

Prof. A. R. Ingraffea

Dwight C. Baum Professor of Engineering Emeritus
Weiss Presidential Teaching Fellow
Cornell University

Background, Publications, and Projects Related to Hydraulic Fracturing, Methane Emissions, and Gas Pipeline Safety

PROFESSIONAL SOCIETIES

American Rock Mechanics Association/Foundation

- Founding Member
- Member of the Board, 1999-2003

International Society for Rock Mechanics

Society of Petroleum Engineers

AWARDS IN ROCK MECHANICS

National Research Council/U.S. National Committee for Rock Mechanics 1978 Award for Outstanding Research in Rock Mechanics at the Doctoral Level

National Research Council/U. S. National Committee for Rock Mechanics 1991 Award for Applied Research for the paper, "Simulation of Hydraulic Fracture Propagation in Poroelastic Rock with Application to Stress Measurement Techniques", co-authored by **TJ Boone**, *Int. J. Rock Mech. Min. Sci. & Geomech. Abstr.*, **28**, 1, 1-14, 1991.

International Association for Computer Methods and Advances in Geomechanics 1994 Significant Paper Award: One of Five Significant Papers in the category of Computational/Analytical Applications in the past 20 years, "A Numerical Procedure for Simulation of Hydraulically-driven Fracture Propagation in Poroelastic Media", co-authored with **TJ Boone**, *Int. J. Num. Analyt. Meth. in Geomech.*, **14**, 1, 1990.

INDUSTRY RECOMMENDED PRACTICE

Principal Author of American Petroleum Institute Recommended Practice: **API 1102** - Steel Pipelines Crossing Railroads and Highways

ARCHIVAL JOURNAL PUBLICATIONS

Bold Italics indicates student or post-doctoral fellow of Prof. Ingraffea

Bold indicates Oil&Gas industry scientist/engineer

1. Ingraffea AR, Heuze FE. Finite Element Models for Rock Fracture Mechanics. *Int. J. Num. Analyt. Meth. Geomech.*, **4**, 1980, 25 - 43.
2. Ingraffea AR, **Gunsallus KL, Beech JF, Nelson PP**. A Short - Rod Based System for Fracture Toughness Testing of Rock. ASTM STP 855: Chevron - Notched Specimens: Testing and Stress Analysis, 1984, 152 - 166.

3. **Boone TJ, Wawrzynek P**, Ingraffea AR. Simulation of the Fracture Process in Rock with Application to Hydro-fracturing. *Int. J. Rock Mech. Mining Sciences*, **23**, 3, 1986, 255 - 265.
4. **Boone TJ, Wawrzynek P**, Ingraffea, AR. Finite Element Modeling of Fracture Propagation in Orthotropic Materials. *Eng. Fract. Mech.*, **26**, 2, 1987, 185 - 201.
5. Ingraffea AR, **Barry A**. Analytical Study of Transmission, Distribution Lines under Railroads. *Pipe Line Industry*, October 1989, 34 - 39.
6. **Boone TJ**, Ingraffea AR. A Numerical Procedure for Simulation of Hydraulically - Driven Fracture Propagation in Poroelastic Media. *Int. J. Num. Analyt. Meth. Geomech.*, **14**, 1990, 27-47.
7. **Boone TJ**, Ingraffea AR, **Roegiers J - C**. Visualization of Hydraulically- Driven Fracture Propagation in Poroelastic Media Using a Super – Workstation. *J. Petroleum Tech*, June 1989, 574 - 580.
8. Heuze F, Shaffer RJ, Ingraffea AR, Nilson RH. Propagation of Fluid-driven fractures in Jointed Rock. Part 1 - Development and Validation of Methods of Analysis. *Int. J. Rock Mech. Mining Sci. & Geomech. Abstr.*, **27**, 4, 243 - 254, 1990.
9. **Boone TJ**, Ingraffea AR, **Roegiers JC**. Simulation of Hydraulic Fracture Propagation in Poroelastic Rock with Application to Stress Measurement Techniques. *Int. J. Rock Mech. Min. Sci. & Geomech. Abstr.*, **28**, 1, 1-14, 1991.
10. **Sousa J, Carter B**, Ingraffea AR. Numerical Simulation of 3D Hydraulic Fracture Using Newtonian and Power-Law Fluids. *Int. J. Rock Mech. Min. Sci. & Geomech. Abstr.*, **30**, 7, 1265-1271, 1993.
11. **Shah KR, Carter BJ**, Ingraffea AR. Hydraulic Fracturing Simulation in Parallel Computing Environment. *Int. J. Rock Mech. & Min. Sci.*, **34**, 3-4, Paper 282, 1997.
12. **Hwang CG, Wawrzynek, PA**, Ingraffea AR. On the virtual crack extension method for calculating the derivatives of energy release rates for a 3D planar crack of arbitrary shape under mode-I loading. *Eng. Fract. Mech.*, **68**:925-947, 2001.
13. **Hwang CG**, Ingraffea AR. Shape prediction and stability analysis of Mode-I planar cracks. *Eng. Fract. Mech.*, **71**:1751-1777, 2004.
14. **Hwang CG**, Ingraffea AR. Virtual crack extension method for calculating the second order derivatives of energy release rates for multiply cracked systems. *Eng. Fract. Mech.*, **74**:1468-1487, 2007.
15. Howarth RW, Santoro R, Ingraffea AR. 2011. Methane and the greenhouse gas footprint of natural gas from shale formations. *Climatic Change Letters*, doi: 10.1007/s10584-011-0061-5, 2011.
16. Howarth R, Ingraffea AR. Should Fracking Stop? Yes, It's Too High Risk. *Nature*, **477**, 271-273, 2011.
17. Howarth, R, Santoro, R, Ingraffea AR. Venting and Leaking of Methane from Shale Gas Development: Response to Cathles et al., *Climatic Change*, doi: 10.1007/s10584-012-0401-0, 2012.
18. Caulton D, Shepson P, Santoro R, Howarth R, Ingraffea AR, Sparks J, Cambaliza M, Sweeney C, Davis K, Lauvaux T, Stirm B, Belmecheri S, Sarmiento D. Quantifying Methane Emissions from an Area of Shale Gas Development in Pennsylvania. *Proceedings of the National Academy of Science*, April, 2014, doi:10.1073/pnas.1316546111.

19. Ingraffea A., Wells M., Santoro R., Shonkoff S. Assessment and risk analysis of casing and cement impairment in oil and gas wells in Pennsylvania, 2000–2012. *Proceedings of the National Academy of Sciences*. doi: 10.1073/pnas.1323422111, June 2014.

BOOK CHAPTERS

1. Ingraffea A R. Numerical Modelling of Fracture Propagation. Chapter 4 in Rock Fracture Mechanics, H. P. Rossmannith, editor, CISM Courses and lectures No. 275, International Center for Mechanical Sciences, Udine, Italy, Springer - Verlag, Wien - New York, 1983, pp. 151 - 208.
2. Ingraffea A R. Fracture Propagation in Rock. Chapter 12 in Mechanics of Geomaterials, Z. P. Bazant, editor, John Wiley & Sons, Limited, 1985.
3. Ingraffea A R. Theory of Crack Initiation and Propagation in Rock. Chapter 3 in Rock Fracture Mechanics, B. Atkinson, editor, Academic Press, Inc., 1987.
4. Ingraffea A R, **Boone T J**, **Swenson D V**. Computer Simulation of Fracture Processes. Chapter 22 in Comprehensive Rock Engineering, J. Hudson, Editor-in-Chief, Pergamon Press, Oxford, 1993.
5. Carter B J, **Desroches J**, Ingraffea A R, Wawrzynek P A. Simulating Fully 3D Hydraulic Fracturing. In Modeling in Geomechanics, Ed. Zaman, Booker, and Gioda, Wiley Publishers, pp 525-557, 2000.

REVIEWED PROCEEDINGS

1. Ingraffea, A. R., Heuze, F., Ko, H. - Y., "Fracture Propagation in Rock: Laboratory Tests and Finite Element Analysis," Proc. 17th U.S. Symposium on Rock Mechanics, Snowbird, Utah, 1976, 5C4 - 1, 5C4 - 6.
2. Ingraffea, AR., Heuze, F, Gerstle, WH., "An Analysis of Discrete Fracture Propagation in Rock Loaded in Compression," Proc. 18th U.S. Symposium on Rock Mechanics, Keystone, Colorado, 1977, 2A4-1, 2A4-7.
3. Ingraffea, AR., "On Discrete Fracture Propagation in Rock Loaded in Compression," Proc. of the First International Conference on Numerical Methods in Fracture Mechanics, A. R. Luxmoore and D.R.J. Owen, eds., Swansea, 1978, 235 - 248.
4. Ingraffea, AR., "The Strength - Ratio Effect in the Fracture of Rock Structures," Proc. 20th U.S. Symposium on Rock Mechanics, Austin, Texas, 1979, 153 - 169.
5. Ingraffea, AR., **Saouma, V.**, **Blandford, G.**, **Chappell, J.**, "Crack Propagation in Rock and Concrete Structures", Proc. International Symposium on Absorbed Specific Energy, C. Sih, E. Sgoboly, and H. Gillemot, Eds., Budapest, September, 1980, 207 - 221.
6. Ingraffea, A. R., Ko, H. - Y., "Determination of Fracture Parameters for Rock", Proc. of First USA - Greece Symposium on Mixed Mode Crack Propagation, National Technical University, Athens, Greece, August 18 - 22, 1980, G. C. Sih and P. S. Theocaris, Eds., Sijthoff & Noordhoff, Alphen aan den Rijn, the Netherlands, 1981, 349 - 365.
7. Shaffer, R., Thorpe, R., Ingraffea, A. R., Heuze, F., "Numerical and Physical Studies of Fluid - Driven Fracture Propagation in Jointed Rock," Proc. of the 25th U.S. Symposium on Rock Mechanics, Evanston, Illinois, June, 1984, 113 - 126.
8. Ingraffea, AR., **Wawrzynek, PA.**, "Modeling of the Fracture Process Zone in Rock," Rock Masses: Modeling of Underground Openings, Probability of Slope Failure, Fracture of Intact Rock, C. H. Dowding, Ed., ASCE, publisher, 1985, 151 - 157.

9. Shaffer, R. J., Ingraffea, A. R., Heuze, F. E., "An Improved Model for Fluid - Driven Cracks in Jointed Rock," Proc. of the 26th U.S. Symposium on Rock Mechanics, Rapid City, South Dakota, June, 1985.
10. Heuze, F. E., Shaffer, R. J., Ingraffea, A. R., "A Coupled Model for Fluid Driven Fractures," Coupled Processes Associated with Nuclear Waste Repositories. Ching - Fu Tsang, Ed., Academic Press, 1987, 655 - 662.
11. Shaffer, R., Heuze, F., Thorpe, R., Ingraffea, A. R., Nilson, R., "Models of Quasi - Static and Dynamic Fluid - Driven Fracturing in Jointed Rocks," Proc. of the 6th Int. Congress on Rock Mech., Montreal, Canada, G. Herget and S. Vongpaisal, eds, A.A. Balkema/Rotterdam, 1987.
12. **Thiercelin, M., Roegiers, J.C., Boone, T.J.,** Ingraffea, AR., " An Investigation of the Material Parameters that Govern Behavior of Fractures Approaching Rock Interfaces," Proc. of the 6th Intl. Congress on Rock Mech. Mon-treal, Canada, G. Herget and S. Vongpaisal, Eds., A.A. Balkema/Rotterdam 1987, 263 - 269.
13. **Wawrzynek, P., Boone, T.,** and Ingraffea, AR., "Efficient Techniques for Modeling the Fracture Process Zone in Rock and Concrete," Proc. of the Fourth International Conference on Numerical Methods in Fracture Mechanics, March 23-27, 1987, San Antonio, Texas, A. R. Luxmoore, D. R. J. Owen, Y. S. Rajapakse, and M. F. Kanninen, Eds., 473 - 482.
14. Shaffer, R. J., Heuze, F. E., Thorpe, R. K. Ingraffea, A. R. and Nilson, R. H., "Models of Quasi-Static and Dynamic Fluid- Driven Fracturing in Jointed Rocks," Proc. of the Fourth International Conference on Numerical Methods in Fracture Mechanics, March 23-27, 1987, San Antonio, Texas, A. R. Luxmoore, D. R. J. Owen, Y. S. Rajapakse, and M. F. Kanninen, Eds, 505 - 518.
15. **Boone, TJ.** and Ingraffea, AR.. "Simulation of the Fracture Process at Rock Interfaces," Proc. of the Fourth International Conference on Numerical Methods in Fracture Mechanics, March 23 - 27, 1987, San Antonio, Texas, A. R. Luxmoore, D. R. J. Owen, Y. P. S. Rajapakse, and M. F. Kanninen, Eds, 519 - 531.
16. Ingraffea, AR., **Boone, TJ,** "Simulation of Hydraulic Fracture Propagation in Poroelastic Rock," Numerical Methods in Geomechanics, G. Swoboda, editor, Balkema, Rotterdam, 1988, 95 - 105.
17. **Boone, TJ,** Ingraffea, AR., "Simulation of Fracture Propagation in Poroelastic Materials with Application to the Measurement of Fracture Parameters," Fracture Toughness and Fracture Energy: Test Methods for Concrete and Rock, Mihashi, H., Takahashi, H., Wittman, F., Eds., A.A. Balkema, Rotterdam, 1989, 325 - 344.
18. **Boone TJ,** Ingraffea, AR., "An Investigation of Poroelastic Effects Related to Hydraulic Fracture Propagation in Rock and Stress Measurement Techniques," Proc. of the 30th U.S. Symposium on Rock Mechanics. A. W. Khair, Ed., A. A. Balkema, Publisher, Rotterdam, 1989, 73- 80.
19. **Sousa JL., Martha LF, Wawrzynek PA.** and Ingraffea, AR., "Simulation of Non - Planar Crack Propagation in Three - Dimensional Structures in Concrete and Rock," Fracture of Concrete and Rock: Recent Developments, S. P., Shah, S.E. Swartz, B. Barr, Eds., Elsevier Science Publishing, New York, N.Y., 1989, 254 - 264.
20. **Morales H, Brady B,** Ingraffea AR, "Three-Dimensional Analysis and Visualization of the Wellbore and the Fracturing Process in Inclined Wells", Paper SPE25889, Society of

Petroleum Engineers Joint Rocky Mountain Regional Meeting and Low Permeability Reservoirs Symposium, Denver, CO, April 12-14, 1993.

21. **Carter B, Wawrzynek P**, Ingraffea, AR, "Hydraulic Fracture from the Interface of a Cased Wellbore", Rock Mechanics: Models and Measurements Challenges from Industry, Proceedings of the First North American Rock Mechanics Symposium, P. Nelson, S. Laubach, Eds., A. A. Balkema, Rotterdam, 185-192, 1994.
22. **Carter B, Ingraffea AR**, "Effects of Casing and Interface Behavior on Hydraulic Fracture", Computer Methods and Advances in Geomechanics, H. Siriwardane and M. Zaman, Eds., A. A. Balkema, Rotterdam, 2, 1561-1566, 1994.
23. **Carter BJ**, Ingraffea, AR., and Engelder, T., 2001, Natural hydraulic fracturing in bedded sediments: International Association for Computer Methods and Advances in Geomechanics: Annual Meeting, Tuscon Arizona. p. 1-10.
24. TD O'Rourke, **KB Burnham**, BM New, HE. Stewart, AR. Ingraffea, "Practice and Performance Record for Pipelines at Railroad and Highway Crossings", Pipeline Crossings, J. P. Castronovo, Ed., ASCE, New York, 248-262, 1991.
25. TD O'Rourke, HE Stewart, AR Ingraffea, S El Gharbawy, "Influence of Soil-Pipeline Stiffness on Bending Stresses from Surface Loading", Pipeline Crossings, J. P. Castronovo, Ed., ASCE, New York, 406-417, 1991.

EXTERNALLY FUNDED RESEARCH PROJECTS

1. "An Investigation into Mixed - Mode Fracture Propagation in Rock," National Science Foundation Research Initiation Grant ENG78 - 05402, 4/78 - 3/80, \$25,000, Principal Investigator.
2. "Laboratory Testing of the Crack - at - an - Interface Problem," Sandia National Laboratories Contract No. 13 - 5038, 5/79 - 5/80, \$42,000, Principal Investigator.
3. "Research in Fracture Mechanics", Exxon Education Foundation, 9/89-9/92, \$30,000, Principal Investigator.
4. "Numerical Investigations into Crack Propagation in Rock," National Science Foundation Grant CEE - 8316730, 6/1/84 - 5/30/86, \$150,000. Principal Investigator
5. "Influence of Perforations Upon Subsequent Hydraulic Fracturing," Digital Equipment Corp. and Dowell Schlumberger, 1/88 - 12/96, \$448,000. Principal Investigator.
6. "Computational Simulation of Hydrofracturing", NSF CISE Postdoctoral Associate Award for Dr. K. Shah. 11/95-10/97, \$46,200. Principal Investigator.
7. "Evaluation of Cased and Uncased Gas Distribution and Transmission Piping Under Railroads and Highways", Gas Research Institute, 11/86 - 1/94, \$ 3,602,035. Co-Principal Investigator. T. D. O'Rourke and H. Stewart, Co-Principal Investigators.
8. "An IGERT Training Program In Sustainable Energy Recovery From The Earth-Education At The Intersection Of Geosciences And Engineering". July 2010-June 2015, National Science Foundation, \$1,137,047. Co-Principal Investigator. Prof. Jeff Tester, Principal Investigator, Profs. Terry Jordan, Paulette Clancy, Co-PI's.