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The New Face of Engineering

A Keynote Address by

Dr. W. David Williams
Director, Information Solutions & Services Center
Sandia National laboratories

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Introduction

Thank you for inviting me to present the Keynote Address to the Iowa Advance Manufacturing Conference at Kirkwood Community College. I consider it a great honor to be invited "home" to Iowa.

I said I am coming "home" to Iowa for I have a very special relationship to this state. My grandfather was Pastor of the Congregational Church in Spencer, IA. As a young boy, I recall vividly my extended summer stays at grandpa and grandma's house. Iowa also became the retirement home of my namesake uncle, Col. David Parsons. Uncle David had the good sense to marry a Fairfield, IA farm girl during his time as a student at Parsons College – no relation. Upon completion of a brilliant and distinguished Army career, he held true to his word – a family practice – and moved to Burlington, IA where his widow, my beautiful aunt Helen resides to this day. My Uncle David and my mother are buried in a small country church's cemetery, near my aunt's farm north of Fairfield.

And, on a professional level, it has been my honor and privilege to be the Sandia National Laboratories' side of a very wonderful collaborative relationship with Jack Harris and Rockwell Collins. Jack and I championed and led a Cooperative Research & Development Agreement. Through this CRADA we, at Sandia National Laboratories in Albuquerque NM, were able to design a radar fuse deck to Rockwell Collins' manufacturing rules and our mission needs. We electronically transferred the design from Albuquerque, NM to Cedar Rapids where its manufacturability to Rockwell Collins rules and standards was assessed and improved. One design iteration later, the product was realized on the highly agile, ***production*** manufacturing floor at the Rockwell Collins' Cedar Rapids plant and pin testers automatically programmed to our design's test vectors. Futuristic "Big M" manufacturing? To be sure – but, this was done in 1996.

So, you see on both a very personal and professional level, I often fondly think of Iowa as "home." And, I would be honored if you would permit me to continue in this practice. Were you to impose a residency for such an honor, then I would add that I have spent sixteen of the most challenging and spirit-raising weeks of my life as an Iowa resident. I have been privileged to ride RAGBRAI sixteen times. I have enjoyed Iowa's hospitality, and I been fueled by Maid-Rites and farm cooking across OUR beautiful rolling hills. It wasn't all wonderful – I have cursed OUR river valleys as I "powered" my bike out of their clutches, and I have been drummed to near-death as I was hammered by OUR rumble strips at country road intersections. But, I have also slept a peaceful sleep on OUR college campuses, OUR capital grounds, and in OUR parks and fairgrounds. Iowa, if you will have me, I am proud to call you my adopted state, and it is great to be home again.

For all of these reasons, I am very pleased to be here today. In addition, I am very pleased today to represent the men and women of Sandia National Laboratories as your Keynote speaker for this session.

A Proud Heritage – Slide 2

Sandia is proud of its science and engineering heritage. We've had a major impact on the wellbeing of this country, starting with our role as engineers of the nation's nuclear weapon stockpile and continuing as developers of new science and technology that has made the stockpile safe and reliable over the decades. And we are not just proud of *what* we've accomplished, we are also proud of *how* we have accomplished it. Our success has always been enabled by the science foundations that underpin everything Sandia does.

Response to October 1957 – Slide 3

The beeps from Sputnik, launched by Russia into orbit in October 1957, were responsible for galvanizing our country's commitment to investing in science and engineering. That commitment paid off big-time: it allowed us to become the unsurpassed leader in creating, engineering and selling innovative high-technology products in the world marketplace. It enabled a standard of living in the United States that other nations envy and that we as citizens have begun to take for granted.

The world is complex and getting more so – Slide 4

But times have changed significantly since 1957. The world is changing; it is getting much more complex every day. There are escalating old threats – such as proliferation of nuclear weapons and severe natural disasters – and worrisome new threats – such as US competitiveness in the marketplace, terrorism, increasing domestic violence and biological warfare – that confront US citizens today. The increased complexity of these problems forces us to reexamine our engineering methodology and the preparation of our engineers. What changes must we make to our engineering methodology to enable us to tackle such complex new problems successfully? Do we need to make changes in how we educate our future engineers to equip them to solve these problems?

Speed, cost, and reliability are drivers for new engineering methodology – Slide 5

Today, economic and marketplace drivers are dictating the nature of our engineering attributes. Regardless of the product that is being engineered, the world demands that it be designed, developed and produced in much shorter time and at much lower cost than ever before. Once it is produced, the product is expected to achieve unprecedented reliability during its service life.

Gathering Storm and State of the United States – Slide 6

For decades, we have learned to take for granted our nation's supremacy in science and technology. That technological supremacy resulted in US preeminence in the sales of high-technology products throughout the world. But the world is changing! Several nations have faster growing economies than ours, and they are investing an increasing percentage of their resources in science and technology research and education. Study after study warns us that our technological supremacy and our economic wellbeing will be at risk if we remain satisfied with the *status quo*.

Engineering as we practiced it – Slide 7

Sandia engineers have always strived to base their engineered solutions to problems on a thorough understanding of the physics underlying their problem. Furthermore, they always attempted to embody their understanding in analytical or computational models so that they could predict engineering outcomes of candidate designs before they built them.

For many years, however, the predictive models - and the computers on which they ran - were unable to reproduce the relevant physics with sufficient fidelity. So Sandia relied primarily upon full-scale testing as the basis for designing and developing new products. Over the years, we developed world-class test capabilities and outstanding engineers in support of our mission for the Department of Energy. We look back with pride at the safe and reliable DOE weapon systems that this test-based engineering approach has produced over the past 50 years.

Engineering as we need it – Slide 8

But what worked in those days won't automatically work tomorrow unless we enable it to keep pace with our customers' needs. In this rapidly changing world of new technology and new products, our engineering approach must be much more agile and efficient than has been required before. To achieve these demanding levels of agility and efficiency, Sandia must move from its tried-and-true test-based engineering approach to a *predictive*, *science-based* engineering approach. We call this approach "science-based" because we base it upon a thorough understanding of the underlying physical phenomena that govern the operation of the product. We call it "predictive" because we intend to capture our physical understanding in validated numerical simulations – computer models – and use them instead of full-scale test results to provide the information needed to make decisions. Because engineering problems must span such a wide range of technologies and engineering functions, we expect to see engineers working together in teams much more often than in the past.

***Columbia*: a hard problem – Slides 9, 10 and 11**

You undoubtedly remember with sadness that on February 1, 2003, the Space Shuttle *Columbia* broke up during its return to Kennedy Space Center and the lives of seven astronauts were lost. At the time, the precise cause of the accident was not known; all NASA had was film of the liftoff of *Columbia* showing that some foam insulation came loose from the external fuel tank and hit somewhere on the underside of the wing (Slide 9). Sandia was asked to apply its science-based modeling and simulation codes to help NASA pinpoint the specific cause of the accident.

Sandia's large deformation mechanics codes were used to predict the extent of the damage caused by the impact of the piece of foam into the reinforced carbon-carbon (RCC) wing leading edge (the blue objects in Slide 10). Sandia performed experiments to measure the mechanical properties of both the foam and the RCC; these material properties were then put into the numerical simulation. The red colors in Slide 10 show the regions where the bending stresses are more than enough to break the RCC. The calculations indicated that the most probable cause of the accident was foam impacting the leading edge of *Columbia's* left wing. Several months later, NASA conducted full-scale tests of the same foam impact scenario that confirmed Sandia's numerical predictions (slide 11).

Tires are not what you really think – Slide 12

Even commonplace products like automobile tires can benefit from the insights provided by computational modeling and simulation. Because we are so used to them, we may lose sight of the fact that they are a complex structure, especially when they are subjected to the extreme environments of racing. At 330 mph, the tires of this top fuel dragster are not even close to being round; standing waves emanating from the tire's contact patch cause extreme distortions of the tire, shaping them into a grotesque pentagon as the dragster crosses the finish line. At the start of the race, the tires are distorted by the enormous torque that they must transmit from the engine and drive train to the race track surface. Engineering the tire to survive – let alone provide optimal traction – in this environment is a difficult task.

Our work with Goodyear – Slide 13

For decades, Goodyear Tire and Rubber Company had used a test-based engineering process for designing its tires for both the street and the racetrack. But in the early 1990s, they realized that they needed to reduce the time required to design a tire that met performance requirements and get it to the marketplace. Goodyear partnered with Sandia to develop finite element modeling and simulation codes that could be used in tire design instead of their design-by-test approach. The computer model of a tire is as complex as the tire itself; all of the different layers and materials that comprise a real tire have to be modeled as connected elements in the computer model. The laws of physics that govern the forces and moments acting on each element are also modeled on the computational simulation.

Matrix Shorthand for Whole Tire – Slide 14

Then the computer forms a matrix which represents the combination of physical laws, material properties, and connections between elements. A complete tire model would have approximately 450,000 elements. A person using a hand-held calculator would require approximately 2.7 years (with no time off!) to solve all of the matrices associated with 450,00 elements.

Fully Treaded and Rolling Model – Slide 15

It gets harder when the effects of rolling and cornering of the tire must be taken into account. For this real-world problem, more than one thousand million - million calculations must be made to predict the tire's stress "footprint" with enough fidelity and clarity to determine that the calculation does indeed represent reality.

It took Goodyear and Sandia several years to bring the computational models to the point where they could be trusted as a tire design tool. Today, Goodyear's executives are telling the world that these computational models have helped to transform the marketplace success of their company. They are used in the design and development of their entire line of passenger car tires.

Small, smart things are among us – Slide 16

Have you noticed how the latest high-tech products are shrinking? Electronic devices that used to be cumbersome in the past are now smaller – and at the same time smarter – than ever before. Advances in microsystems are making this possible …

The future of microelectronics – Slide 17

… but how long can this go on? The consumer doesn't want it ever to stop because each new generation of devices has higher performance, greater utility, and new features at an affordable price – all made possible by technology that continues to shrink the feature size of microsystems.

The secret to a successful future in microelectronics rests in how well engineering can translate the latest discoveries in material sciences and physics into innovative, manufacturable products for the marketplace.

Extreme Ultraviolet Lithography (EUVL) – Slides 18, 19, 20 and 21

How does an engineer build devices that are too small to see, let alone measure? A few years ago, Sandia led a team of Department of Energy laboratories to develop a new process for manufacturing the wafers used in microsystems. The process is called Extreme Ultraviolet Lithography (EUVL). For EUVL to be successful, however, it must project a very precise image of the desired wafer features onto the wafer; this is accomplished by shining extreme ultraviolet laser light onto a "mask" and then projecting the image from the mask onto the wafer.

Sounds simple, right? But it's not. That is because the image must be accurate to within a few nanometers (one billionth of a meter), or else the wafer must be thrown away. However, the heating of the mask by the laser can cause thermally-induced deformations of the projected image that are larger than a few nanometers. Therefore, the EUVL engineering challenge is to design the illuminator and main wafer manufacturing chambers of the Engineering Test Stand (ETS) (Slide 18) to assure that distortions of the mask (Slide 19) due to laser heating are less than a few nanometers. Because there was no existing method to measure such small deformations at that time, the engineers had to rely solely on computational modeling of the chambers, mirrors, masks and wafers to establish the chamber design and mask material properties that met these stringent requirements.

Engineers prepared a thermal model of the entire EUVL Engineering Test Stand. Slide 20 shows that the image distortions predicted by the thermal computational model were unacceptably large when the mask was made of silicon. That undesirable result was caused by the large coefficient of thermal expansion (CTE) of the silicon material. So the engineers looked for other materials with lower CTE values. When they replaced the silicon mask with a mask made from Ultralow Expansion Glass in their computational model, the predicted distortions were reduced to an acceptable level (Slide 21). The computational model was then used to define the EUVL ETS design. The project engineers trusted the predictions and built ETS hardware based entirely upon them.

Predictive science-based engineering - Slide 22

The EUVL project illustrates both the *process* and the *power* of predictive science-based engineering. Starting with a thorough understanding of the underlying physical phenomena, computational models of the phenomena are prepared, validated and used to design complex engineering systems *before* building any hardware.

Engineering the invisible - Slide 23

As engineers are called upon to design smaller and smaller advanced microsystem components, they will have to learn about the behavior of materials at the nanoscale and then translate that understanding into computational models. Because the physics at the nanoscale is so different from the physics at the macroscale (the size range that our unaided eye can see), we should expect that success in "engineering the invisible" will come only if we conduct research to enable our understanding and conduct experiments to validate the computational models.

MESA: A revolution in the making – Slide 24

Center for Integrated Nanotechnologies (CINT): Getting to the bottom of it – Slide 25

The Department of Energy has made major investments at Sandia to provide the research and manufacturing facilities needed to engineer future generations of microelectronics for the country. "MESA" stands for Microsystems and Engineering Sciences Applications. The MESA facility is the largest investment in Sandia's history — $462 million. When opened later this year, MESA will bring together unprecedented capabilities for advancing the science, systems engineering and components of microsystems. CINT contains state-of-art special equipment devoted to the characterization, synthesis and integration of nanotechnologies. Sandia's vision is to use these facilities as centers for learning and collaboration in microsystems and nanotechnology with scientists throughout the country.

Today, we are engineering at the nanoscale – Slide 26

To obtain the desired performance from the next generation of microsystems, engineers must engineer materials at the nanoscale. "Engineering at the nanoscale" means arranging and organizing groups of atoms – roughly 50 atoms across – to create "designer materials," whose properties can be tailor-made for the needs of the next microsystem. The tools used to design these designer materials are computer simulations which (as shown in Slide 26) predict how the suspended groups of atoms will respond to the magnetic fields imposed upon the materials in suspension.

Training the next generation of engineers – Slide 27
Advancing the practice of engineering – Slide 28
The Engineer of 2020: rethinking how engineers are trained – Slide 29

It stands to reason that the next generation of engineers will have to be prepared to take advantage of the advances in science and technology and to turn them into innovative products that serve mankind well and are successful in the marketplace. While engineering students will still require a solid foundation in mathematics and the physical sciences, they will also be required to bridge multiple technologies (because the things they engineer embody multiple physical phenomena) and multiple disciplines (including business, social and communication skills).

Sandia is already using its state-of-the-science MESA facilities and computing resources as centers for bringing together students and Sandia experts to advance the practice of engineering in microsystems (Slide 27). Many students from around the country have already benefited from the access to Sandia's people and unique engineering capabilities. Sandia's outreach to universities is critical to bring along the next generation of engineers.

Advancing the practice of engineering would be impossible if it were not for the enormous advances in computing made during the past decade. Slide 28 shows how much Sandia's computing capacity has increase over that time period. The key to a successful predictive science-based engineering capability is harnessing the massive power of modern computers and computational algorithms to our understanding of the physics of the things we want to engineer. Successful modeling and simulation is not just about computing faster; it's really about *computing smarter*! And that's what Sandia's Computer Science Research Institute (CSRI) is about. It's about figuring out how to "figure out" better. It's about thinking through what a computer can do and doing it in a very efficient way, a very clever way, with fundamental mathematics and people who have put creative thought into it. The CSRI is a place to bring people from all over, to get those ideas, pull them together, and enable this idea of rethinking how computing is done, and hence rethinking how *thinking* is done.

Painting the future: a call to leadership – Slide 30

Combining Sandia's formidable engineering research and development facilities with its world class computational capability is a key driver in helping the United States revolutionize engineering and innovative thinking. This is about a new beginning for American technology and our rightful place on the globe. But that's just one part of the vision we have for Sandia and America's engineering schools. To make this vision real, the country needs leadership, both now and in the future. I believe that Iowa's industry and universities can provide much of that necessary leadership in engineering and technology.

We'll need many of us in this room to step up to the challenge. The wellbeing of our nation – its security, its prosperity, and its ability to provide for itself enough energy to run the country – is at stake. Time is short because technological advances are accelerating and economic competition is rising up quickly. Our vision is that the country's best engineering laboratories must partner with the country's best industries and universities to grow the next generation of engineering and manufacturing leadership. Be vigilant, the stewardship and growth of innovative engineering and manufacturing – the very thing that made our country prosperous in the last century - is placed in our hands in this century.