Dr. M. Kumosa's Key Academic and Research Accomplishments

Feb 2021

Personal Information; Born on July 13, 1953 in Warsaw, Poland.

Key Research Interests; Physical Properties, Life Prediction, and Manufacturing of Advanced Materials and Structures for Extreme Applications including High Voltage (HV), High Temperature (HT), High Strain/Stress (HSS), combined HVTS, and others.

Education; BS/MS (1978) and Ph.D. (1982) in Applied Mechanics and Materials Science at Wroclaw University of Science and Technology (PWR, http://pwr.edu.pl/en/) in Poland. Dr. Kumosa's Ph.D. program was jointly sponsored by PWR and the US National Science Foundation (NSF) through the Marie Curie Foundation, International Programs. His Polish academic advisor was Professor L. Golaski, and Professor K. Ono from the University of California Los Angeles (UCLA) was his American advisor. As part of Dr. Kumosa's Ph.D. program, he was invited in 1981 by the NSF to visit UCLA as well as other research organizations in the USA.

Current Employment

1. John Evans Professor at the University of Denver (DU), Department of Mechanical and Materials Engineering, University of Denver, 2155 East Wesley Avenue, Denver, Colorado 80208 tel: (303) 871-3807, fax: (303) 871-4450; mkumosa@du.edu.
2. Center Director: National Science Foundation Industry/University Cooperative Research Center (I/UCRC) for Novel High Voltage/Temperature Materials and Structures ("HVT Center").

HVT Center Highlight (www.HVTCenter.org); see also the Appendix and Dr. Kumosa's full Vitae

1. Center established on March 15, 2014; in Phase I for the past 5 years; one of about 60 I/UCRCs in Engineering in the US.
2. Three original sites: DU, Michigan Technological University (MTU) and University of Illinois at Urbana- Champaign (UIUC). The University of Connecticut (UConn) was added in Feb 2016.
3. Created by M. Kumosa based on his HV and HT research experience and accomplishments (see below) with very significant help and contributions from Professor G. Odegard (MTU site director), Professor I. Jasiuk (UIUC site director), Professor Martin Ostoja-Starzewski (UIUC) and Professor Y. Cao (UConn site director).

4. According to NSF, Division of Industrial Innovation and Partnership (IIP), Directorate of Engineering, the HVT Center was in good standing in 2015, 2016, 2017, 2018, 2019 and 2020 (all federal conditions fully satisfied!).

5. As of January 2021, the Center has graduated 29 PhD and 16 MS students. It is anticipated that before the end of Phase I in Feb 2022, up to 34 PhD students will graduate from the Center.

6. 135 journal papers in the best int. journals have been published so far by the four sites.

7. Total HVT Funding

   7.1 In the first 5 "regular" years between March 15, 2014 and March/April 2019

   - $2.60M in industrial and federal fees
   - $1.65M from NSF
   - $10M-11M in various leveraged funds

   7.2. Funding in two no-cost extension years between March 1, 2019 and March 1, 2021

   - NSF - $0k
   - First Year (March 1, 2019 and Feb 28, 202) in fees – $480k plus $100k in kind including: $40k from ABB, $50k from BPA, $100k from DOE Headquarters, $40k from G&W, $40k from CTC Global, $50k from Eversource, $40k from Marmon, $50k from Tri-State, $100k from WAPA and $100k (in-kind) from USBR
   - Second year (March 1, 2020 and Feb 28, 2021) in fees -$180k including: $80k from CTC Global, $50k from BPA and $50k from Tri-State

   7.2 Total funding since inception in March 15, 2014

   - $2.61M in cash in private and federal fees (plus at least $1M in-kind)
   - $1.65M in NSF supporting grants
   - $11-12M in various leverage funds

8. Industries (20) supporting HVT from 2014 to the present:

   ABB, Boeing, Bonneville Power Administration, BP, CTC Global, Composites Technology Development, DOE Headquarters; Electricity Office, Eversource, G&W, General Cable, General Electric, John Crane, Marmon Engineered Wire & Cable, Lockheed Martin Space Systems, Prysmian Group, Southwire, Tri-State Transmission and Distribution, USi, US Bureau of Reclamation, Western Area Power Administration.

   (Most are large multibillion dollar corporations).

9. The Center was evaluated by its members for 2017. For the quality of its research, meetings and management, the Center received 4.1/5, 4.2/5 and 4.2/5, respectively, all noticeably above the national averages. The evaluations for 2016 were very similar (for research 4.8/5).

10. The following federal evaluation was provided to the HVT Center by Dr. Andrei Marshall, NSF I/UCRC program director on Apr**il 11, 2018:** ***"After review of your annual report, I am writing to inform you that HVT has met NSF member requirements and is considered to be in good standing. The HVT Center has made significant research contributions during Phase I. We ask HVT to carefully consider a Phase II proposal submission."***

11. According to Dr. Lindsey McGowen in her NSF Evaluator's Report, February 28, 2019

"This is the final year of Phase 1 for the Center for Novel High Voltage/Temperature Materials & Structures (HVT Center). During the award period, the Center has established policies and procedures necessary for successful operation of an IUCRC. With the support and involvement of their industry and government members, the Center has established an industrially relevant program of research in multiscale design and development; advanced manufacturing; environmental degradation; damage prevention; and monitoring and diagnosis of HVT materials, structures, and equipment. Since their launch in 2014, the HVT Center has been supported by 19 member organizations, investing $2.7M in industrial funding for Center research, with an additional ~$3M in additional support from NSF and other federal grants. They have produced over 100 journal publications, 84 conference presentations, graduated 14 MS and 20 PhDs. ***When compared to other Phase 1 IUCRCs, HVT Center is a leader in many respects: they are in the top 10 for number of university sites, number of IAB members, students trained, students graduated, and publications. And they are on par with their Phase 1 peers in terms of total annual budget and membership support.***"

Memberships on Editorial Boards

1. Composites Science and Technology (#1 int. j. in composites; Impact Factor 6.3), since 2001
2. Structural Durability & Health Monitoring (http://www.techscience.com/sdhm/)
3. Fibers (http://www.mdpi.com/journal/fibers)

Academic Awards

1. John Evans Professor, the highest recognition at DU for outstanding internationally recognized research or other creative, scholarly achievement, awarded in April 2006. One of 25 recipients selected between 1990 and present.

2. Distinguished Teaching Award, Oregon Graduate Institute (OGI), Portland, OR, 92-93; the highest recognition for research and graduate teaching at the Oregon Graduate Institute of Science and Technology (OGI), Portland, Oregon.

Completed Graduate Programs under M. Kumosa supervision/advising

1. 20 PhDs
2. 20 MS projects

Most Accomplished Graduate Students Advised by M. Kumosa

1. Professor N. Sukumar, MS at OGI in 1992; presently Professor of Computational Mechanics, University of California, Davis
2. Dr. A. Bansal, PhD at OGI in 1995; presently Senior Manager at Applied Materials Inc.
3. Professor G. Odegard, PhD at DU in 2000; presently
    - Professor of Computational Mechanics at MTU
    - HVT Site Director at MTU since March 2014
    - Director of the NASA Institute for Ultra-Strong Composites by Computational Design; since August 2017, $15M grant from NASA for five years
4. Dr. K. Searles, PhD at OGI in 2000; presently Senior Research Engineer at Exxon-Mobil Corporation – Upstream Research, Kingwood, TX
5. Dr. B. Benedikt, PhD at DU in 2003; presently Senior Scientist at Los Alamos National Laboratory
6. Dr. P. Rupnowski, PhD at DU in 2005; presently Senior Scientist at NREL in Golden, CO
7. Dr. Z. Loftus, PhD at DU in 2013; presently Lockheed Martin Technical Fellow, Denver Colorado
8. Dr. B. Burks, PhD at DU in 2012; presently VP Engineering at Digital Wave Corp., Englewood, CO
9. Dr. J. Hoffman, PhD at DU in 2015; presently Deputy Director of HVT Center
10. Dr. E. Hakansson, PhD at DU in 2016; presently Lecturer in Mechanical Engineering, University of Auckland, Auckland, NZ. World's fastest female motorcycle rider (*evahakanssonracing.com*)
11. Dr. C. Henderson, PhD at DU in 2019, presently senior manager with the US Bureau of Reclamation in Denver, CO.

Recently Graduated Outstanding PhD Students

12. Dr. J. Middleton, PhD at DU in 2014 at DU; presently Senior Engineer at SoloAero, NM
13. Dr. M. Bleszynski, PhD at DU in 2018, presently Research Scientist at DU
14. Dr. Tianyi Lu, PhD at DU in 2019

Other Highly Accomplished Students Involved in Dr. Kumosa's research

1. Dr. L. Kumosa (son); PhD in Bioengineering from UCSD in 2011; presently Postdoctoral Fellow at Neuronano Research Center (NRC) at Lund in Sweden, 1520 citations and h-index 23 on Google

Scholar. Between 1999 and 2003, Dr. L. Kumosa worked with Dr. M. Kumosa as an undergraduate research assistant/associate at DU and published jointly 25 journal papers in materials science, composites and electrical engineering. Dr. L. Kumosa has recently published a few papers in the best int. bioengineering journals in the neuroscience area (Acta Biomateriala, Biomaterials and others).

Present Research Group

- 4 regular PhD graduate students
- Dr. J. Hoffman, Research Assistant Professor

Total Competitive Research Funding between 1990 and 2020

Approximately $7.93M (both federal grants and private/federal contracts), including:

- Federal Grants: $2.750 M (5 NSF and 5 AFOSR grants, all with MK as PI)
- Private/Federal Contracts: $4.88M (including multiple BPA, WAPA, NASA Glenn individual contracts and HVT memberships)

Average per Year: ~ $275k in 29 years

Publications

1. 137 published in international journals including:
   a) 34 papers in Composites Science and Technology (#1 in composites)
   b) 19 in major IEEE journals (Transactions on Dielectrics and Electrical Insulation, Transactions on Power Delivery, Insulation Magazine, Transactions on Reliability, and Transactions on Instrumentation and Measurement)
   c) 73 papers in other composites, physics, materials science, mechanics, general science and other journals
   d) 11 journal papers not listed under Web of Science; for example, Acoustic Emission (1982), Additive Manufacturing (2017), CIGRE journal (2016), Polish Technical Journals, and others
   e) Other papers in press (1), submitted (3) and to be submitted (4)
2. 60 papers at international conferences, 9 articles in major engineering magazines, and others
3. At least 50 large industrial and scientific reports, including two EPRI final published reports ($20k per copy) and numerous HVT Center annual reports to NSF and HVT industrial members
4. Citations

   3706 citations according to Google Scholar; h-index 36 and i10-index 97

Most Important Engineering and Scientific Accomplishments

Cambridge Years between 1984 and 1990

After graduating at WPR (one of the top engineering schools in Poland) in 1982, Dr. Kumosa was appointed an Assistant Professor of Applied Mechanics and Materials Science at WPR in 1983. In January 1984, mostly due to economic reasons, he left Poland and sought academic employment abroad. Initially, between January 1984 and December 1984, he worked as a Visiting Research Fellow at the University of Liverpool. Then, in December 1984, he moved to Cambridge, England where he spent more than six very productive years. In the Department of Materials Science and Metallurgy at the University of Cambridge working with Professor Derek Hull, FRS, Sir Alan Cottrell, FRS and Professor John Knott, FRS, Dr. Kumosa was exposed to state-of-the-art material science research and advanced composites research. Dr. Kumosa's final title at Cambridge was Senior Research Associate which is similar to our Research Fellow/Associate Research Professor.

At Cambridge, Dr. Kumosa conducted research on (1) application of Finite Element Methods (FEM) to failure predictions of advanced composite structures subjected to multiaxial loading conditions, (2) stress corrosion cracking (SCC) of Glass Reinforced Polymer (GRP) composites, (3) mixed mode failure and fracture of both GRP and Carbon Fiber Reinforced (CFRP) composites, (4) environmental failures of HT polymers, (5) application of Acoustic Emission (AE) for monitoring composite structures, and (6) composite crashworthiness. In particular, Dr. Kumosa made significant contributions to:

- development of the Iosipescu shear test showing how the test could be modeled by FEM including the presence of axial splits and their effect on composite failure predictions, a highly unique approach. He also jointly with W. Broughton redesigned the test to include biaxial shear dominated conditions (highly novel at that time).
- multiaxial testing of filament wound composite tubes; evaluated by FEM with experimental verification of the presence of hoop cracks in thin walled composite tubes (first time ever, not widely cited, however).
- crushing of composite structures; proposed the very first numerical model of a composite tube subjected to axial crashing (still widely cited internationally).
- monitoring of stress corrosion cracking in GRPs using acoustic emission (widely cited); showed how fractured fibers in SCC of GRPs can be precisely counted using AE.

Also at Cambridge, Dr. Kumosa finalized his PhD research on the initiation of cracking by mechanical twins in silicon iron. Using an anisotropic Eshelby approach, he predicted and experimentally verified stresses required to initiate cracks by terminated mechanical twins. While at Cambridge, Dr. Kumosa published fourteen international journal papers and several international conference papers. According to Dr. J. Knott FRS and Sir Alan Cottrell FRS, Dr. Kumosa made significant contributions to science during his Cambridge years as stated in their recommendation letters (copies available). Then, in May 1990, due to family reasons Dr. Kumosa moved to the Oregon Graduate Institute of Science and Technology in Portland, Oregon. The SCC and shear testing of composites projects moved with Dr. Kumosa to OGI. They subsequently became the nuclei of two very large research programs at OGI and later at DU on (1) the biaxial failures of HT polyimide composites and (2) in service failures of HV transmission composite insulators (the SCC research).

GE90 Research between 1990 and 1995

At OGI, between 1990 and 1995, Dr. Kumosa was involved, as a PI, in the failure analysis and design of advanced metallic alloys for jet engine applications as part of the GE90 project jointly supported by General Electric Aircraft Engines (GEAE), Precision Castparts Corporation, the State of Oregon and the Federal Bureau of Mines. His first research group in the US investigated the resistance to HT fracture and fatigue of nickel based superalloys and titanium aluminides used in the GE90 engine. HT fracture and fatigue tests were performed on a nickel based superalloy (Rene 220C) at room temperature and at 1200°F to evaluate the effects of hold times, frequencies, load amplitudes, creep, microstructure and other variables on crack growths in the alloys, simulating in-service conditions in the GE90 jet engines, which were about to be installed on Boeing 777 aircraft. Then, after the first two years and after accomplishing the original goals of the Rene 220C project, the efforts, still funded by the same sponsors, moved to the improvement of ductility of titanium aluminides, also for the GE90 project.

Dr. Kumosa's GE work was highly proprietary and not too much was published with the exception of one journal paper (Scripta Metallurgica, 29-5, Sept. 1993), **several successful technical reports (copies available) submitted to the sponsors and one PhD thesis (Dr. J. Ding, OGI, 1995). According to the sponsors at GEAE, Drs. Ken Wright, Ken Bain, and others, the superalloy and titanium aluminides projects managed by Dr. Kumosa at OGI were highly successful.**

Transition to PMC Research between 1991 and 1996

Also at OGI, when working on the GE90 project, Dr. Kumosa started in 1991/92 developing new research programs in the area of Polymer Matrix Composites (PMC), which was more consistent with his research experience gained at Cambridge. The PMC research programs were moved subsequently to the University of Denver. Dr. Kumosa's main research activities at DU between 1996 and 2014 were primarily related to (1) the use of PMCs at temperatures as high as 350°C for aerospace applications and (2) the use of PMCs in HV electric fields (up to 500kV) for power transmission applications. The successful programs were supported by three different consortia of federal and private sponsors all built originally by Dr. Kumosa at OGI and subsequently expanded at DU.

HV Transmission Line Insulator Research between 1992 and 2006

Between 1992 and 2006, Dr. Kumosa supervised major interdisciplinary research efforts in the area of HV composite insulators, also called Non-Ceramic Insulators (NCIs). The insulators are widely used in transmission line and substation applications in the US and abroad. In-service, the insulators are subjected to the combined action of extreme mechanical, electrical and environmental stresses. Due to the presence of these stresses, catastrophic failures of the insulators would occur quite frequently in-service in many regions of the world. Because of his composites background, in 1992 the US Government (DOE) requested Dr. Kumosa's involvement in a major study leading to the comprehensive evaluation of the suitability of polymers and their glass fiber composites in HV transmission line applications. The request came from the Bonneville Power Administration (BPA) and the Western Area Power Administration (WAPA). For more information please contact Mr. Mike Staats, Senior Manager at BPA and Mr. Ross Clark, VP for Engineering at WAPA (retired).

The primary goal of the HV insulator research was to understand the fundamental mechanisms leading to the premature mechanical and electrical failures of the insulators in-service and to greatly improve the design of the insulators to prevent those failures. This research was extensively funded through multiple contracts by the Electric Power Research Institute (EPRI) and a consortium of electric utilities and insulator manufacturers consisting of BPA, the Alabama Power Company (APC), WAPA, Pacific Gas & Electric (PG&E), the National Rural Electric Cooperative Association (NRECA), NGK-Japan and

Glasforms, Inc. Thanks to the generous support of these sponsors, Dr. Kumosa's research groups, initially at OGI and then at DU, made highly significant contributions to the entire field of composite insulator technology. Dr. Kumosa's most important accomplishments in this area consist of:

- Satisfactory explanation of several devastating groups of large HV transmission line insulator failures by brittle fracture experienced by:
    - Western Area Power Administration; catastrophic 345 kV failures in 1991/92 on their very large Craig Bonanza line in Colorado resulting in 14 energized line drops
    - Pacific Gas & Electric; 5 catastrophic 500 kV line drops on their Monterrey Moss Landing Line in California in 1995/96
    - several less severe but equally important in-service insulator failures internationally.
- First identification of the type of acid responsible for the brittle fracture failures in CA, CO and in many other parts of the world.
- First simulation of brittle fracture in the insulator GRP composites with and without high voltage; a very unique accomplishment and absolutely critical for the entire HV insulator industry.
- First comprehensive model and explanation of insulator failures caused by improper crimping.
- First identification of several critical conditions leading to brittle fracture and other mechanical and electrical failures of NCIs, which was the first comprehensive approach of this type leading to extensive insulator improvements across the globe.
- First ranking of the commonly used GRP rod materials for their resistance to HV brittle fracture and other HV failure modes (electrical, overcrimping, mishandling, etc.).
- Recommendation of numerous experimental and numerical procedures critical for insulator design.

Most of Dr. Kumosa's insulator research has been published in numerous major IEEE Transactions and composites journals (see his full Vitae). This research is still internationally cited and the citation rates are steadily increasing. The HV composite insulator research had a major international impact on the entire HV transmission industry (see 1-4 below). The 1992 and 1995 insulator failures at WAPA and PG&E had had devastating effects on the manufacturers and users of the NCIs around the world. The confidence in their suitability and in many cases their superiority over the old porcelain designs was reestablished by Dr. Kumosa and his internationally recognized HV composite research which was completed around 2006.

1. Interview with Maciej Kumosa of the University of Denver, Research of Brittle Fractures in Composite Insulators, Insulator News & Market Report, July/August 1997, pp. 47-51.

2. Research Program on Brittle Fracture Concludes at University of Denver; Interview with Maciej Kumosa, Insulator News and Market Report, July/August 2005, pp. 78-83.

3. Composite Insulator Failures Lead to Improved Designs, Transmission and Distribution World, January 2006 pp. 42-48.

4. Maciej Kumosa: Pioneering High-Voltage Research, Transmission and Distribution World, October 2012. http://tdworld.com/etrain/featured_instructor/kumosa-hv-research-1012/

HT PMC Combustion Chamber Research between 1991 and 2004

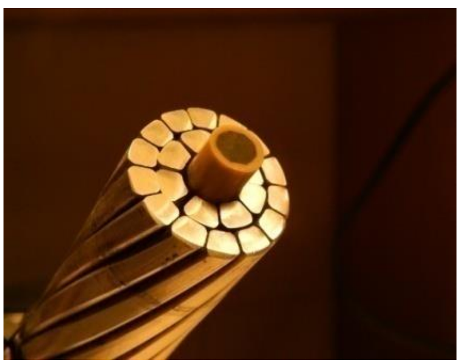
The second area of Dr. Kumosa's research on PMCs initially at OGI and then at DU was the numerical and experimental failure analysis of advanced HT carbon fiber/ epoxy and polyimide matrix systems for aerospace and space applications. The primary goal of this research was to understand fundamental failure mechanisms in HT composites based on medium and high stiffness carbon fibers and various HT polyimide resins. Particular attention was given to determining the effect of physical and chemical aging on the strength properties of the composites as a function of temperature and biaxial shear dominated loading conditions. Jointly with NASA Glenn, Boeing and 24 other large US industrial organizations, Dr. Kumosa was involved in the development of multidisciplinary technologies for affordable propulsion engine components that would enable systems to operate at higher temperatures with reduced cooling while sustaining performance and durability (http://www.grc.nasa.gov/WWW/RT2002/5000/5150sutter.html).

As part of the HT PMC efforts of the entire consortium, unique carbon/polyimide composites and fabrication technologies were developed, suitable for manifolds, thrust chamber supports and attachments. The usage of such composites allowed the replacement of heavy metal engine components to provide a high thrust to weight ratio. The designed and manufactured combustion chamber (see left) was successfully tested by NASA Glenn for five days in 2004 under full thrust conditions. Dr. Kumosa's portion of the study was extensively and jointly funded for nine years by the National Science Foundation (three consecutive grants), Air Force Office of Scientific Research (five consecutive grants), and the NASA Glenn Research Center (three contracts) with lots of interactions with the entire consortium. The work was supervised by Dr. Jim Sutter at NASA Glenn (for the entire consortium) and Drs. Tom Han, Ozden Ochoa and Charles Lee at AFOSR. The work of Dr. Kumosa's group and his graduate students resulted in:

- the development of highly unique experimental/numerical techniques based on embedded Al inclusions, X-ray diffraction and non-linear multiple inclusion Eshelby models for the prediction of residual manufacturing stresses in the HT PMC composites for unidirectional and woven laminates with various fabric architectures.
- predictions of failure properties of the composites at HT under multiaxial shear dominated conditions.
- evaluation of aging resistance of the composites in nitrogen (physical aging) and in air (chemical aging) at temperatures as high as 400°C, and many other important but less critical accomplishments.

The HT combustion chamber composites were optimized through the proper selection of fibers and matrices by Dr. Kumosa and his graduate students at DU for their HT behavior. This subsequently resulted in the successful testing of the combustion chamber (see above).

Polymer Core Composite Conductor Research between 2008 and 2014 at DU and then in the HVT Center after March 2014



Since 2008, Dr. Kumosa and his graduate students have been investigating HT HV Polymer Core Composite Conductors (PCCC) for HV transmission line applications. This research was initially funded between 2008 and 2014 by BPA, WAPA, Tri-State, CTC Global and NSF (GOALI) and then moved, in 2014, to the HVT Center. Due to the rapidly increasing demand for electric power and the development of new sources of energy, there is an urgent need in this country and abroad to be able to transport more electrical power, more efficiently, using the existing rights-of-way. However, the current designs of HV conductors based on strands of steel (for strength) and aluminum (for conduction), used in regional grids are limited by their propensity to sag. One of the incidents involving sagging of a steel/aluminum conductor and a subsequent HV discharge to a tree occurred in Ohio in 2003 (https://en.wikipedia.org/wiki/Northeast_blackout_of_2003) affecting 55 million people in Canada and the US. Therefore, new conductors, so called High Temperature Low Sag (HTLS) conductors with significantly better resistance to sagging are being designed. One of them is the PCCC design (see upper left).

The PCCC conductors are based on a unidirectional PMC core with carbon and glass fibers for strength and stiffness, and aluminum strands for conduction. They can transport up to three times more power than the current designs based on steel and aluminum. In addition, the PCCC sag less than established overhead conductors (carbon fibers shrink on heating!). Since the conductors are designed with an expected life of 50 years, their structural deterioration with time needs to be well understood considering in-service temperatures of up to 180°C, high concentrations of ozone, atomic oxygen, nitric acid and other pollutants, as well as a variety of extreme dynamic mechanical and electrical loading conditions. The major accomplishments of Dr. Kumosa's group to date in the HTLS conductor area are as follows:

- The critical bend radius of the most popular HT LS PCCC was determined numerically and verified experimentally by Dr. Kumosa and his students at DU in 2008-2010. This analysis subsequently explained three catastrophic international failures of the US manufactured conductors in Poland in 2008. Dr. Kumosa's involvement in the 2008 conductor failures was requested by the US government (WAPA, Mr. Ross Clark) and the explanations were reported to the international transmission line community in 2010 (IEEE PES, Minnesota July 2010) and in several IEEE papers. Dr. Kumosa's explanation of the Polish failures of this novel US transmission line technology helped rebuild the reputation of the manufacturer and reestablished its international standing. It also reestablished trust in the PCCC technology.
- In 2011, Dr. Kumosa was asked again by DOE (Mr. Ross Clark) to explain another PCCC failure, this time in Salt Lake City in Utah on a 230 kV line. The failure was caused by excessive bending under severe dynamic conditions. Similar to the Polish failures, the Utah failure was correctly explained and reported to the IEEE community.
- It was shown in 2009-2012 for the first time that PCCC rods could be sensitive to transverse loading under aeolian vibrations. It was also suggested that the bearing stresses due to crimping the conductor at a dead-end connection of a transmission line could be considered for effective fatigue life design. This effect was also for the first time evaluated for the PCCC rods at various stages of environmental aging (a highly unique combined experimental/numerical approach).
- Life predictions of the PCCC conductors were performed by the same group. It has been shown that the exposure to HT seems to be much more damaging to PCCC rods than the effect of highly

concentrated ozone. Considering the possible environmental conditions (HT, ozone pollution, and others), it was predicted that the PCCC rods could survive in service for many years if the operating temperature did not exceed 120°C with an ozone concentration of no more than about 1%. This however, should be further independently verified.

- Dr. Kumosa's group showed that the in-service life of the conductors could be greatly extended (by 75%) if special Teflon coatings were placed on the rods. Such coatings were designed in the Center and their feasibility was internationally demonstrated in 2015.
- The current PCCC design was evaluated for its resistance to corrosion on transmission lines (a major problem facing utilities using the traditional steel/aluminum design especially in coastal environments). In particular, a new powerful analytical model of atmospheric galvanic corrosion of the PCCC conductors was recently suggested and then numerically and experimentally verified in 2016 (rapidly gaining international recognition, Hakansson et al, Corrosion Science, 2017).
- The PCCC conductors were studied by the HVT Center in 2014-2017, for the first time, for their resistance to low velocity excessive transverse impacts by using unique impact fixtures and by simulating the impact behavior by FEM (Waters et al, Int. J. Impact Engineering, 2017). In this area, the conductors also demonstrated their superiority over their Al/steel counterparts.
- Dr. Kumosa's research group has also demonstrated that the PCCC conductors can be successfully monitored in service for a variety of static and dynamic loads using Fiber Bragg Grating sensors. The sensors can also be used to accurately monitor the conductors during installation and in service for both small and large deformations. Such monitoring can identify potential damage to the PCCC rods which may result in major catastrophic failures of the conductors in-service, even several years after their installation (the Polish failures). This important development was published in two papers in the IEEE Transactions on Instrumentation and Measurement (Waters, Hoffman and Kumosa, 2018, and Hoffman, Waters and Kumosa, 2019).

Dr. Kumosa and his research teams have improved the understanding of in-service performance of the next generation of HV HTLS Polymer Core Composite Conductors (similar to his previous HV composite insulator project), and suggested numerous potential improvements to their designs (see 1 below). No other research team has made similar contributions in this area so critical to so many utilities all over the world. One of the reasons why the HVT Center was awarded to Dr. Kumosa and his research partners from MTU, UIUC and UConn in 2014 was the exceptional progress of the PCCC research at DU between 2008 and 2014.

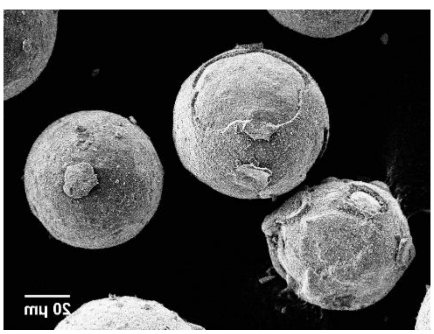
1. University of Denver Professor: New Transmission Line Product Would Save Lives, Denver Business Journal, May 24, 2013 http://www.bizjournals.com/denver/print-edition/2013/05/24/university-of-denver-professor-new.html?page=all

I/UCRC for Novel High Voltage Materials and Structures since 2014

It is beyond the scope of this document to adequately describe the size, complexity and national/international importance of all research efforts in the HVT Center. Four large research teams (34 mostly PhD students, 12 faculty, and 4-6 postdocs) in some of the best engineering graduate schools in the country have been solving major engineering problems and closely interacting with numerous industrial members. Since its inception, the Center has completed about 60 research projects concentrated in 5 major research areas (see the Appendix and the HVT Center Highlights). So far the Center has completed 12 major meetings, including; one grant planning, 5 our semi-annual, and five annual meetings with the industrial members, NSF representatives, the sites, and numerous invited guests.

Below, some of the key accomplishments from the recently completed and active HVTprojects just at DU under Dr. Kumosa's advising and supervising between 2017 and 2020 are presented showing their engineering/scientific complexities, importance and relevance to HVT technologies globally.

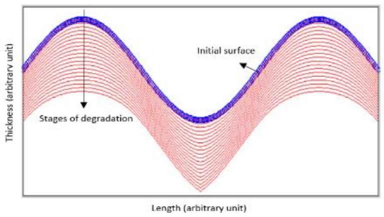
1. Effect of Oxygen Aging on Ti/Al/V Powders used in Additive Manufacturing



Jointly with NIST and Lockheed Martin, the HVT Center has shown for the first time that the effect of oxygen on the toughness of aerospace Ti/Al/V parts made by additive manufacturing can be accurately determined using an entirely new approach proposed by Grell, Kumosa, Loftus, et al., Additive Manufacturing, 2017. Ti/Al/V powders were first artificially oxidized in air and then used to make Charpy specimens with oxygen contents up to 0.5%. This resulted in a dramatic decrease in the toughness of the alloy. Using such data, aerospace and other industries can now relate, for the first time, oxygen contents in their AM powders due to the use of recovered unmelted powders to the reduction in the resistance to fracture of their parts made by AM.

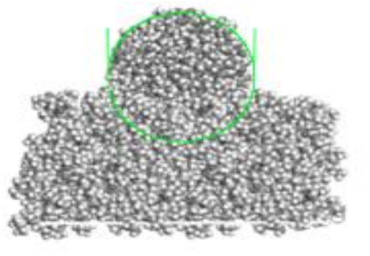
2. Synergistic Aging of Polymers and their Composites

Synergistic aging of polymers and GRPs composites exposed to UV, water (rain), temperature, and time was numerically simulated and experimentally verified. Unique numerical models of UV degradation of uneven polymer surfaces were constructed. Polymer micro-particles created by UV were then numerically



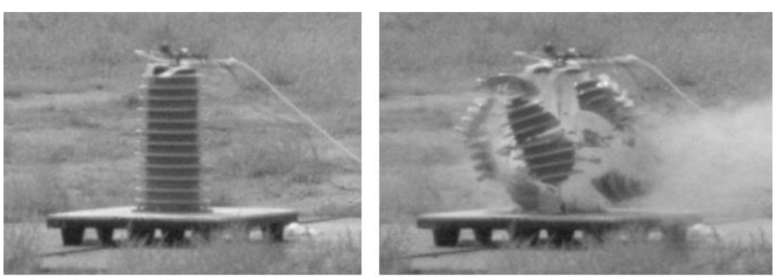
removed from polymer and composite surfaces by slowly moving rainwater. The numerical cleaning by water was supported by experimental verifications. The work has recently been published in Polymer Degradation and Stability (PDS) and in CST (Lu, Solis-Ramos, Kumosa et al, 2017).

3. Prevention of HV Silicone Rubber Aging in Extreme Environments



Extreme aging of silicone rubbers used in HV voltage applications was investigated in this highly transformative research. New molecular dynamics (MD) models of aging of the rubbers were proposed. The models were used to design the next generation of HV rubbers with embedded titanium dioxide particles to improve their resistance to extreme oxidative aging. As a result, a HV silicone rubber was designed, manufactured and tested with its resistance to extreme aging improved by about 50%. This critical HV transmission technology work has been published in PDS (Bleszynski and Kumosa, 2017) and in CST (Bleszynski and Kumosa, 2018). In addition, a new model of residual dielectric strength of the rubbers under dry band arcing and pollution has also between proposed (Allen, Kumosa et al, 2018).

4. Prevention of Ballistic Damage to HV Substations



(a) (b)

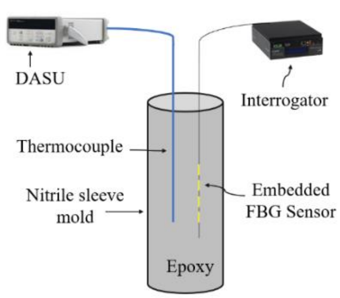
In this highly unique study performed jointly by the HVT Center, the US Bureau of Reclamation and the FBI, HV porcelain transformer bushings subjected to high power rifle damage were experimentally modeled as pressurized glass cylinders under air gun impacts. The cylinders were tested with ballistic polymer coatings for damage initiation and fragmentation. In their subsequent work, the authors tested full scale porcelain transformed bushings under high power rifle impact to demonstrate the effectiveness of the coatings for damage protection. It was shown for the first time that the bushings could be protected if sufficient coating thicknesses are used even under high energy, high velocity rifle impact conditions. The first part of this research, critical for electric utilities worldwide, was published in Int. J. Impact Engineering (Henderson, Kumosa et al, 2018). The full scale ballistic testing work on coated bushings was also published in the same journal (Henderson, Kumosa et al, 2019). Recently, we have also evaluated the efficiency of polymeric coatings in impact protection of brittle materials subjected to drop tower tests (Henderson et al, 2020, Int. J. Impact Engineering).

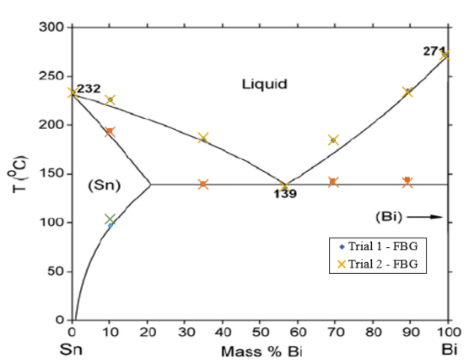
5. Monitoring PCC Conductors for in-Service Failures

The application of FBG sensors for the monitoring of full-scale transmission lines based on PCCC by (Waters, Hoffman and Kumosa, IEEE TIM, 2018 and 2019) has been described above. We have also recently completed a study to determine the strength limits of their composite cores. Both the effect of axial tension and the influence of fiber misalignment on the conductor's bending strength were investigated using a combined experimental, analytical, and numerical analysis. Using three and four-point bending experiments and a non-linear finite element model, the axial stresses and likely failure initiating locations were identified in the rods. Damage modes considered included tensile failure and compressive failure due to fiber buckling and kink band formation.

6. Evaluation Polymerization and Solidification using FBG Sensors

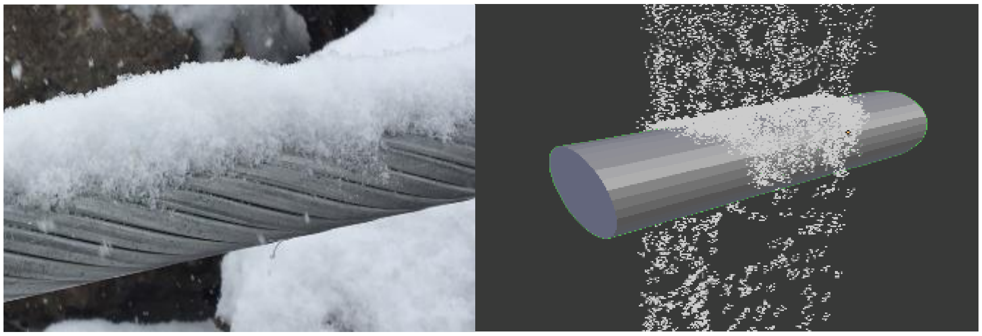
A novel technique using FBG sensors has been created in the HVT Center to evaluate the responses of modeled polymer and metal composites to manufacturing conditions. For the polymers (epoxies), FBG sensors were used to identify the beginning and end of curing, the gel point, cooling strains and stresses. Unique algorithms were developed to calculate the residual stress in the matrix using a non-destructive technique (Hoffman et al. CST, 2020 and Khadka et al, 2020, Composites Part A). For the metals, a new approach was developed to determine phase diagrams and an algorithm was created to identify residual strains and stresses in the fiber and the metal, all based on FBG measurements (Khadka et al, Acta Materialia, 2020 to be submitted). This non-destructive technology is being rapidly developed to monitor in-service aging of materials and extreme aging including thermal and chemical decomposition, various





manufacturing methods (including stresses during additive manufacturing), and the impact of many other stressors.

7. Design of Next Generation Icephobic Barriers



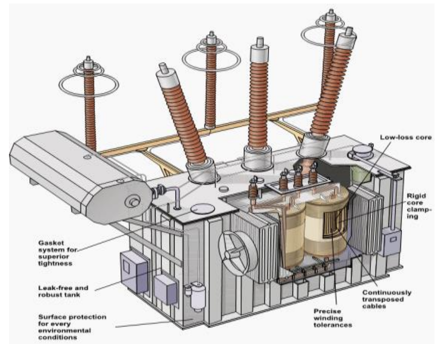
Ice adhesion to ultra-low energy surfaces, ice shedding, ice accumulation prevention and aging of ice barriers have been very successfully studied by Bleszynski, Woll, Middleton and Kumosa since 2016. The group managed to reduce ice accumulation on HV PCCC by 50% by coating the conductors with a new icephobic barrier very recently designed by the HVT Center. Ice adhesion to the barriers was also reduced to about 7kPa, which is very low in comparison with the adhesion of ice to Al (about 500kPa). Unique MD, FEM and particle physics based type models of ice adhesion, ice melting and accumulation, and ice prevention have also been recently proposed by Dr. Kumosa's graduate students in several papers; Polymer Degradation and Stability (Bleszynski et al, 2019), Materials & Design (Bleszynski and Kumosa, 2019), and Bleszynski et al, , Int. J. Molecular Sciences, 2020.

8. Other Recently Completed HVT Research Projects by Dr. Kumosa's Research Group at DU

- "Recycling Carbon and Glass Fiber Polymer Matrix Composite Waste Into Cementitious Materials" by Clark et al. in Resources, Conservation and Recycling, 2020.
  In this highly successful research, we investigated if hybrid carbon and glass FPMC waste could be recycled as an admixture for cementitious materials in order to improve their properties for seawater applications. We assessed the compression strength of ordinary Portland cement (OPC) with 6% wt of various FPMC admixtures before and after accelerated salt-water aging. The experimental part of this research was strongly supported by molecular dynamics simulations (MD) to examine the effect of FPMC admixtures on moisture diffusion in OPC.

- "Visualizing Polymer Damage Using Hyperspectral Imaging" by Bleszynski et al, in Polymers, 2020. Hyperspectral imaging (HSI) and previously investigated aging methods were successfully used as a proof of concept to show how HSI may be used to detect various types of aging damage in different SIR materials. The spectral signature changes in four different SIRs subjected to four different in-service aging environments all occurred between 400—650 nm.

9. Modernization of the Large Power Transformer Tanks; New Venture On Going Project Funded by DOE Headquarters through HVT Center



Large Power Transformers (LPT) are a key component of the electrical grid. A formalized approach has been developed at DU to identify substitute materials for LPT tanks (Williams et al, Materials &Design, 2021, submitted). The ideal materials should be capable of maximizing reliability parameters, such as strength, stiffness, toughness, and resilience, while minimizing weight. In addition, the selection process is designed to incorporate the potential for self-healing and smart sensing. A preliminary selection stage followed by a TOPSIS optimization stage identified five advanced composite materials as potential replacements.

Appendix

I. Original Research Goals and Objectives of HVT Center

The I/UCRC for Novel High Voltage/Temperature Materials and Structures ("HVT Center") works jointly with the electric utility, aerospace, nuclear, military, environmental, automotive, health, and other industries with needs of novel HV/T materials and structures. The objectives of the Center are: (1) Design of novel and evaluation of existing HV/T energy transmission/transfer multifunctional materials for next generation composite conductors, insulators, underground cables, towers, and other electric power transmission structures; (2) Design and development of novel advanced high energy transfer materials for aerospace, oil/gas, automotive, and other industrial applications; (3) Failure prediction and prevention of HV/T materials and structures under in-service conditions through state-of-the-art multi-scale modeling and material performance evaluations; (4) Development of new failure monitoring techniques and material repair methods in HV/T materials under laboratory conditions and their subsequent transfer to in-service inspection and repair.

The HVT Center has a diverse and interdisciplinary educational, research and business environment for (1) undergraduate and graduate students, including those from underrepresented groups, funded by the research projects of the Center; (2) faculty members from a variety of disciplines, including junior faculty starting their academic careers; (3) utility, aerospace and national lab engineers and designers developing various types of HV/T materials and structures; and (4) utility managers supervising HV transmission lines across the country. The Center enhances the reputation of U.S. HV/T manufacturing around the world and, in particular, improves the level of confidence among the potential users of novel HV/T structures. The center targets long-term benefit to infrastructure, manufacturing, energy transport and efficiency of the electric grid, and the durability of other HV/T and high energy transfer structures.

II. Current Project Portfolio since May 16, 2018

Research Area 1. Multiscale Design and Development of Novel HVT Materials

- 1.2 Aluminum Alloys for High Conductivity and Strength (MTU)
- 1.3 Aging Resistant RTV Silicone Rubbers and their Nanocomposites (DU)
- 1.5 Development of Durable Icephobic Barriers (DU)
- 1.6 HVDC/MVDC Cabling: Electronic Structure of Polyolefin (UConn)
- 1.7 HVDC/MVDC Cabling – Space Charge Dynamics (UConn)

Research Area 2. Advanced Manufacturing of HVT Materials

2.2 High Temperature/Voltage Polymers and Nanocomposite (UIUC)
2.5 Titanium (Ti) Intermetallics, Ti Alloys and Superalloys for Extreme HT Aerospace, Automotive and other Applications (DU)

Research Area 3. Environmental Degradation of HVT Materials and Structures
3.4 In-Situ Sensing of Manufacturing and Aging of HVT Polymer Matrix Composites (DU)
3.5 Recycling Fiber Reinforced Polymer Matrix Composite Materials (DU)

Research Area 4. Damage Prevention of HVT Materials and Structures
4.2 Prevention of High Velocity Impact Damage to Substations (DU)
4.4 HVDC Grid Hardening against Geomagnetic Disturbance (UConn)
4.5 Discharge Resistant Materials for Circuit Breaker (UConn)

Research Area 5. Monitoring and Diagnosis of HVT Structures/Equipment
5.1 Applications of FBG Sensors in HVT Materials and Structures (DU)
5.5 Vibration of HVT Cable Structures (UIUC)
5.6 Photo-acoustic Based Dissolved Gas Analysis (UConn)
5.7 HT FBG Sensors for Temperature and Strain Sensing Applications (DU)
5.8 Remote Sensing of HVT Structures Using Hyperspectral Imaging (DU