale stratum and on two key features of the measured gas outflow which are 1) the time to peak flux and 2) the halftime of flux decay, it is shown that the crack spacing must be only about 0.1 m.

Attainment of such a small crack spacing requires preventing localization in parallel crack systems. Therefore, attention is subsequently focused on the classical solutions of the critical states of localization instability in a system of cooling or shrinkage cracks. Formulated is a hydro-thermal analogy which makes it possible to transfer these solutions to a system of hydraulic cracks.

It is concluded that if the hydraulic pressure profile along the cracks can be made almost uniform, with a steep enough pressure drop at the front, the localization instability can be avoided. To achieve this kind of profile, which is essential for obtaining crack systems dense enough to allow gas escape from a significant portion of kerogen-filled nanopores, the pumping rate (corrected for the leak rate) must not be too high and must not be increased too fast.

Furthermore, numerical solutions are presented to show that an idealized system of circular equidistant vertical cracks propagating from a horizontal borehole behaves similarly. It is pointed out that one useful role of the proppants, as well as the acids that promote creation of debris in the new cracks, is to partially help to limit crack closings and thus localization.
To attain the crack spacing of only 0.1 m, one must imagine formation of hierarchical progressively refined crack systems. Compared to systems of new cracks, the system of preexisting un-cemented natural cracks or joints is shown to be slightly more prone to localization and thus of little help in producing the fine crack spacing required. The overall conclusion is that what makes fracking work, from the fracture mechanics viewpoint, is the suppression or mitigation of localization instabilities of crack systems, which requires achieving and maintaining sufficiently uniform pressure profiles along the cracks.

**Proposals Developed and Funded:**
Aside from the research results described above, this ISEN Grant helped the PI to develop two research proposals:

1) One to Los Alamos National Laboratory (LANL), which was granted as a subcontract with Department of Energy as the original sponsor (3 years at $90,000).
2) Another to the NSF Geophysics program, which is under review ($46,000 for 3 years). *Thanks to the ISEN Grant*, the PI was able to find a more effective approach and refocus the NSF proposal from shock fragmentation (which was found, computationally, to affect only insufficient volumes of shale) to localization and stability of hydraulic cracks, interaction with fluid flow in cracks, and diffusion of gas from nano-voids towards the cracks.

**Paper published (acknowledgment to ISEN given):**

This paper was downloaded >2000-times within 2 weeks of publication!

**Named, endowed and plenary lectures:**
The PI has by now received invitations for 5 named endowed university lectures and one plenary opening conference lecture on this subject.

**Funded Proposal:**
Los Alamos National Laboratory (LANL), NU subcontract No. 267313

**Develop and Numerically Test a Fracture Model for Fragmentation of Brittle-Frictional Material—Gas Shale**
Start date: 5/1/14. Three years at $90,000/year.

Only first year granted so far.

Original Sponsor: Department of Energy

**Proposal Under Review:**
NSF Proposal 1520737, submitted on 12/2/14 to NSF Geophysics Program

**Interactive Fracture and Fluid Mechanics of Fracking:**
Theory, Efficiency Optimization, Environmental Mitigation
Summary of the NSF Proposal:

**Motivation:** Despite the recent startling success of hydraulic fracturing, aka fracking, which has already made the U.S. self-sufficient in energy, major problems and challenging questions for basic research remain: 1) Only about 5%--15% of gas in the shale strata is getting extracted and the rest remains underground. 2) The environmental problems, though much less severe than those of the coal industry, are significant and must be mitigated. 3) Although the horizontal drilling and many other aspects of the fracking operation are highly advanced, the fracture mechanics of systems of interactive hydraulic cracks and interaction with the flow of pressurized fluid through the cracks is not yet understood. 4) Neither is, mechanics-wise, the gas transport from shale nanopores through the cracks and horizontal and vertical pipes to the surface drillpad. 5) A realistic material model for shale fracturing is unavailable.

**Objectives and Approach:** The goal is to make advances in all the aforementioned problems. The approach will be mostly theoretical, although some vital tests of the highly anisotropic constitutive and fracture properties of Marcellus shale will be carried out in collaboration with the Geology Department. The objective of enhanced gas recovery requires preventing localization of a growing system of distributed cracks into single large cracks. When many cracks are critical, i.e., are growing, the prevention of localization is a stability problem. Its solution will include the localization dependence on the distribution of pressure along the cracks, which depends on fluid flow, with the effects of viscosity and proppants. Since there must be billions of hydraulic cracks with a fracking stage, a smeared continuum model for the spread of hydraulic cracks will be formulated and a computer program developed. The diffusion of gas from the shale nanopores, through the cracks and pipes to the surface, will be described analytically and solved computationally, to assess the spacing of hydraulically created cracks. Limited model tests of hydraulic fracture localization will be also performed. The overall objective is to push the gas extraction percentage well above the current 5%--15% while using the same amount of fracking water, and thus reducing the amount of contaminated water per unit amount of gas, which will benefit the environment. Making fracture growth more distributed will also reduce seismicity and will have spinoffs for deep sequestration of various fluids where seismicity is a much bigger problem.

**Intellectual Merit:** The modeling and prediction of fracking is one of the toughest unresolved problems of solid mechanics. What makes it particularly difficult are its interdisciplinary aspects, including the interaction of fracture mechanics with fluid flow in cracks and open rock joints, and with diffusion of gas from the kerogen filled nanopores in shale, and the stability problems of crack localization in a large system. All the previous work considered the fracking water to be incompressible, but its compressibility is in fact an order of magnitude higher than that of shale and presents a challenge for a stable mathematical model. So does a stable computational approach for a large interactive crack system and identification of its localization instabilities. Overcoming these problems would be a significant advance in basic research on theoretical and applied mechanics.

**Attachment:**
Powerpoint Slide on the main results