Anthony R. Ingraffea, Ph.D., P. E.

Consulting Structural Engineer

309 Cayuga Heights Road

Ithaca, New York 14850

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May 17, 2010

Law Office of Gary A. Abraham
170 No. Second Street
Allegany, NY 14706

RE: Cuttings Waste Disposal at Chemung County Landfill

Dear Mr. Abraham:

You asked me to review and comment on the subject of an April 6, 2010 report by CoPhysics submitted in this matter on behalf of New England Waste Systems of New York (NEWSNY), and the April 7, 2010 and May 18, 2010 memoranda submitted in this matter by Dr. Marvin Resnikoff. I find both Resnikoff memoranda to be accurate.

Whether the CoPhysics report is accurate is less important than whether it is relevant to this matter. As I understand the issue, NEWSNY is or will be disposing wastes from drilling sites in Pennsylvania extracting natural gas from the Marcellus shale formation, and there is concern that this waste may be radiologically contaminated such that it would be improper to manage it at a municipal solid waste landfill. There is no information in the CoPhysics report that allows the reader to determine whether the waste sampled and tested, as reported, originates from Marcellus shale. To appreciate the different levels of radiological contamination that can occur at different stages of development of a Marcellus shale well I offer the following characterization of the

process by which drill cuttings are generated at a Marcellus shale gas well, the nature of cuttings waste, and the processes that explain how the waste becomes concentrated with natural radioactivity in the shale. I also offer to testify on these subjects should the propriety of disposing cuttings waste be certified as an issue for further adjudication.

My background makes me particularly suited to comment on these subjects. I have over 30 years of research and development in the area of rock fracture mechanics, and for a period of over 15 years I helped to develop novel approaches for simulating the hydraulic fracture process in hydrocarbon wells, including horizontal wells such as those used to extract gas from the Marcellus shale. My work has received awards including 2 from the National Research Council. My most recent archival publication in this area was in 2000, and I continue to coordinate with Schlumberger the dissemination of my hydraulic fracture simulator created with their sponsorship. I have incorporated my rock fracture mechanics research into my teaching duties up to the present and continue to follow the manner in which the research field develops in response to information from the field, as Marcellus Shale gas exploration progress in Pennsylvania. My curriculum vitae is attached.

Development of a gas well in the Marcellus shale using vertical and horizontal drilling and high-volume, slickwater hydraulic fracturing occurs in three stages, each of which involves movement of fluids. The first stage involves a process of excavating the borehole, both vertical and horizontal, and readying the well for subsequent stages. For the upper reaches of the vertical segment of the borehole, in order to expel drill cuttings from the wellbore, stabilize the borehole, and to cool the drill bit, compressed air is forced into the inside of the drill string, up the annulus between outside of drill string and inside of borehole. In the rest of the vertical segment, below the level where fresh water might be encountered, and for the horizontal segment of the borehole drilling "mud," a mixture of water and proprietary chemical additives, is then also forced down the inside of the drill string, up the annulus between outside of drill string and inside of borehole. The purpose of utilizing drilling mud in this way is to carry drill cuttings to the surface, including Marcellus cuttings and associated naturally occurring radioactive materials (NORM) from the horizontal leg, and to lubricate and cool the drill bit, provide pressure to stabilize the wellbore

before casing and cementing, and to apply pressure to control the upward migration of formation fluids (e.g. blowout control).

Depending on total length of the wellbore and the geology, tens of thousands of gallons of drilling mud are typically required for a Marcellus horizontal and fracked well. This mud is continuously circulated from the surface, down the well string to the drill bit, and back to the surface. When it returns to the surface, some process must be used to remove the drill cuttings, so that the remainder of the mud can be reused. This process is called "dewatering". In Pennsylvania, active dewatering processes are applied to the collected used mud, and the dewatered waste is buried on site or transported offsite to a disposal facility.

During this first stage, formation fresh water can also be encountered during drilling of the upper reaches of the vertical segment of the wellbore. This fresh water can mix with compressed air and/or drilling mud when encountered.

The second stage of Marcellus shale gas extraction involves Hydraulic Fracture Stimulation ("fracking"), a process designed to increase the effective permeability of the target formation by fracturing it and/or opening its natural joints using fluid pressure. During the fracking action, fracturing fluid, a mixture of water, proppant (typically silica sand), and proprietary chemicals are forced down the production casing under high pressure. The purpose of fracturing the shale in this way is to provide an incompressible medium to transmit pressure from the wellhead to the target formation, thereby causing fractures and/or opening existing joints in the formation. The various additives provide fracture opening control, viscosity control, lubrication, corrosion control, bacterial growth control, wellbore and perforation cleanout. Depending on total fracture interval, Chesapeake (CHK) reports an average of 5.5 million gallons of fracturing fluid are used per well in their Pennsylvania operations. During this stage and, after the fracking action, flowback fluid comes back up the casing to the surface. Fluid from the flowback operation is a mixture of the fracturing fluid and formation brine [1], and various solids released from the Marcellus formation during the perforating, fracking, and flowback operations, including NORM. The volume of flowback fluid returned to the surface varies with well and the length of time before the production stage. Industry sources state that 10 to 100% of volume of fracturing

fluid is returned in first 30 days, but some of this is formation (extant) brine and its transported materials. This fluid is initially stored in a waste pit at the drill pad or, if the fluid is reused in subsequent fracturing action, in steel holding tanks.

The third and final stage involves capturing gas from a completed and stimulated well. However, there is a somewhat artificial boundary in time between the flowback operation and production stage. When an operator declares the well to be in production, fluids still coming back up the well are called "produced water" or "formation water." This produced "water" comes back up for as long as the well is in production, but usually at a decreasing rate. In fact, this produced "water" consists of fracturing fluid and formation brine, all carrying the same solids materials as the frack fluid during the flowback operation, including NORM. Over time, the concentrations of the various chemical and radiological components of this "water" change. As the well is developed, materials returned to the surface from the vertical segment decline and the returned materials originate more and more from the horizontal segment. It is unclear how much produced water returns to the surface. I am reliably informed that, over a few years, almost all of the fracturing fluid returns, along with whatever extant brines were in the fractured formation. This fluid is then stored in holding tanks on the drill pad until it can be transported to properly equipped treatment plants or deep injection wells.

On May 12, 2010, I spent about an hour on a CHK drilling pad near Towanda, Pa. I saw the drilling mud/cuttings process in action, and spoke with two of the personnel operating this process. Briefly, here is what I saw:
-- drilling mud, with cuttings, returning from up the well and being flowed though a shale shaker;
--the mud/cuttings being circulated through a set of separators wherein the cuttings and some of the mud were settled out;
-- this "settled" material was separated from much of the fluid portion of the mud/cuttings and placed in large, open steel bins;
--in the bins, more settling occurs, and the remaining mud separates out to the surface of this mixture;
--this mud is then skimmed out of these bins for reuse, leaving a wet cuttings residue.

I inquired of the mud manager how the wet cutting residue is finally dewater and was told these materials left in the bins are further processed by putting them through a device that aerates by blowing air through the materials as they are tumbled, resulting in a dry powder-like residue. This power-like residue is the cuttings ready for disposal in a landfill.

I trust you will find this information useful.

Sincerely yours,

Anthony R. Ingraffea, Ph.D., P.E.

[1] Brine occurs naturally in and around the Marcellus shale formation, owing to its origins in an ocean environment. Fracking the formation forces brine into the shale fractures, allowing the brine to leach naturally occurring soluble radionuclides and heavy metals out of the shale, where they become concentrated in the brine.

CURRICULUM VITAE

Anthony R. Ingraffea

Dwight C. Baum Professor of Engineering
Weiss Presidential Fellow
School of Civil and Environmental Engineering
Cornell University
Ithaca, N.Y. 14853 USA

GENERAL

Born: April 4, 1947, Easton, Pennsylvania, USA
Residence: 309 Cayuga Heights Road, Ithaca, N.Y. 14850
Telephone: Home 607-257-1104 Office 607-254-8844 or 5-3336 Cell 607-351-0043
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EDUCATION

University of Notre Dame
B.S., Aerospace Engineering, *Magna Cum Laude*, June 1969.
Polytechnic Institute of New York
M.S., Civil Engineering, Grumman Masters Fellow, June 1971.
University of Colorado/Boulder
Ph.D., Civil Engineering, May 1977, University Fellow: 1974, 1975, 1976.

AREAS OF EXPERTISE

Structural Engineering, Structural Mechanics, Computational and Experimental Fracture Mechanics, Microstructural Simulation of Fatigue and Fracture Mechanisms, Rock Mechanics, Numerical Methods, Engineering Education

PROFESSIONAL EXPERIENCE

June 1969 - June 1971

Grumman Aerospace Corporation. Bethpage, L.I., N.Y.
Rotating traineeship in the following areas: preliminary design on Navy F - 14; loads and dynamic studies, stress analysis, and final design on NASA Space Shuttle proposal. Two in - house technical publications.

July 1971 - June 1973

Peace Corps. Bejuma, Venezuela
County Engineer. Responsible for all technical services to a county of 40,000 people. Directed surveying, design, and construction of farmers' market, tourist hotel, and cemetery. Directed urban planning resource study. Co - directed urban renewal plan and data collection for section of state capital city.

September 1973 - August 1977

University of Colorado/Boulder
Department of Civil, Environmental and Architectural Engineering
Instructor for Courses:
Analytical Mechanics, Theoretical Fluid Mechanics
Teaching Assistant for Courses:
Mechanics of Materials
Materials Testing Laboratory
Research Assistant in Project: Constitutive Relations for Coal

September 1977 - June 1982
Cornell University, Department of Structural Engineering
Assistant Professor

September 1979 - July 1983
Cornell University, Department of Structural Engineering
Manager of Experimental Research

July 1982 - June 1987
Cornell University, Department of Structural Engineering
Associate Professor

August 1983 - August 1984
Lawrence Livermore National Laboratory Livermore, California
Visiting Research Engineer

January 1986 - September, 1986
Cornell University, Computer Aided Design Instructional Facility,
College of Engineering
Director

September 1986 - October, 1990
Cornell University, College of Engineering
Faculty Coordinator for Instructional Computing

July 1987 - Present
Cornell University, School of Civil and Environmental Engineering
Professor

September 1987 - April 1992
Cornell University, Program of Computer Graphics
Associate Director

October 1990 - October 1994
Cornell University
Director, NSF-Synthesis National Engineering Education Coalition

July 1993 - Present
Cornell University
Dwight C. Baum Professor of Engineering

October 1994 - October 1995
Cornell University
Associate Director, NSF-Synthesis National Engineering Education Coalition

December 1997 –August 2005
Cornell Center for Theory and Simulation in Science and Engineering
Associate Director
Coordinator, Computational Materials Institute

July 1998 – December 1999
Cornell University
Coordinator, Infrastructure Group, School of Civil and Environmental Engineering

November 2002-Present
Cornell University
Member, Graduate Fields of Mechanical and Aerospace Engineering

May 2004-Present
Wright Patterson Air Force Base/AFRL/Air Vehicle Directorate/Structures Division
Structural Sciences Center of Excellence
Visiting Scientist

August 2005 – July 2007
Cornell University
Acting Director, Cornell Center for Theory and Simulation in Science and Engineering

November 2005 – Present
Cornell University
Weiss Presidential Fellow

July 2006 – December 2007
Cornell University
Coordinator, Infrastructure Group, School of Civil and Environmental Engineering

August 2005 – Present
Cornell University
Co-Editor in Chief, *Engineering Fracture Mechanics*

AWARDS AND HONORS

- **3 - M Corporation Scholarship**, 1965 - 1969
- **Grumman Masters Fellowship**, 1969 - 1971
- University of Colorado **Graduate Fellowships**, 1974 - 1976
- Cornell School of Civil Engineering "**Professor of the Year**," 1977 - 78
- National Research Council/U.S. National Committee for Rock Mechanics 1978 **Award for Outstanding Research in Rock Mechanics at the Doctoral Level**
- Cornell College of Engineering "**Professor of the Year**," 1978 - 79
- Cornell School of Civil Engineering "**Professor of the Year**," 1981 - 82
- **Presidential Young Investigator Award**, National Science Foundation, 1984 - 1989
- **Dean's Prize for Innovation in Teaching**, Cornell College of Engineering, 1989.
- **Dean's Prize for Innovation in Teaching**, Cornell College of Engineering, 1991.
- 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 Dr. T. J. 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 T. J. Boone, *Int. J. Num. Analyt. Meth. in Geomech.,* 14, 1, 1990.
- The **NASA Group Achievement Award** for contributions, with former students Drs. Paul Wawrzynek and David Potyondy, to the Fuselage Structural Integrity Analysis Team, NASA Langley Research Center, 1996.
- The First **Society of Women Engineer's Professor of the Year Award**, Cornell College of Engineering, 1997.
- **J. P. and Mary Barger '50 Excellence in Teaching Award**, Cornell College of Engineering, 1997.
- The **MTS Visiting Professor Chair**, Department of Civil Engineering, University of Minnesota, May, 1998.
- **Aviation Safety Turning Goals into Reality Award**, NASA Airframe Structural Integrity Program Team, NASA Langley Research Center, with Dr. Paul Wawrzynek, 1999.
- **1999 Premier Award for Educational Software** for "Cracking Dams-HTTP://www.simscience.org", with Megann Polaha
- **Daniel Luzar '29 Excellence in Teaching Award**, Cornell College of Engineering, 2001.
- **Honor Award, University of Notre Dame,** College of Engineering, for "Significant Contributions to the Advancement of Engineering", 2002.
- **Weiss Presidential Teaching Fellow,** Cornell University, 2005.

- **George R. Irwin Medal**, American Society for Testing and Materials, 2006.
- **Richard J. Almeida Award, Project High Jump,** given each year to an individual whose dedication and contribution to High Jump have been extraordinary, 2008.
- **Fellow, International Conference on Fracture,** 2009, "For his pioneering contributions to the advanced computational simulation of fatigue and fracture processes leading to improved understanding for practical applications to integrity assessment of engineering structures" .

HONORARY/PROFESSIONAL SOCIETY MEMBERSHIP

Tau Beta Pi (1967 -
Chi Epsilon (1974 -
Sigma Xi (1977 -
American Academy of Mechanics (1988 -
American Society of Civil Engineers (**Fellow, 1991**)
Chairman, Committee on Properties of Materials (1983 - 1985)
Member, Committee on Finite Element Analysis of Reinforced Concrete
Member, Committee on Computer Applications and Numerical Methods
International Society for Boundary Elements
International Society for Rock Mechanics
Society for Experimental Mechanics
American Society for Testing and Materials
Committee E - 8 on Fracture and Fatigue
Committee D - 18 on Soil and Rock for Engineering Purposes
Committee C - 9 on Concrete
American Concrete Institute
Committee 446 on Fracture Mechanics
RILEM
Committee 90 - FMA on Fracture Mechanics Applications
Member, Committee 89 - FMT on Fracture Mechanics Testing
American Rock Mechanics Association/Foundation
Founding Member
Member of the Board, 1999-2003

PROFESSIONAL REGISTRATION

Colorado	PE No. 14837
New York	PE No. 081309-0
Alaska	Professional Fishing Guide

UNITED STATES PATENT

Number 481,826, Hand - held, direct reading, fully mechanical fracture loading device for short-rod/bar specimens

PROFESSIONAL JOURNAL EDITORSHIPS AND ADVISORY BOARDS

Co-Editor-in-Chief:
Engineering Fracture Mechanics, August, 2005-present

Editorial Advisory Board:
International Journal for Numerical and Analytical Methods in Geomechanics
Boundary Element Communications
Engineering with Computers
Engineering Computations
International Journal for Multiscale Computational Engineering

PUBLICATIONS

TEXTS EDITED

1. **Fracture Mechanics of Concrete: Material Characterization and Testing**, co - edited with A. Carpinteri, Martinus Nijhoff Publishers, 1984.

PUBLISHED IN TEXTS

1. Ingraffea, A R (co - author). Modelling of Reinforcement and Representation of Bond. Chapter 3 in **Finite Element Analysis of Reinforced Concrete,** State - of - the - Art report prepared by the Task Committee on Finite Element Analysis of Reinforced Concrete Structures, Structural Division, ASCE, 1982, pp. 149 - 203.

2. Ingraffea A R (co - author). Concrete Cracking. Chapter 4 in **Finite Element Analysis of Reinforced Concrete**. State-of-the-Art report prepared by the Task Committee on Finite Element Analysis of Reinforced Concrete Structures, Structural Division, ASCE, 1982, pp. 204 - 233.

3. Ingraffea A R. Numerical Modelling of Fracture Propagation. Chapter 4 in **Rock Fracture Mechanics**, H. P. Rossmanith, editor, CISM Courses and lectures No. 275, International Center for Mechanical Sciences, Udine, Italy, Springer - Verlag, Wien - New York, 1983, pp. 151 - 208.

4. Ingraffea A R, Saouma V. Numerical Modeling of Discrete Crack Propagation in Reinforced and Plain Concrete. Chapter 4 in **Application of Fracture Mechanics to Concrete Structures: Structural Application and Numerical Calculation,** G. C. Sih and A. DiTommaso, editors, Martinus Nijhoff Publishers, 1984.

5. Ingraffea A R, Gerstle W. Non - Linear Fracture Models for Discrete Crack Propagation. **Application of Fracture Mechanics to Cementitious Composites,** S. P. Shah, editor, Martinus Nijhoff Publishers, 1985, pp. 171 - 209.

6. Ingraffea A R. Fracture Propagation in Rock. Chapter 12 in **Mechanics of Geomaterials,** Z. P. Bazant, editor, John Wiley & Sons, Limited, 1985.

7. Ingraffea A R. Theory of Crack Initiation and Propagation in Rock. Chapter 3 in **Rock Fracture Mechanics**, B. Atkinson, editor, Academic Press, Inc., 1987.

8. Ingraffea A R, Gerstle W H, Perucchio R. Fracture Analysis with Interactive Computer Graphics. **Boundary Element Methods in Structural Analysis**, D. E. Beskos, Editor, ASCE, 1989, pp. 235 - 271.

9. Ingraffea A R, Sections 9.3, 12.3, 13.4, and 15.2, of **Fracture Mechanics of Concrete Structures: From Theory to Applications**, L. Elfgren, Editor, Chapman and Hall, London, 1989.

10. 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.

11. 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.

12. Ingraffea A R, Wawrzynek P A. Crack Propagation. In the **Encyclopedia of Materials: Science and Technology**, Elsevier Science, 2001.

13. Ingraffea A R, Wawrzynek P A. Finite Element Methods for Linear Elastic Fracture Mechanics. Chapter 3.1 in **Comprehensive Structural Integrity**, R. de Borst and H. Mang (eds), Elsevier Science Ltd., Oxford, England, 2003.

14. Ingraffea A R. Computational Fracture Mechanics. Volume 2, Chapter 11, **Encyclopedia of Computational Mechanics**, E. Stein, R. de Borst, T. Hughes (eds.) John Wiley and Sons, 2004, 2nd Edition 2008.

PUBLISHED IN JOURNALS

1. Ingraffea AR. Nodal Grafting for Crack Propagation Studies. *Int. J. Num. Meth. Eng.,* **11**, 7, 1977, 1185 - 1187.

2. Lynn PP, Ingraffea AR. Transition Element to be Used With Quarter - Point Crack Tip Elements. *Int. J. Num. Meth. Eng.,* **12**, 6, 1978, 1031 - 1036.

3. Ingraffea AR, Heuze FE. Finite Element Models for Rock Fracture Mechanics. *Int. J. Num. Analyt. Meth. Geomech.,* **4**, 1980, 25 - 43.

4. Ingraffea AR, Manu C. Stress - Intensity Factor Computation in Three Dimensions With Quarter - Point Elements. *Int. J. Num. Meth. Eng.,* **15**, 10, 1980, 1427 - 1445.

5. Blandford G, Ingraffea AR, Liggett JA. Two-Dimensional Stress Intensity Factor Calculations Using the Boundary Element Method. *Int. J. Num. Meth. Eng.,* **17**, 1981, 387 - 404.

6. Beech J, Ingraffea, AR. Three - Dimensional Finite Element Stress Intensity Factor Calibration of the Short Rod Specimen. *Int. J. Fracture*, **18**, 3, 1982, 217 - 229.

7. Perucchio R, Ingraffea AR, Abel JF. Interactive Computer Graphic Preprocessing for Three - Dimensional Finite Element Analysis. *Int. J. Num. Meth. Eng.,* **18**, 6, 1982, 909 - 926.

8. Saouma V, Ingraffea AR, Catalano D. Fracture Toughness of Concrete: K_{Ic} Revisited. *J. Eng. Mech. Div.*, ASCE, **108**, No. EM6, 1982, 1152 - 1166.

9. Perucchio R, Ingraffea AR. Interactive Computer Graphics Preprocessing for Three - Dimensional Boundary Integral Element Analysis. *J. Computers Structures*, **16**, 1 - 4, 1983, 153 - 166.

10. Ingraffea AR, Blandford G, Liggett JA. Automatic Modelling of Mixed - Mode Fatigue and Quasi - Static Crack Propagation Using the Boundary Element Method. *ASTM STP **791**: Proc. of the 14th National Symposium on Fracture Mechanics*, June, 1983, I - 407 - I - 426.

11. 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.

12. Ingraffea AR, Perucchio R, Han T - Y, Gerstle WH, Huang YP. Three - Dimensional Finite and Boundary Element Calibration of the Short - Rod Specimen. *ASTM STP **855**: Chevron-Notched Specimens: Testing and Stress Analysis*, 1984, 49 - 68.

13. Manu C, Ingraffea AR. Numerical Evaluation of the Growth Rate Material Parameters in Fatigue Propagation of Surface Flaws. *Nucl. Eng. Design,* **77**, 2, March, 1984, 131 - 138.

14. Ingraffea AR, Gerstle W, Gergely P, Saouma V. Fracture Mechanics of Bond in Reinforced Concrete. *J. Structural Division,* ASCE, **110**, 4, 1984, 871 - 890.

15. Perucchio R, Ingraffea AR. An Integrated Boundary Element Analysis System with Interactive Computer Graphics for Three Dimensional Linear - Elastic Fracture Mechanics. *J. Comp. Structures*, **20**, 1985, 157 - 171.

16. Nelson PP, Ingraffea AR, O'Rourke TD. TBM Performance Prediction with Rock Fracture Parameters. *Int. J. Rock Mech. Mining Sciences*, **22**, 3, June, 1985, 189 - 192.

17. Elices M, Llorca J, Ingraffea AR. Fractura del Hormigon en Regimen Elastico y Lineal. Un Ejemplo: La Presa de Fontana (in Spanish), *Informes de la Construccion.* **37**, 372, July, 1985, 19 - 33.

18. Ingraffea AR, Gerstle WH, Mettam K, Wawrzynek P, Hellier AK. Cracking of Welded Crane Runway Girders: Physical Testing and Computer Simulation. *Iron and Steel Engineer,* **62**, 12, 1985, 46 - 52.

19. 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.

20. Abel JF, Ingraffea AR, McGuire W, Greenberg DP. Interactive Color Graphical Postprocessing as a Unifying Influence in Numerical Analysis Research. *Finite Elements in Analysis and Design*, **2**, 1986, 1 - 17.

21. Boone TJ, Wawrzynek P, Ingraffea, AR. Finite Element Modeling of Fracture Propagation in Orthotropic Materials. *Eng. Fract. Mech.,* **26**, 2, 1987, 185 - 201.

22. Gerstle WH, Martha L, Ingraffea AR. Finite and Boundary Element Modeling of Crack Propagation in Two - and Three – Dimensions. *Eng. with Computers*. **2**, 1987, 167 - 183.

23. Hellier AK, Sansalone M, Ingraffea AR, Carino NJ, Stone, C. Finite Element Analysis of the Pullout Test Using a Nonlinear Discrete Cracking Approach. *Cement, Concrete and Aggregates*, **9**, 1, Summer 1987, 20 - 29.

24. Wawrzynek P, Ingraffea AR. Interactive Finite Element Analysis of Fracture Processes: An Integrated Approach. *Theor. Appld. Fract. Mech*. **8**, 1987, 137 - 150.

25. Wawrzynek P, Ingraffea AR. An Edge - Based Data Structure for Two-Dimensional Finite Element Analysis. *Eng. with Computers*, **3**, 1987, 13 - 20.

26. Llorca J, Elices M, Ingraffea AR. Analisis Lineal Y No Lineal De Propagacion De Fisuras En Hormigon," (In Spanish), *Revista Internacional de Metodos Numericos para Calculo y Diseno en Ingenieria*, **3**, 3, 1987, 309 - 333.

27. Swenson DV, Ingraffea AR. Using Combined Experiments and Analysis to Generate Dynamic Critical Stress Intensity Data. *ASTM STP **969**: Fracture Mechanics: 19th Symposium*, T. A. Cruse, Ed., American Society for Testing and Materials, Phila., 1988, 405 - 426.

28. Gerstle WH, Ingraffea AR, Perucchio R. Three-Dimensional Fatigue Crack Propagation Analysis Using the Boundary Element Method. *Int.J. Fatigue*, **10**, 3, 1988, 187 - 192.

29. Swenson DV, Ingraffea AR. Modelling Mixed-Mode Dynamic Crack Propagation Using Finite Elements: Theory and Applications. *Computational Mech.,* **3**, 1988, 187-192.

30. Linsbauer HN, Ingraffea AR, Rossmanith H P, Wawrzynek PA. Simulation of Cracking in a Large Arch Dam: Part I. *J. Structural Eng.,* **115**, 7, July 1989, 1599 - 1615.

31. Linsbauer HN, Ingraffea AR, Rossmanith HP, Wawrzynek PA. Simulation of Cracking in a Large Arch Dam: Part II. *J. Structural Eng.,* **115**, 7, July, 1989, 1616 - 1630.

32. Ingraffea AR. Case Studies of Simulation of Fracture in Concrete Dams. *Eng. Fracture Mech.*, **35**, 1/2/3, 1990, 553-564.

33. Vossoughi H, Soudki K, White RN, Ingraffea AR, Sansalone M. Fatigue of Thick Steel Plates Bent to a Low R/t Ratio. *J. Pressure Vessel Tech.,* **111**, August 1989, 259 - 265.

34. 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.

35. Grigoriu M, Saif M, El Borgi S, Ingraffea AR. Mixed - Mode Fracture Initiation and Trajectory Prediction Under Random Stresses. *Int. J. Fracture*, **45**, 1990, 19-34.

36. 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.

37. Wawrzynek PA, Ingraffea AR. An Interactive Approach to Local Remeshing Around a Propagating Crack. *Finite Elem. in Analys. and Design*, **5**, 1989, 87 - 96.

38. Ingraffea AR, Barry A. Analytical Study of Transmission, Distribution Lines under Railroads. *Pipe Line Industry,* October 1989, 34 - 39.

39. Gray LJ, Martha LF, Ingraffea AR. Hypersingular Integrals in Boundary Element Fracture Analysis. *Int. J. Num. Meth. Eng.*, **29**, 1990, 1135-1158.

40. Mann KA, Bartel DL, Wright TM, Ingraffea AR. Mechanical Characteristics of the Stem-Cement Interface. *J. Ortho. Research,* **9**, 798-808, 1991.

41. 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.

42. Swenson DV, Ingraffea AR. The Collapse of the Schoharie Creek Bridge: A Case Study in Concrete Fracture Mechanics. *Int. J. Fracture*, **51**, 73-92, 1991.

43. Gerstle WH, Ingraffea AR. Does Bond-Slip Exist? *Concrete International*, **13**, 1, 44-48, 1991.

44. Gerstle WH, Ingraffea AR. Compliance and Stress-Intensity Factor Calibration of the CENRBB Specimen. *Int. J. Rock Mech. Mining Sci. & Geomech. Abstr.,* **28**, 1, 85-92, 1991.

45. Bittencourt TN, Barry A, Ingraffea AR. Comparison of Mixed-Mode Stress Intensity Factors Obtained Through Displacement Correlation, J-Integral Formulation, and Modified Crack-Closure Integral. *ASTM STP 1131: Fracture Mechanics: Twenty Second Symposium (Vol. II)*, Philadelphia, 69-82, 1992.

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13. Ingraffea, A. R., "An Experimental Study of Propagation of Cracks Near Interfaces in Rock," Department of Structural Engineering Report 82 - 4, School of Civil and Environmental Engineering, Cornell University, February, 1982, 45 pp.

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16. Perucchio, R. S., Ingraffea, A. R., "An Integrated Boundary Element Analysis System with Interactive Computer Graphics for Three Dimensional Linear - Elastic Fracture Mechanics," Department of Structural Engineering Report 84 - 2, School of Civil and Environmental Engineering and Program of Computer Graphics, Cornell University, Ithaca, N.Y., January, 1984.

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18. Ahmed, I., O'Rourke, T. D., Perucchio, R. S., Kulhawy, F. H., Ingraffea, A. R., "Analytical Study of Cast Iron Pipeline Response to Shallow Trench Construction," Report to New York Gas Group, Geotechnical Engineering Report 84 - 2, Cornell University, May,1984.

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20. Wawrzynek, P., Ingraffea, A. R., "The Effect of Stiffeners on the Forces Transmitted to the Web - to - Flange Junction of Crane Runway Girders," Task II, Report No. 3, Document 85 - 3, AISE/Cornell University Crane Runway Girder Project, January 20, 1985, 50 pp.

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28. Ingraffea, A. R., McGuire, W., Pekoz, T., Gerstle, W., Mettam, K., Wawrzynek, P., Hellier, A., Final Report. Volume 1 of 2. Task IV, Document 86 - 1, AISE/Cornell University Crane Runway Girder Project, June 23, 1986, 47 pp.

29. Mettam, K., Ingraffea, A. R., Gerstle, W. H., "A Bibliography on Fatigue in Crane Runway Girders," Task I, Report No. 1, in Final Report - Appendices. Volume 2 of 2. Document 86 - 1, AISE/Cornell University Crane Runway Girder Project, June 23, 1986, 22 pp.

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41. Martha, L. and Ingraffea, A. R., "Topological and Geometrical Modeling Approach to Numerical Discretization and Arbitrary Fracture Simulation in Three-Dimensions," Department of Structural Engineering Research Report 89 - 9, , School of Civil and Environmental Engineering, Cornell University, August, 1989, 331 pp.

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43. Ingraffea, A., Grigoriu, M., "A Validation of Predictive Capability", Department of Structural Engineering Research Report 90 - 8, School of Civil and Environmental Engineering, Cornell University, August, 1990.

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47. Bittencourt, T., Ingraffea, A. R., "Computer Simulation of Linear and Nonlinear Crack Propagation in Cementitious Materials," Department of Structural Engineering Research Report 93-3, School of Civil and Environmental Engineering, Cornell University, May, 1993, 303 pp.

48. Potyondy, D., Ingraffea, A. R., "A Software Framework for Simulating Curvilinear Crack Growth in Pressurized Thin Shells", Department of Structural Engineering Research Report 93-5, School of Civil and Environmental Engineering, Cornell University, August, 1993, 370pp.

49. P. Wawrzynek, Ingraffea, A., "FRANC2D: A Two-Dimensional Crack Propagation Simulator Version 2.7 User's Guide", NASA Contractor Report 4572, National Aeronautics and Space Administration, Langley Research Center, Hampton, VA, March, 1994, 59 pp.

50. "Fracture Mechanics Life Analytical Methods Verification Testing-Final Report", NAS8-38103, for the George C. Marshall Space Flight Center, NASA, Nichols Research Corporation/Cornell University/ Fracture Analysis Consultants, Inc., 1994.

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54. Hanson, J. H., Ingraffea, A. R., "Proposed Standard Test Method for Round Double Beam Fracture Toughness of Concrete," *Research Report*, 00-1, Department of Structural Engineering, Cornell University, Ithaca, NY, Jan. 2000.

55. Chen, C.S., Wawrzynek, P.A., and Ingraffea, A.R. "Finite Element Stress Analysis Subroutines for RAPID", Final Report to Federal Aviation Administration, Project DTFA0300C00002, 2000.

56. Lewicki, D. G., Spievak, L., Wawrzynek, P. A., Ingraffea, A. R., Handshuh, R., „Consideration of Moving Tooth Load in Gear Crack Propagation Predictions“, NASA/TM-2000-210227, ARL-TR-2246, DETC2000/PTG-14386, July, 2000.

FUNDED RESEARCH PROJECTS

Structural Engineering

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. "Finite Element Analysis of Reinforced Concrete for Cyclic Loading," National Science Foundation Grant PFR - 7900711, 4/79-3/81, $84,000, Principal Investigator. P. Gergely and R. N. White, Co - Principal Investigators.

3. "Laboratory Testing of the Crack - at - an - Interface Problem," Sandia National Laboratories Contract No. 13 - 5038, 5/79 - 5/80, $42,000, Principal Investigator.

4. "Three - Dimensional Interactive Computer Graphics in Structural and Geo - Mechanics," National Science Foundation Grant CME79 - 16818, 1/80 - 6/82, $500,000, Faculty Investigator. J. F. Abel, D. P. Greenberg, W. McGuire, Co-Principal Investigators; F. H. Kulhawy, Faculty Investigator.

5. "Interaction Between Steel and Concrete for Earthquake-Type Loadings," National Science Foundation Grant CME80 - 20925, 4/1/81 - 9/30/83, $140,000, Principal Investigator. P. Gergely, Co - Principal Investigator.

6. "Interactive Color Display of Three - Dimensional Engineering Analysis Results," National Aeronautics and Space Administration, Grant NAG3 - 395, 3/1/83 - 2/28/87, $133,285, Associate Investigator. J. F. Abel, Principal Investigator.

7. "Welded Crane Runway Girder Study," Association of Iron and Steel Engineers, 8/83 - 8/85, $234,348, Principal Investigator. W. McGuire, T. Pekoz, Co - Principal Investigators.

8. Presidential Young Investigator Award in Structural Mechanics, National Science Foundation Grant 8351914, 6/84 - 6/89, $500,000, Principal Investigator.

9. "Fatigue Behavior of Thick Steel Plates," Electric Boat Division/General Dynamics, PO# R2041 - 907, 1/86 - 12/88, $233,218, Co - Principal Investigator. R. N. White, Principal Investigator.

10. "Probabilistic Fracture Mechanics," AFOSR, 4/87 - 4/90, $269,624, Co - Principal Investigator. M. Grigoriu, Co - Principal Investigator.

11. "CISE Research Instrumentation: Computer Graphics Dynamic Simulation for Scientific Inquiry," National Science Foundation Grant CCR - 8717024, 4/1/88 - 9/30/89, $145,600, Co - Principal Investigator. M. Cohen, D. Greenberg, and J. Abel, Co - Principal Investigators.

12. "Visualization for Supercomputing: A Graphics Workstation Approach," National Science Foundation, Grant ASC - 8715478, 8/1/88 - 1/31/90, $202,532, Co - Principal Investigator. D. Greenberg, Principal Investigator. J. Abel, M. Cohen, D. Caughey, Co - Principal Investigators.

13. "Advanced Computational Fracture Mechanics," Digital Equipment Corporation, 7/89 - 7/90, $100,000, Principal Investigator.

14. “Fatigue and Damage Tolerance”, Northrop-Grumman Corporation, 6/89-12/00, $249,000, Principal Investigator.

15. "Research in Fracture Mechanics", Exxon Education Foundation, 9/89-9/92, $30,000, Principal Investigator.

16. "Crack Growth Prediction Methodology for Multi-Site Damage", NASA Langley Research Center, 9/90-9/98, $926,147, Principal Investigator.

17. “Fracture Mechanics Life Analytical Methods Verification Testing", Nichols Research Corp. /NASA MSFC, 8/91 - 8/94, $183,860, Principal Investigator.

18. "Mode I/III Fatigue Crack Growth Measurements in 2024 Aluminum Sheet", NASA Langley Research Center, 6/91-9/93, $159,836, Co-Principal Investigator. A. Zehnder, Co-Principal Investigator.

19. “A Study of Failure Mechanisms of Advanced Flex Cables”, IBM Corporation, 1/20/92-1/19/93, $25,000, Co-Principal Investigator. A. Zehnder, Co-Principal Investigator.

20. “Detecting Cracks in Concrete Dams”, U. S. Army Engineer Waterways Experiment Station, 4/1/94-1/1/95, $39,339, Co-Principal Investigator. M. Sansalone, Principal Investigator.

21. “Measurement of Fracture Toughness of Concrete Using the Short-Rod Procedure”, NSF CMS 9414243, 9/95-8/98, $203,854. Principal Investigator.

22. "Simulation of Damage Tolerance in Honeycomb Core Structure", Boeing Commercial Airplane Co., 5/96-12/98, $204,000. Principal Investigator.

23. "Simulation of Crack Growth in Spiral Bevel Gears", NASA Glenn Research Center, 12/96-12/00, $289,961. Principal Investigator.

24. "Fracture of Steel Joints", CUREe SAC Phase II Subcontract No. 28, 9/96-12/96, $23,000. Co-Principal Investigator. Prof. G. Deierlein, Principal Investigator.

25. “Multidisciplinary Center for Earthquake Engineering Research”, NSF, 10/97-9/02, $1,500,000. Associate Investigator. Prof. R. White, Co-Principal Investigator; Profs. G. Deierlein, M, Grigoriu, Associate Investigators.

26. “Simulation of Crack Propagation on Teraflop Computers”, NSF, 1/98-12/00, $1,800,000. Co-Principal Investigator. Profs. S. Vavasis and K. Pingali, Co-Principal Investigators.

27. “Probabilistic Simulation of Fatigue Crack Initiation”, AFOSR, 3/98-2/01, $600,000. Principal Investigator. Profs. M. Grigoriu, M. Miller, P. Dawson, Co-Principal Investigators.

28. “Development and Implementation of T-Stress Criterion”, NASA Langley Research Center, 8/97-3/98, $20,128. Principal Investigator.

29. “Crack Turning and Arrest Mechanisms for Integral Structures”, NASA Langley Research Center, 1/98-6/00, $103,642. Principal Investigator.

30. “Basic Research in Crack Growth Prediction Methodologies”, NASA Langley Research Center, 1/98-11/99, $185,000. Principal Investigator.

31. “Fatigue Crack Growth in Aluminum Alloys”, Alcoa Foundation, 6/97-5/98, $10,000. Principal Investigator.

32. “Multiscale Modeling of Defects in Solids”, NSF 9873214, 10/98-9/01, $1,500,000. Co-Principal Investigator. Profs. P. Dawson, and J. Sethna Co-Principal Investigators, C. Myers, Co-Principal Investigator.

33. “A Two-Tier Computation and Visualization Facility for Multiscale Problems”, NSF 9972853, 10/99-9/04, $1,500,000. Co-Principal Investigator. Profs. K. Pingali, N. Chrisochoides, C. Cruz-Neira, Guang Gao, Co-Principal Investigators.

34. “Finite Element Stress Analysis Subroutines for RAPID”, Federal Aviation Administration, 9/99-4/2000, $34,438. Principal Investigator.

35. “Finite Element/Fracture Mechanics Simulation of Trajectories During Slitting of Plastic Films”, Eastman Kodak Company, 1/1/99-12/31/01, $110,000. Principal Investigator.

36. “ITR: Adaptive Software for Field-driven Simulations”, NSF 0085969, 9/1/00-8/31/04, $5,000,000. Co-Principal Investigator. Prof. K. Pingali, PI, B. K. Soni, J. F. Thompson S. A. Vavasis, Co-PIs.

37. “Developing Technologies for Modeling Damage in Stiffened Thin Shell Structures”, NASA LaRC, 11/1/01-10/31/04, $160,107. Principal Investigator.

38. “Computational Micro-Mechanical Investigations of Crack Initiation in Metallic Polycrystals”, NASA LaRC, 2/1/02-1/31/05, $230,182. Principal Investigator.

39. “The Institute for Future Space Transport”, NASA Marshall RC University Research, Engineering and Technology Institute, 8/1/02-9/15/07, $15,616,120, Co-Principal Investigator. W. Shyy, Principal Investigator, B. Soni, B. Davidson, J. Olds, Co-Principal Investigators.

40. “Structural Integrity Prognosis System-SIPS”, DARPA, 10/1/03-8/31/08, $1,288,400, Cornell Principal Investigator. J. Madsen, Northrop Grumman Corp. Project Manager.

41. "Fracture Mechanics Analysis of MANPADS-Damaged Aircraft Structures", NASA LaRC, 5/05-9/06, $74,000. Principal Investigator.

42. “Advanced Digital Material Machine (ADMM) “AFOSR/DURIP, 2006, $300,000. Principal Investigator.

43. “Multi-Scale Simulation of Cracking Processes in Metallic Materials“, NASA LaRC, NNX07AB69A, 1/07-12/10, $392,526. Principal Investigator.

44. “Constellation University Institute Project: Computational Simulation of Damage Tolerance for Composite and Metallic Structures”, NASA, 10/1/07-9/30/10, $450,000, Principal Investigator.

45. “Multi-scale Simulation of Fatigue Damage”, Northrop Grumman Corporation, 1/1/07-12/31/09, $55,000, Principal Investigator.

46. “Computational Methods in Physics-Based Modeling of Damaged Flight Structures”, NASA LaRC NNX08AC50A, 1/1/08-12/31/2010, $299,972, Principal Investigator.

47. “Collaboration between Cornell Fracture Group and Exponent, Inc.”, Exponent Inc., 3/08-12/08, $29,204, Principal Investigator.

48. “Geometrical Simulation of Complete Process of Microstructurally Small Fatigue Cracking” E DARPA, HR0011-09-1-0002, 1/09-12/09, $150,000, Principal Investigator.

49. “Parallel File Serving R&D”, IBM, $20,200, 7/09-6/10, Principal Investigator.

50. “Prognosis of Long-Term Load-Bearing Capability in Aerospace Structures: Quantification of Microstructurally Short Crack Growth“, Air Force Office of Scientific Research, $750,000, 5/10/5/13, Co-Principal Investigator.

Geotechnical Engineering

1. "TBM Performance Study," U.S. Dept. of Transportation, 3/80 - 3/82, $164,000, Associate Investigator. T. D. O'Rourke, Principal Investigator; F. H. Kulhawy, Associate Investigator.

2. "A Study of Cast Iron Gas Main Replacement," New York Gas Group, 8/81 - 12/83, $287,000, Associate Investigator. T. D. O'Rourke, Principal Investigator; F. H. Kulhawy, Associate Investigator.

3. "Uplift/Compression Transmission Line Structure Foundation Research," Electric Power Research Institute, RP1493 - 4, 1984 - 1988, $2,450,000, Associate Investigator. F. H. Kulhawy, Principal Investigator; T. D. O'Rourke, M. Grigoriu, Associate Investigators.

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. "Workshop on Interactive Computer Modeling and Graphics for the Design and Optimization of Field and Laboratory Experiments in Geotechnical Engineering." National Science Foundation Grant CEE 8413471, 12/84 - 11/86, $39,681. Principal Investigator.

6. "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.

7. "Influence of Perforations Upon Subsequent Hydraulic Fracturing," Digital Equipment Corp. and Dowell Schlumberger, 1/88 - 12/96, $448,000. Principal Investigator.

8. “Computational Simulation of Hydrofracturing”, NSF CISE Postdoctoral Associate Award for Dr. K. Shah. 11/95-10/97, $46,200. Principal Investigator.

9. "3D Crack Initiation and Propagation in Transparent Rock Like Materials Loaded in Compression", NSF, 9/96-8/99, $148,000. Principal Investigator.

Engineering Education

1. "Study of Complementary Research and Teaching in Engineering Science - PROJECT SOCRATES," U. S. Department of Education, Fund for the Improvement of Post - Secondary Education, G 008642170, 9/15/86 - 9/14/89, $236,496, Project Director.

2. "Workstations For Instructional Computing in the College of Engineering," Digital Equipment Corporation, 5/1/88 - 4/31/90, $664,000. Project Director.

3. "Workstations for Project SOCRATES," Apollo Computer, Inc., June, 1989, $87,105. Project Director.

4. "Workstations for Project SOCRATES", Sun Microsystems, Inc., June, 1990, $89,415. Project Director.

5. "Synthesis National Engineering Education Coalition", National Science Foundation, 9/30/90 - 9/30/94, $12,278,036. Project Director.

6. "1992 Summer Institute for Computer Graphics", New York State Education Department, $56,000, 7/19/92-8/8/92, Project Co-Director. C. Mink, Director.

7. "Support for Educational Computing Equipment", Hewlett Packard, 6/92, $427,318. Project Director.

8. "Synthesis Coalition/GE Foundation Faculty Exchange Award", GE Foundation, Spring 1994 - Spring 1997, $230,000, Principal Investigator.

9. "Synthesis Coalition/Raytheon Company Student Award" Raytheon Company, 1994-1995, $24,000, Principal Investigator.

10. "Application and Infrastructure Linkage to Altoona Area School District and Manhatten Center for Science and Math High School", Synthesis Coalition/NSF/GE Foundation/Mr. A. Misciagna, 10/1/94-9/30/96, $284,000, Project Director.

11. "Integration of Information Age Networking and Parallel Supercomputer Simulations into University and General Science K-12 Curricula", NSF, 1/96-12/98, $102,000, Co-Principal Investigator. J. Sethna, Co-Principal Investigator.

12. REU Supplement to "Measurement of Fracture Toughness of Concrete Using the Short-Rod Procedure", NSF, 9/95-9/98, $10,000, Principal Investigator.

13. REU Supplements to "Integration of Information Age Networking and Parallel Supercomputer Simulations into University and General Science K-12 Curricula", NSF, 9/96-9/98, $20,000, Co-Principal Investigator with Prof. James Sethna, Physics.

14. “Tech City Exhibition”, NSF, 7/98-6/01, $639,543, Co-Principal Investigator. Dr. C. Trautmann, Principal Investigator.

15. “An Advanced Interactive Discovery Environment for Engineering Education” NASA/New York State/AT&T, 2/1/01-12/31/07, $4,300,000, Co-Principal Investigator. Prof. B. Davidson, Principal Investigator, Prof. E. Liddy, Co-PI.

Co-operative Research

1. "Co-operative Agreement between Cornell University and the Technical University of Delft", National Science Foundation Grant PFR-8020924, 1/81 - 12/82, $25,800, Co - Principal Investigator. P. Gergely, Principal Investigator; R. N. White, Co – Principal Investigator.

2. "Scientific Visit to Plan Co-operative Research in Hydraulic Fracturing," Catholic University of Rio de Janiero/Cornell University, National Science Foundation Grant INT - 8814466, July 1988, $2,336, Principal Investigator.

3. "Fracture Mechanics Case Studies of Concrete Dams" Technical University of Vienna, Austria/Cornell University, National Science Foundation Grant INT-8814457, 2/89 - 2/92, $8,080, Principal Investigator.

4. International Supplement to National Science Foundation Grant “ITR: Adaptive Software for Field-driven Simulations”, to collaborate with Czech Technical University, Z. Bittnar, Czech Co-PI, 7/99-8/03, $24,375, Co-Principal Investigator.

THESES DIRECTED

Master of Science

1. "A Fracture Mechanics Analysis of the Fontana Dam," John Chappell, May, 1981.

2. "Mixed-Mode Crack Propagation in Mortar and Concrete." Manrique Arrea, January 1982.

3. "The Fracture Mechanics of Bond in Reinforced Concrete," Walter Gerstle. May 1982.

4. "Concrete Fracture: A Linear Elastic Fracture Mechanics Approach," David Catalano, August, 1982.

5. "Interactive and Graphic Two - Dimensional Fatigue Crack Propagation Analysis Using Boundary Element Method," Kodwo Otsei;du, January, 1983.

6. "An Experimental Investigation of Fatigue Cracking in Welded Crane Runway Girders Due to Wheel Induced Stresses," Kirk I. Mettam, January, 1986.

7. "An Investigation of the Failure Process of the STEM - PMMA Interface in Cemented Prostheses," Leonard Daniel - Timmie Topoleski, June 1986.

8. "Interactive Finite Element Analysis of Fracture Processes: An Integrated Approach," Paul A. Wawrzynek, May 1987.

9. "Analytical Study of Stresses in Transmission and Distribution Pipelines Beneath Railroads," J. Russell Blewitt, May 1987.

10. "Case Studies of Cracking of Concrete Dams--A Linear Elastic Approach," Shan - Wern Steve Lin, January 1988.

11. "Fracture Analysis Code: A Computer - Aided Teaching Tool," Maya Srinivasan, January 1988.

12. "Two-Dimensional Numerical Evaluation of Near Wellbore Phenomena: Perforation Performance & Interacting Hydraulic Fractures", Stephen James Lamkin, May 1990.

13. “On Finite Element Analysis of Face Sheet Cracking in Honeycomb Core Sandwich Panels”, Kenneth Ferguson, January 1999.

14. “Simulating Fatigue Crack Growth in Spiral Bevel Gears”, Lisa Eron Spievak, August 1999.

15. “Cracking Dams: An Interactive Web Site for K12”, Megann V. Polaha, August 1999.

16. "Experimental Investigations into Damage Tolerance of Honeycomb Sandwich Panels", Ani Ural, August, 1999.

17. “Simulations of Crack Initiation in Aluminum Alloys with Inclusions“, Ketan Dodhia, January, 2002.

18. “Decohesion of Grain Boundaries in Statistical Representations of Aluminum Polycrystals“, Erin Iesulauro, January, 2002.

19. “An Evaluation of Surface Cracks in Welded Components of Nuclear Reactor Vessels”, John Emery, May, 2003.

20. “Microstructural Reconstruction and Three-Dimensional Mesh Generation for Polycrystalline 7075-T651 Aluminum Alloy“, Michael Veilleux, May, 2007.

21. “A Two-Dimensional Multiscale Method for Fatigue Crack Nucleation in Polycrystalline Aluminum Alloys “, Jeffrey Bozek, May, 2007.

Doctor of Philosophy

1. "Three-Dimensional Finite Element Analysis of Cyclic Fatigue Crack Growth of Multiple Surface Flaws." Corneliu Manu, June, 1980. Professor (Retired) University of Toronto.

2. "Automatic Two-Dimensional Quasi-Static and Fatigue Crack Propagation Using the Boundary Element Method." George E. Blandford, January, 1981. Professor, University of Kentucky.

3. "Interactive Finite Element Analysis of Reinforced Concrete: A Fracture Mechanics Approach," Victor E. Saouma, January, 1981. Professor, University of Colorado/Boulder.

4. "An Integrated Boundary Element Analysis System with Interactive Computer Graphics for Three - Dimensional Linear Elastic Fracture Mechanics," Renato S. Perucchio, January, 1984. Professor, University of Rochester.

5. "Finite and Boundary Element Modelling of Crack Propagation in Two- and Three - Dimensions Using Interactive Computer Graphics," Walter H. Gerstle, January, 1986. Professor, University of New Mexico.

6. "Modeling Mixed - Mode Dynamic Crack Propagation Using Finite Elements," Daniel V. Swenson, January 1986. Professor, Kansas State University.

7. "Simulation of Crack Propagation in Poroelastic Rock with Application to Hydrofracturing and *In - Situ* Stress Measurement," Thomas J. Boone, January, 1989. VP of Research, EXXON.

8. "Topological and Geometrical Modeling Approach to Numerical Discretization and Arbitrary Fracture Simulation in Three-Dimensions," Luiz Martha, August, 1989. Professor, Catholic University of Rio de Janeiro, Brazil.

9. "Numerical Methods for Hypersingular and Near-Singular Boundary Integrals in Fracture Mechanics", Earlin Lutz, May, 1991. Senior Research Engineer, Bentley, Inc.

10. "Discrete Modelling of Crack Propagation: Theoretical Aspects and Implementation Issues in Two and Three Dimensions", Paul A. Wawrzynek, August, 1991. Chief Engineer, Fracture Analysis Consultants, Inc.

11. "Three-Dimensional Simulation of Near-Wellbore Phenomena Related to Hydraulic Fracturing from a Perforated Wellbore", José Sousa, May, 1992. Professor, University of Campinas, Brazil.

12. "Computer Simulation of Linear and Nonlinear Crack Propagation in Cementitious Materials", Tulio Bittencourt, May, 1993. Professor, University of Sao Paulo, Brazil.

13. "A Methodology for Simulation of Curvilinear Crack Growth in Pressurized Shells", David Potyondy, August, 1993. Senior Research Engineer, Itasca, Inc.

14. "Experimental Validation Testing of Numerical Prediction Techniques for Three-Dimensional Fracture and Fatigue", William Riddell, June, 1995. Asst. Professor, Rowan University.

15. “Crack Growth Simulation and Residual Strength Prediction in Thin Shell Structures”, Chuin-Shan Chen, January, 1999. Assoc. Prof., National Taiwan University.

16. “Virtual Crack Extension Method for Calculating Rates of Energy Release Rate and Numerical Simulation of Crack Growth in Two and Three Dimensions”, Changyu Hwang, January, 1999. Professor, Seoul University of Venture and Information.

17. “Crack Turning in Integrally Stiffened Aircraft Structures”, Richard Pettit, August, 2000. Chief Engineer, Pratt &Whitney, Inc.

18. “An Experimental-Computational Evaluation of the Accuracy of Fracture Toughness Tests on Concrete”, James Hanson, August, 2000. Assoc. Prof., Rose-Hulman Institute of Technology.

19. “Interface Modeling of Composite Material Degradation”, Tong-Seok Han, May, 2001 (with Prof. Sarah Billington). Research Engineer, Korea Electric Power Research Institute.

20. “Modeling and Simulation of Fatigue Crack Growth in Metals Using LEFM and a Damage-Based Cohesive Model”, Ani Ural, May, 2004 (with Prof. Katerina Papoulia). Assistant Professor, Villanova University.

21. “Decohesion of Grain Boundaries in Statistical Representations of Aluminum Polycrystals”, Erin Iesulauro, May, 2006. Staff Engineer, Los Alamos National Laboratory.

22. “A Hierarchical, Probabilistic, Damage and Durability Simulation Methodology”, John Emery, May, 2007, Staff Engineer, Sandia National Laboratory.

23. “A Multiscale Method for Fatigue Crack Propagation in Aluminum Alloys”, Jeffrey Bozek, August, 2010 (expected).

24. "Modeling Elastic-Viscoplastic Behavior and Damage Evolution of Two-Phase Polycrystalline Materials", Michael Veilleux, DOE Computational Science Graduate Fellow, August, 2010 (expected).

25. “Simulation of Crack Propagation in Stiffened Shell Structures”, Jacob Hochhalter, NASA Langley Research Center, August, 2010 (expected).

26. “Microstructural Simulation of Fracture Processes in Cortical Bone”, Erin Oneida, August, 2010 (expected).

27. “Residual Strength of Damaged Aerostructures”, Ashley Spear, NSF Graduate Fellow, May, 2012 (expected).

28. “DDSim for Composite Structures“, Brett Davis, May, 2012 (expected).

29. “Geometrical Simulation of Complete Process of Microstructurally Small Fatigue Cracking “ Albert Cerrone, May 2013 (expected).