MULTIPHYSICS SIMULATION

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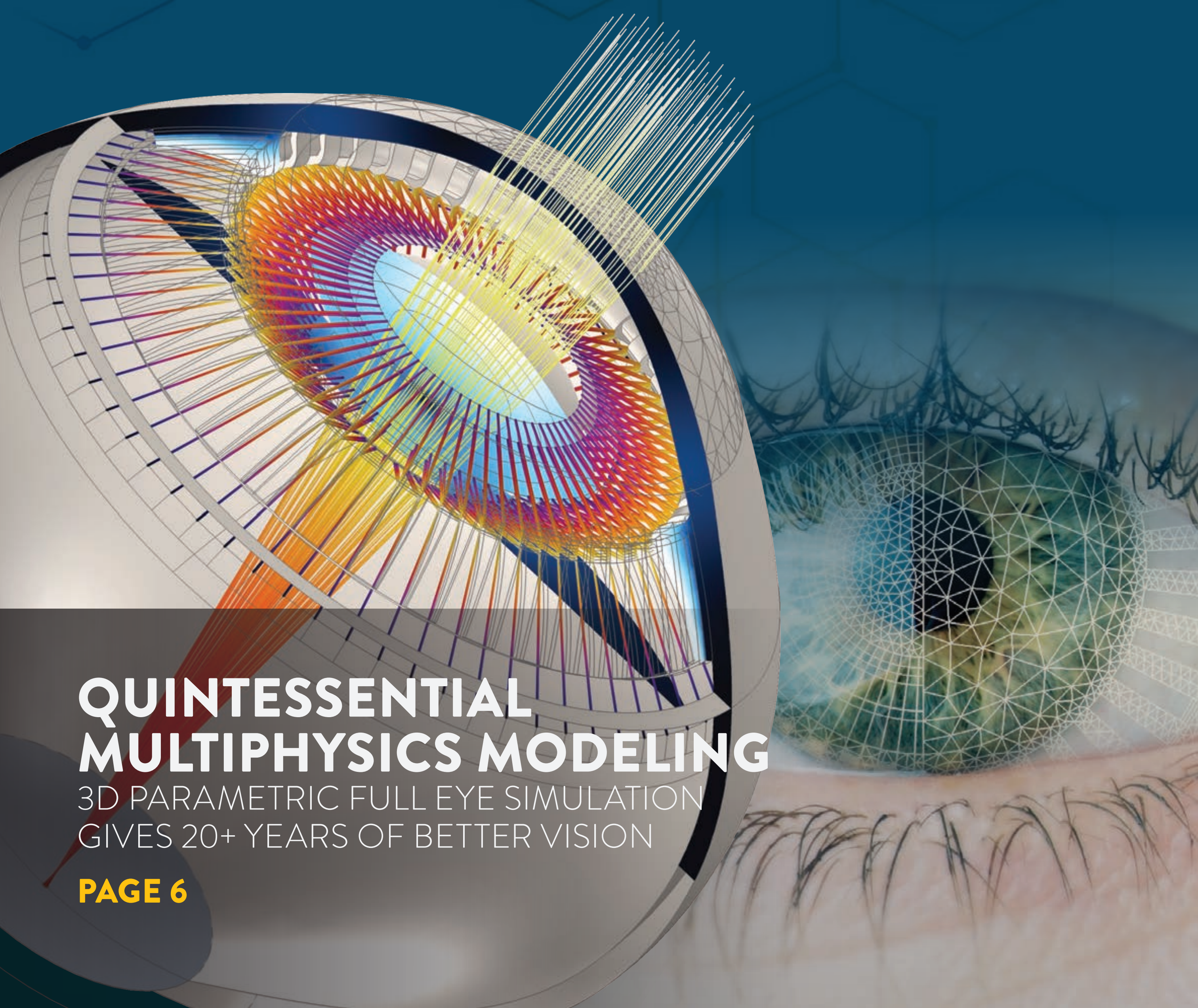


QUINTESSENTIAL MULTIPHYSICS MODELING

3D PARAMETRIC FULL EYE SIMULATION GIVES 20+ YEARS OF BETTER VISION

PAGE 6

MODELING THE FUTURE WITH MULTIPHYSICS SIMULATION

By **MICHAEL FORSTER, MANAGING DIRECTOR — PUBLICATIONS, IEEE**

MULTIPHYSICS SIMULATION is a remarkable and versatile tool. On the medical research front, it's making advances in eye surgery possible. Kejako, a Swiss medical device company, has built a complete simulation of the human eye that models both the mechanical and optical behaviors of this remarkable organ. They are hoping to use this work to develop surgical solutions for patients affected by presbyopia, a disorder of aging eyes that makes it hard to focus on nearby objects.

STMicroelectronics, a world leader in semiconductor solutions, is using multiphysics simulation to build chips optimized for mobile and wearable devices in medical and health monitoring.

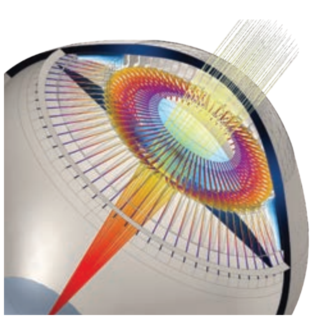
Multiphysics simulation has also made it possible for engineers to tackle research problems that were previously too difficult or too expensive to undertake. For example, researchers at General Atomics are getting closer to achieving one of the holy grails of energy production by using multiphysics simulation to help create magnetically confined fusion in a tokamak machine.

Physicists at Giesecke+Devrient Currency Technology are using it to develop sensors for high-performance banknote processing systems that can securely sort and process millions of banknotes every day.

From life-saving technology to protecting the global economy from counterfeit money, multiphysics simulation empowers organizations worldwide to build innovative products for a better tomorrow.

I hope you enjoy learning about the exciting work featured in this special COMSOL report. ◎

Michael B. Forster, Managing Director, IEEE Publications



ON THE COVER: Visualization of total displacement and ray trajectories in a 3D parametric full eye simulation. Image is courtesy of Kejako SA.

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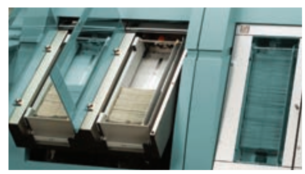

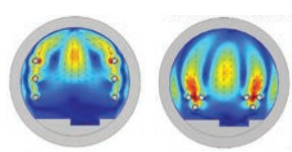

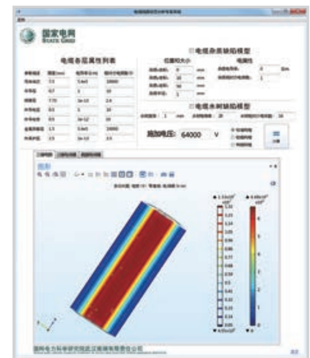

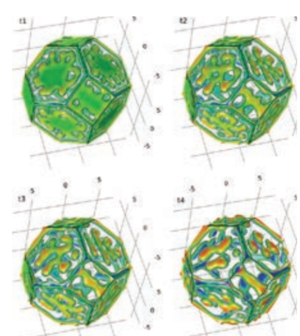

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TIPTOEING THROUGH THE TULIPS TO PROTECT POWER PLANTS

Engineers at ABB are using multiphysics simulation to continuously improve the current-carrying capacity of their generator circuit breakers, protecting power plants around the world from current surges and ensuring uninterrupted generation of electricity.

By **ZACK CONRAD**

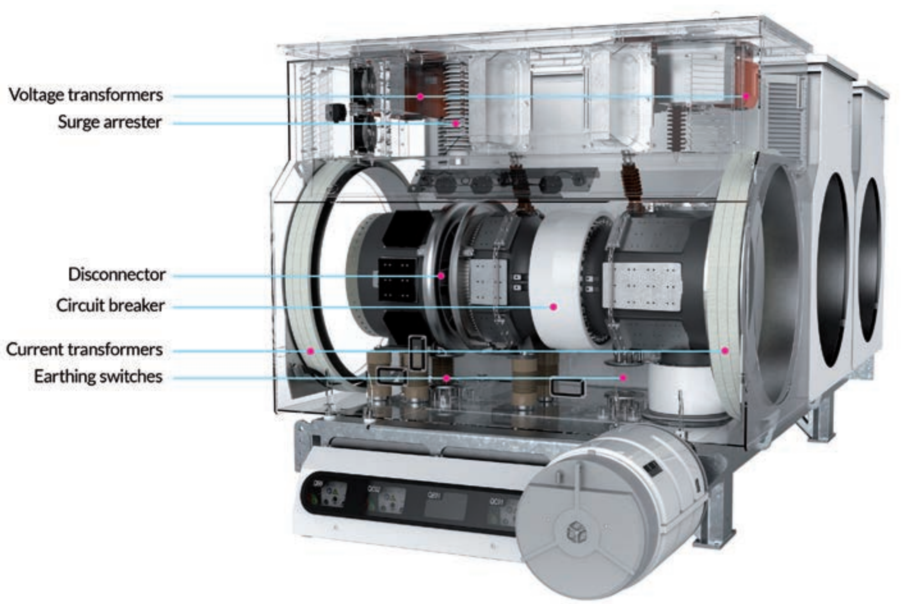


Figure 1. An inside view of an ABB generator circuit breaker (HEC10-210). Image credit: ABB.

IN SOME WAYS power plants are the backbones of modern society. With systems as integral to technological order as these, protection against downtime is pivotal. Whether it's a nuclear, coal-fired, or hydropower plant, they all have one insurance and protection policy in common: generator circuit breakers (GCBs). Playing a key role in power plant protection, GCBs protect plants from high surges of current (Figure 1). By interrupting potentially harmful short-circuit fault currents caused by faulty wiring or grid issues within tens of milliseconds, GCBs prevent important plant assets from severe damages. In a world where the smallest downtime can potentially cost millions of dollars, it is no surprise that these devices are so critical. ABB Group, a multinational leader in electrification products, robotics and motion, industrial automation, and power grids, develops GCBs to safeguard power plants around the world.

The challenge of dealing with short circuit current surges is that they can arise from either the grid or the generator at any given time. Because of this, GCBs must not only be extremely reliable, but they must have exceptional availability and be able to operate flawlessly, even after a long period of dormancy. Under normal operation, the GCB is a regular, low-resistance part of the circuit that connects the generator to the transformer and the grid. The GCB transfers the generated electric energy to the high-voltage transmission system in a dependable way. But when needed, it must be able to interrupt currents many times larger than normal operating conditions and extinguish them without damaging other components.

GROUNDING THE SYSTEM WITH TULIP SWITCHES

EMPLOYED IN THOUSANDS OF POWER plants around the world, the GCBs developed by ABB provide a safe and reliable connection, with a lifetime of at least 30 years. But Francesco Agostini, Alberto Zanetti, and Jean-Claude Mauroux, engineers at ABB, are continuously improving their designs to keep up with modern demands. When an upgraded version is developed, there are extensive testing standards that must be met in order to warrant commercial use. Some of these standards apply to the earthing switches (Figure 2), a critical safety component within the circuit breaker system. "The task of an earthing switch is to ground energized parts of a system, electrically connecting them to the earth," Mauroux explains. "They are also used to protect personnel while working on operational equipment and must therefore be very reliable and safe, even under adverse climactic conditions."

There is a delicate balance that must be met for an earthing switch design. A well-known design that ABB uses for their earthing switches is a tulip configuration. This design employs silver-plated fixed and sliding contact fingers that provide a disconnecting contact for current to flow through and springs to apply static forces to each

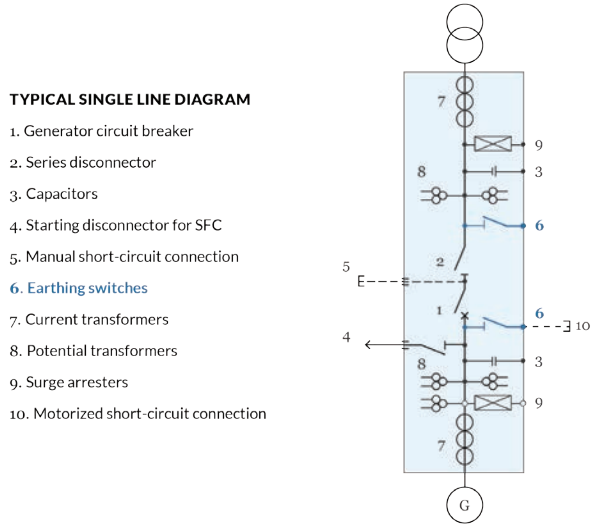


Figure 2. Typical single line diagram of a circuit breaker system showing the placement of the earthing switches.

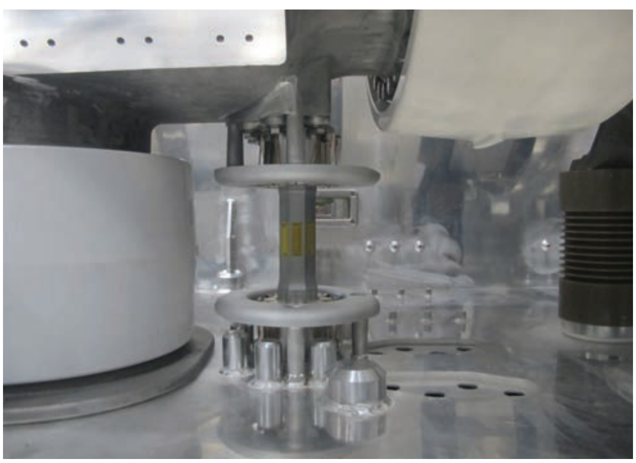


Figure 3. Earthing switch in closed position in a GCB. The moving pin connects the upper and lower tulip contacts. Image credit: ABB.

> *"We passed the type tests with room to spare, demonstrating the harmony in which simulation and experimentation can exist."*
>
> **—FRANCESCO AGOSTINI, HEAD OF TECHNOLOGY DEVELOPMENT GCBS AND MATERIALS, ABB**

finger. On one hand, it must be able to withstand the full short circuit fault current according to the International Electrotechnical Commission (IEC) standards when the contact is closed (Figure 3). On the other hand, the tremendously high currents cause large electromagnetic forces to arise, and the side effects of these must be managed accordingly.

The ultimate focus of the contact system of an earthing switch is the current-carrying capacity, but to understand the complex effects of the contact force on it, Agostini, Zanetti, and Mauroux needed the assistance of multiphysics simulation to quantify the total forces acting on the contact. Using the COMSOL Multiphysics® software, they proceeded to construct an earthing switch tulip contact model to simulate the coupled electromechanical behavior.

» *FINGERS, FIELDS, AND FORCES*

THE EFFECTS OF THE ELECTROMAGNETIC forces that act on the fingers of the tulip contact are twofold. The Holms force, a force that stems from electrical contact points, causes a repulsion. The Lorentz force, a force on a current-carrying object in a magnetic field, causes an attraction. The issue lies with ensuring the attractive force is far greater. A repulsion of the fingers can lead to a lower contact force and possibly separation, significantly increasing the electrical resistance of the contact. A higher resistance leads to higher resistive losses, and those higher losses come with sharp increases in temperature, which can damage the GCB and the earthing switch by welding its contacts. Therefore, the contact force must be adequately large. The tulip contact is an intrinsic solution, which follows the Lorentz law. The welding current capacity further justifies the need for large contact forces. The tulip design plays a vital part in obtaining sufficiently high welding currents and negating the repulsive electromagnetic forces. The ability to withstand high welding currents ensures the extinguishing of the high load without melting the tulip contacts (Figure 4), which guarantees a safe and reliable operation of the entire GCB under extreme conditions. "The object of this tulip design is to provide not just a disconnecting contact, but flat springs to apply static radial pressure to the contact fingers," Mauroux says. "The increased Lorentz force will assist the contact forces and contribute to reaching much higher welding currents."

Evaluating the total force on the contacts requires multiple types of physics to be coupled: The electric current flowing through each finger creates a magnetic field, and each magnetic field in turn creates forces on every other finger because of their respective currents. The team used multiphysics simulation to calculate the force in a variety of ways, lending robustness and credibility to their calculations that have been validated against experiments. They exploited the symmetry of the system to simplify their model and reduce the computational effort. They modeled a single finger (Figures 5 and 6) to capture the behavior of the entire tulip at 1/8th of the computational cost. Using Maxwell's stress tensor, Lorentz force calculations confirmed that the attractive force dominates the repulsive Holms force and that

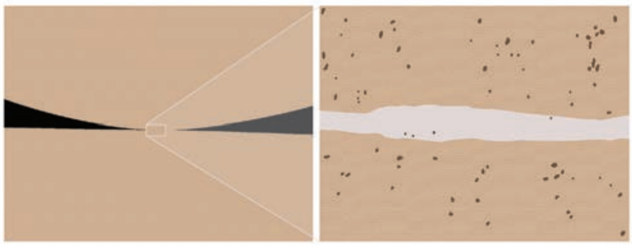


Figure 4. Welding zone. Left: Section of the welded tip (top) onto the pin (bottom). Right: Detail of the welding zone showing the formation and solidification of molten metals forming an alloy. Image credit: ABB.

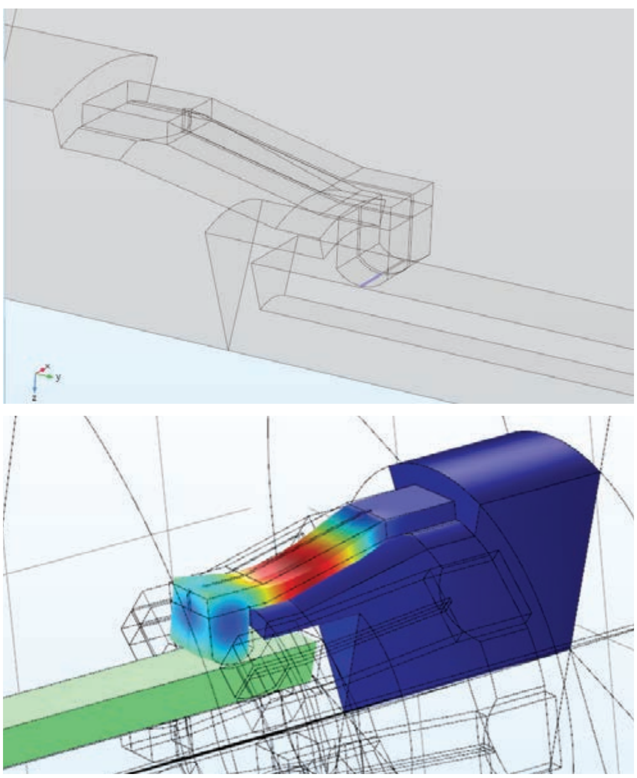


Figure 5. Top: Contact geometry. Bottom: Deformation of a single finger of a tulip design. Image credit: ABB.

the tulip design prevents separation. The simulated total force value can then be used to calculate a theoretical welding current value, which confirmed the ability to carry higher welding currents.

SIMULATION AND EXPERIMENTATION IN HARMONY

ONCE THE SIMULATION WAS COMPLETE, the actual design needed to undergo numerous testing procedures. These tests include dielectric type tests to guard against electrical breakdowns, mechanical endurance tests, and operating temperature tests. Finally, and perhaps most importantly, is the KEMA power test, where the theoretical current values need to be verified experimentally to confirm adherence to IEC current-carrying standards. An empirical investigation is set up to determine a measured value for the welding current, where the switch is exposed to power-plant-like conditions. To become certified, the switch must be capable of delivering peak current in excess of 500 kA. "We passed the type tests with room to spare, demonstrating the harmony in which simulation and experimentation can exist. COMSOL is a very nice tool to combine with empirical testing," says Agostini. "The intuitive interface helped us involve many different physics in a structured and controlled way."

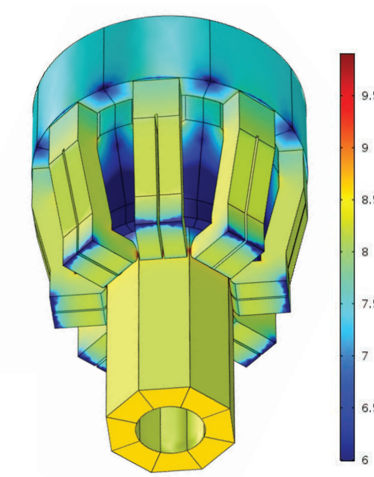


Figure 6. Log of the current density distribution of a tulip configuration. Image credit: ABB.

A FULL ELECTRO-THERMAL-MECHANICAL MODEL

THE TEAM'S ULTIMATE GOAL is to create a full electro-thermal-mechanical model to simulate more complex designs and gain a comprehensive understanding of all of the physics going on in their earthing switches. Furthermore, careful analysis of the physical and chemical processes behind the contact welding mechanism is something they plan to work on in the future. "Continued advancement in the material selection and modification is fundamental to improving the reliability and performance of our products," Mauroux says. "Simulation tools will be developed and extensively adopted and we believe COMSOL is up to the challenges of the future when even more complex situations need to be modeled."

From left to right: Markus Bujotzek, technology manager GCBs; Francesco Agostini, head of technology development GCBs and materials; Jean Claude Mauroux, principal engineer, GCBs technology development; Alberto Zanetti, research engineer, materials.

3D PARAMETRIC FULL EYE MODEL GIVES 20+ YEARS OF BETTER VISION

A research team at Kejako, a medical device company based in Switzerland, share how they are using multiphysics simulation to develop an innovative solution that will delay the need for reading glasses or invasive surgery for decades.

By **GEMMA CHURCH**

PRESBYOPIA IS A NATURAL EFFECT of aging in which a loss of elasticity in the lens of the eye causes far-sightedness. As a result, your visual accommodation gradually declines, as your eyes can no longer effectively change their optical power to maintain a clear image or focus on an object as its distance varies.

The current solutions to this problem are at opposite ends of the treatment spectrum: You can either wear a pair of glasses or opt for an invasive surgical solution that could compromise the quality of your vision (Figure 1).

A novel solution developed by medical device company Kejako will provide a viable treatment that treads the middle ground between surgery and spectacles. Their 3D parametric full-eye model is providing invaluable insights into the root cause of the eye's degeneration over time. As a result, Kejako is edging closer to an innovative solution that will delay the need for reading glasses or invasive surgery for over 20 years.

»PERSONALIZED TREATMENT OPTIONS

KEJAKO'S COFOUNDER AND CEO, David Enfrun, explained: "Our solution has the potential to become the next generation's standard of care in personalized ophthalmic anti-aging medicine," explained David Enfrun, Kejako's cofounder and CEO. We focus on early treatments to maintain enough capacity of visual accommodation by offering personalized anti-aging laser treatments that could give patients an additional 20 years of comfortable vision."

Kejako's solution is designed to treat the root causes of presbyopia and features a series of noninvasive laser eye surgeries, which are prescribed from when a patient starts to develop presbyopia until cataracts develop. This keeps a patient's visual accommodation amplitude above where spectacles are required (Figure 2).

To correct presbyopia, the team is combining the noninvasive treatment with simulation to provide an all-in-one solution called phakorestoration.

Their simulation work features a 3D parametric full-eye model, which the company developed using multiphysics simulation. Enfrun said: "We began our development work in 2015 with an alternative software that we were familiar with. However, it soon became clear that this solution was too restrictive. Our project is quintessentially multiphysics."

"In 2016, we started to work with COMSOL because of the multiphysics nature of the software and the high quality of customer support."

Figure 1. Current surgical solutions result in visual compromises, including halos (top), glare (middle), and poor acuity in dim light (bottom).

The full-eye model has the potential to provide a personalized treatment for every patient. This is important because every patient is different in terms of their physiology and the severity of their presbyopia. Enfrun explained: "One size will not fit all when treating presbyopia, and our model will be fundamental to addressing that issue. We can use the model to optimize each patient's treatment and provide a personalized procedure."

»EYEING THE PHYSICS

TO CREATE AN accurate 3D parametric model of the eye, a full description of this organ must be taken into account and several physics phenomena considered. Aurélien Maurer,

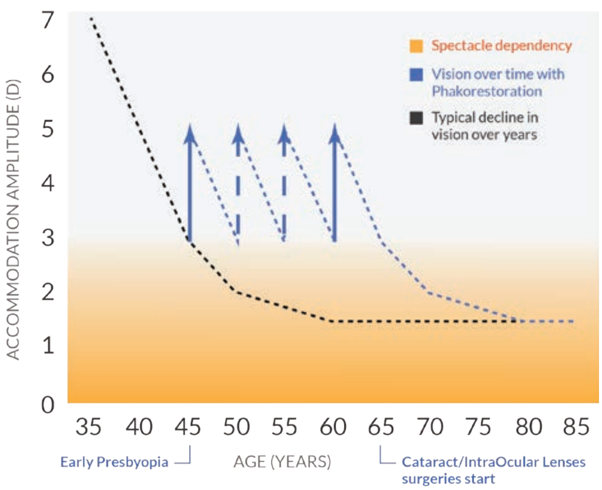


Figure 2. Principle of phakorestoration's action on visual accommodation as a function of age.

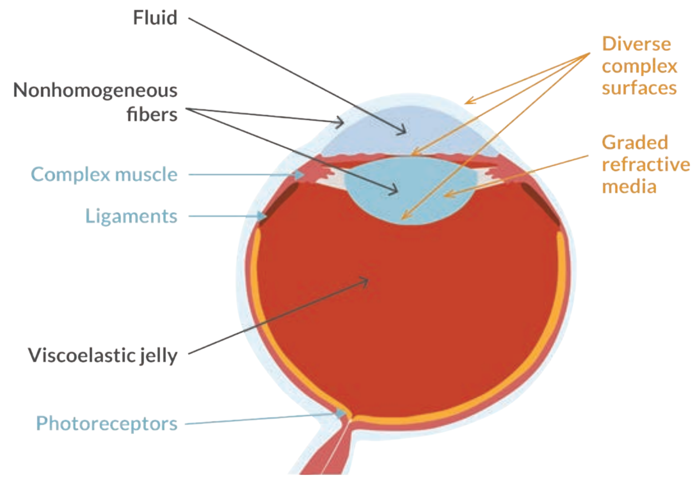


Figure 3. Various components of the eye that needed to be considered for the multiphysics model.

R&D engineer at Kejako and eye model project leader, explained: "We needed a complete solution, including the mechanics and optics of the eye. We wanted to model the entire eye and adapt its properties to look at different outcomes."

A range of complex physics must be considered to achieve this. Within the eye, there are a lot of different physics and material properties to take into consideration, such as the fluidics of the aqueous humor; optical behavior of the lens and cornea material; and the refractive index, which involves modeling the muscle ligaments as they deform the lens.

The team also wanted to model the gradient of the refractive index as light penetrates the crystalline lens, so they coupled structural mechanics and ray optics. Maurer said: "No one before had looked at the relation between the mechanical deformation and the refractive index gradient in the crystalline lens, so we decided to put this in a model and test it against the existing results in the literature."

The team's dual approach of modeling both the mechanical and optical elements of the eye was validated using existing measurements. "If we only model the mechanics or the optics, then we do not get all the information we need. But if we put all of this together, that's where the magic happens," Maurer added.

» MULTIPHYSICS FOCUS

USING GEOMETRIES FROM statistical measurements and standard optical coherence tomography (OCT) imaging techniques, the team began to develop their model by imaging the eye and then translating this information into a parameterized 3D geometry imported in the COMSOL® software.

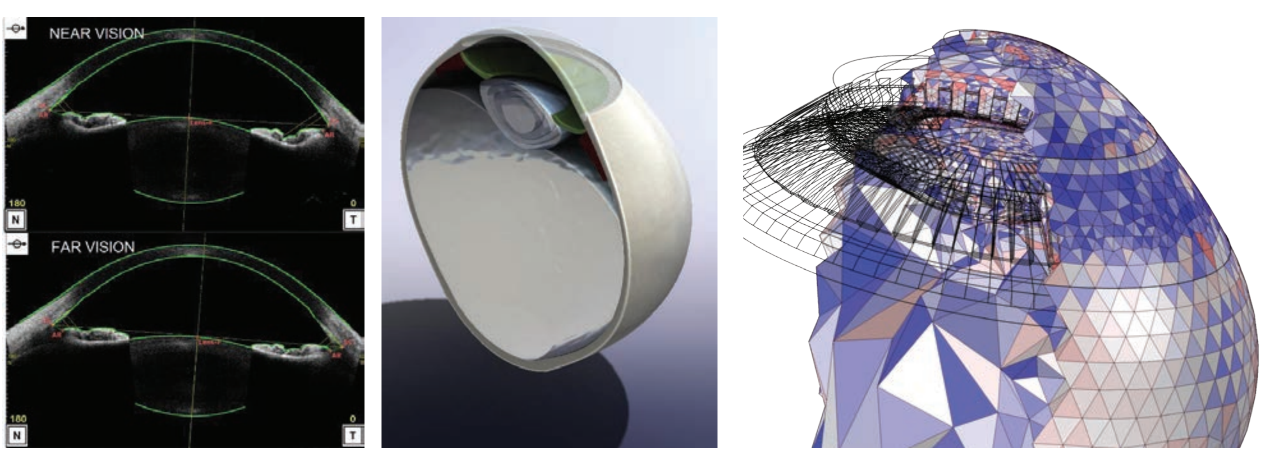


Figure 4. From measurement to simulation. Left: A typical eye imaging from an OCT. Middle: A cross section of the 3D model based on the measurement from the OCT results, created using the SOLIDWORKS® software. Right: Mesh of the 3D model created using COMSOL®.

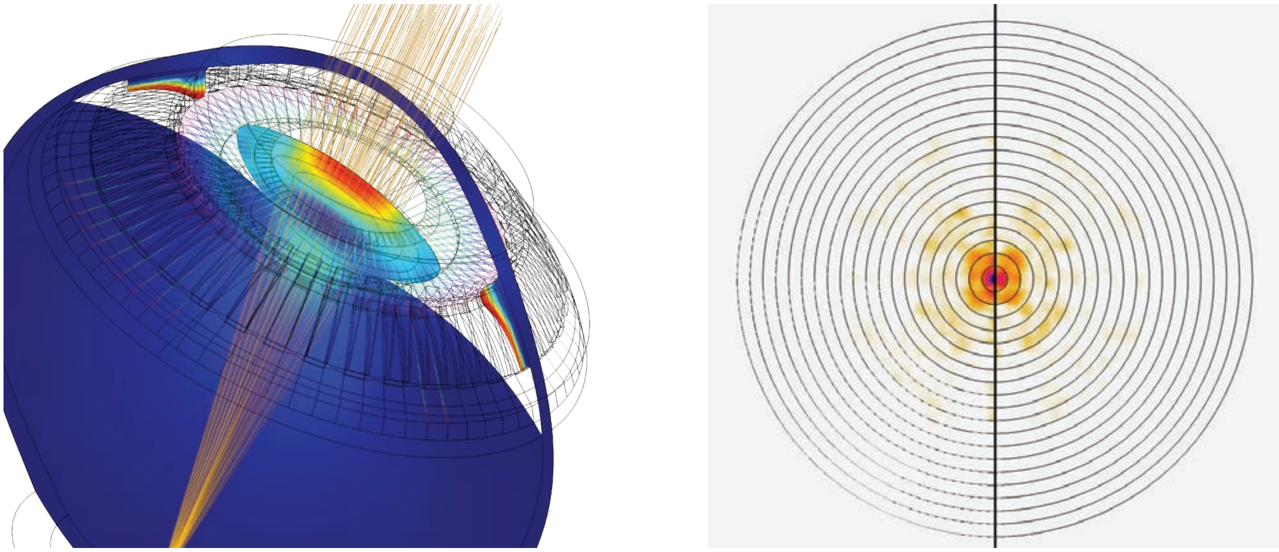


Figure 5. Left: Simulation results showing eye deformation and ray tracing in far vision. Right: Ray focusing after traveling through the eye's optical system. Dark colors represent higher ray density.

The mechanical elements of the eye were then modeled, including the complex muscle ligaments that pull the lens into shape and the viscoelastic properties of the vitreous fluid that fills the eye.

The fibrous nonhomogeneous nature of the sclera was also modeled. Charles-Olivier Zuber, a biomedical PhD student at Kejako and Rostock University, Germany, explained: "The sclera is the white part of the eye and it is made of collagen fibers. Because those fibers are made of collagen, we needed to examine their nonlinear mechanical properties in a multiphysics environment." The displacement of the eye material for a specified accommodation relative to the resting state can be determined by taking all of the elements into account (Figure 5, left).

> *"We started to work with COMSOL because of the multiphysics nature of the software and the high quality of customer support.*
>
> **—DAVID ENFRUN, COFOUNDER AND CEO, KEJAKO**

The ray optics capabilities of the software were used to trace the light rays, modeling the refractive properties of the lens and ray focusing on the retina, considering parallel incoming rays (as if they were emitted by an infinitely far source). This enabled simulations of the patient's sharpness of vision and the objective amplitude of accommodation to be determined. Ray focusing of the eye optical system (cornea and crystalline lens) can be simulated (Figure 5, right). How rays distribute on the retina depends on individual visual acuity. "We can provide models that produce exactly what the patient sees, enabling us to better understand and treat presbyopia. For example, we can see how the image forms on the retina for each individual, so sharpness of vision can be addressed," Maurer added. The team validated its visual accommodation analysis and the presbyopia simulation using measurements from more than 50 eyes.

The ability to model this vast range of parameters was key to the creation and success of the 3D parametric full-eye model. Zuber, explained: "What we appreciate about COMSOL is that we have access to all of these parameters driving the geometric configuration, material properties, and physics involved. Such flexibility is very helpful to improve our comprehension of the problem and find the most effective solution."

Figure 6. Simplified finite multilayer representation of the GRIN with decomposition in equivalent lens. Far vision is pictured on the left, near vision on the right. Colors represent the value of the refractive index with the highest values in red.

» GIVE US A GRIN

MULTIPHYSICS SIMULATION ALLOWED the team to deduce some of the nonmeasurable mechanical properties of the lens, including the gradient of refractive index (GRIN) used in the

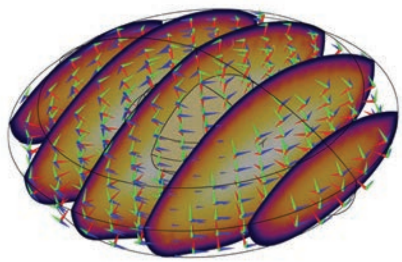


Figure 7. Curvilinear coordinate system used to represent the anisotropic material properties of the lens. The GRIN distribution is shown.

3D parametric model of the eye. The refractive index of the human eye lens has subtle fluctuations and this creates a particular reflectance pattern. The GRIN consists of spatial continuous variation of the refractive index over the lens, which increases from the surface to the center. This repartition has a strong influence on focalization of light, aberration, and thus visual acuity. Through simulation, the GRIN of the eye lens can be calculated, which is vital to understanding how light passes through the structure.

The GRIN acts as a multiplicative factor for the visual accommodation of the eye. As the lens tissues (with their specific refractive index) move with the lens accommodation, it results in two different optical configurations for each extreme state, either far or near vision (Figure 6).

The lens is made of fiber-shaped cells arranged in concentric layers like an onion. This organization is responsible for the lens transparency, but this also has a strong influence on its anisotropic mechanical properties. The model accounts for this microstructure, using the curvilinear coordinate tool available in the software to represent the fiber arrangement (Figure 7). The GRIN value is incredibly difficult to measure directly, but its incorporation into the team's parametric model (Figure 8) was vital to ensure the accuracy of the model and, subsequently, the effectiveness of any proposed treatment.

> *"We can provide models that produce exactly what the patient sees, enabling us to better understand and treat presbyopia."*
>
> **—AURÉLIEN MAURER, R&D ENGINEER, KEJAKO**

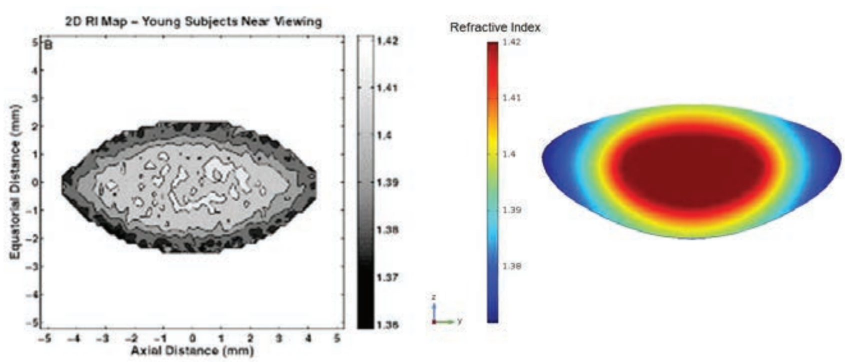


Figure 8. Left: Example of a GRIN measured with magnetic resonance imaging (MRI). Right: Parametric model of the GRIN.

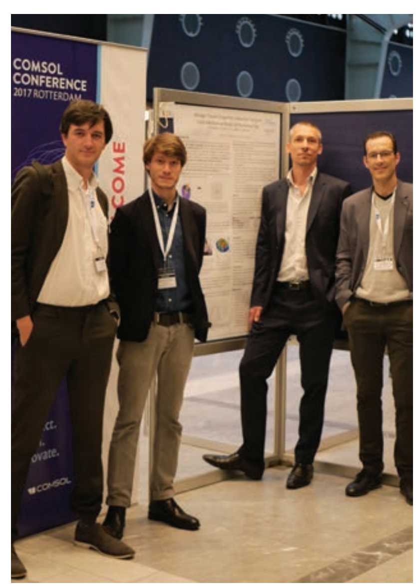
SIMULATION FOR ALL

THE TEAM IS NOW BUILDING SIMULATION apps, using the Application Builder available in the software to extend the reach of the 3D parametric full-eye model and prepare the company for market maturity.

Once the multiphysics model is packaged into a simulation app with an easy-to-use interface, Kejako's work is ready for a clinical setting through a straightforward process. A clinician can use standard OCT imaging to image the patient's eye. This information is sent to Kejako, where the team of experts can create a personalized 3D parametric full-eye model. This model is then further optimized and a customized phakorestoration procedure is created.

The projected prevalence of presbyopia is predicted to reach more than 1.3 billion people by 2020, so apps will be fundamental to keep up with the demand, as nonexperts in simulation can benefit from multiphysics to create each patient's phakorestoration treatment.

"Simulation and modeling have allowed for time savings with regards to our *in vivo* and *ex vivo* tests. We will move to trial when we are confident that we can do something significant in the human body and are convinced of our solution, and COMSOL Multiphysics will help us to achieve that in a much shorter time frame," Enfrun added. ◎



From left to right: Aurélien Maurer, Charles-Olivier Zuber, David Enfrun, and John Speyrer.

THE BRAINS OF BANKNOTE PROCESSING SYSTEMS

Engineers and physicists at Giesecke+Devrient Currency Technology are using multiphysics simulation to develop magnetic, optical, and ultrasonic sensors for high-performance modular banknote processing systems that can securely sort and process millions of banknotes every day.

By **ZACK CONRAD**

THE PHRASE "CASH IS KING" may reverberate with many of us, but not nearly as much as it does with professional cash centers that process and handle millions of banknotes every day. There is more cash in circulation today than ever before, and this surge in volume, coupled with the growing variety in banknote security features and increasing complexity in banknote design, has drastically raised the requirements for automated cash handling systems. All around the world, printing plants have to guarantee the highest possible quality of each freshly printed banknote. Furthermore, central and commercial banks and cash-in-transit companies face the need to sort banknotes based on denomination, currency type, orientation, authenticity, and degree of fitness with astounding speed and accuracy. Jan Domke and Klaus Thierauf, physicists at Giesecke+Devrient (G+D) Currency Technology, develop sensors for modular, high-performance banknote processing systems (BPS) for these professional cash centers (Figure 1).

To lower processing costs and ensure secure output of the processed banknotes, G+D Currency Technology's processing systems use extensive arrays of sensors that guarantee reproducible results and lasting durability. Banknotes are fed into the machine and transported through a round belt conveyor system (Figure 1, left), that permits full-face measurement on both sides of each banknote. Decisions regarding sorting are made by a variety of sensors along the way. Counterfeit banknotes are rejected reliably, whereas unfit banknotes, due to their insufficient quality, are separated or even shredded. Banknotes passing the inspection are bundled together and returned to the cash cycle or bank vault. A typical machine made by G+D Currency Technology can detect a multitude of different currency types in all four physical orientations in a single run. The fastest systems can process more than 150,000 banknotes per hour. "In our department, we develop the sensor systems and evaluations that are responsible for classifying banknotes to counterfeits or authentic and fit or unfit," Domke says. "They are the eyes and brains of these machines."

SENSING AND SORTING

WHEN TRAVELING THROUGH the processing system, the banknotes are exposed as three main sensor systems: magnetic, optical, and ultrasonic sensors. The different sensing properties are used in conjunction with each other to seamlessly and efficiently inspect and sort banknotes. Magnetic sensors detect special imprinted magnetic security features; optical sensors operate in the UV, NIR, and visible range to classify bills based on denomination and currency types, and ultrasonic sensors verify fitness requirements (tears, holes, tape, etc.). Domke and Thierauf, as part of their team's continuous developmental work to sharpen sensor performance, use multiphysics simulation to better comprehend the complex underlying physics. As an important step in the development process, simulation is used to prove principal

Figure 1. The BPS X9, the fastest banknote processing system in the world, has a processing speed of 44 banknotes per second and can achieve an effective throughput of more than 150,000 banknotes per hour. The dimensions of the central module are 1.9 m x 5.7 m (H x W).

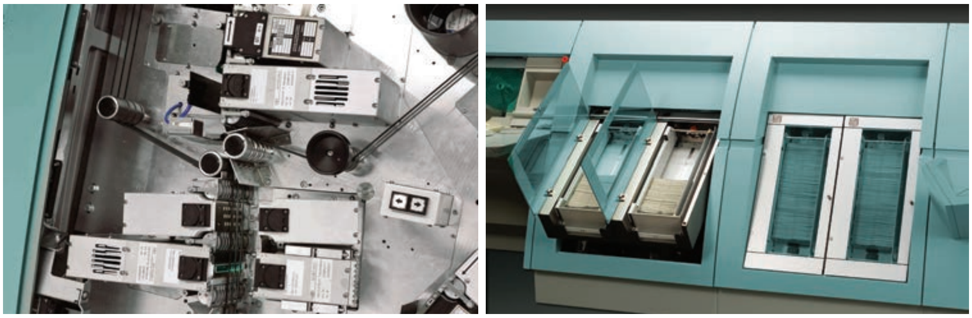
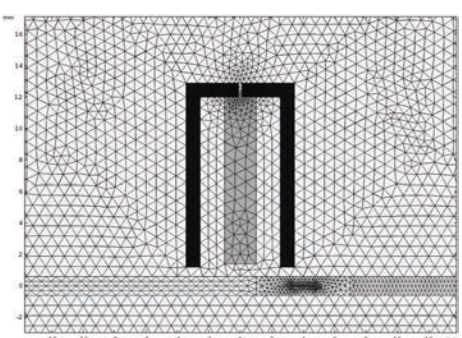


Figure 2. Left: Part of the sensor section with a round belt conveyor system that transports the banknotes through the banknote processing system. Right: Sorting banknotes into the large delivery module is an option to provide loose banknotes, for example, for filling cash dispensers.

ideas, which can then be discussed, for example, with the algorithm development team. "The COMSOL® software is a very important tool to get the entire team on the same page with their visualizations and understanding of the physics effects at play," Domke says. "It is an essential part of the sensor development process."

DETECTING SECURITY FEATURES

A CRITICAL SECURITY FEATURE of banknotes is the magnetic ink imprinted on them. The ink acts as a magnetic probe. As the bill travels through the transport system, the probe will interact with the guided field of permanent magnets in the sensors. They can then analyze the effects on the field lines as a signal in real time and yield information according to specific algorithms. In order for the algorithms to be accurate, readings of the changes in the magnetic field need to be simulated beforehand. Thierauf uses numerical simulation to model this behavior. By setting up the assembly of the magnetic sensor with a predefined magnetization in the software and using a moving mesh technique to model the passing by of the soft magnetic probe, they can create magnetic readings and tweak parameters to tailor the field geometry to their needs.



When the probe passes by the sensor, there is an interaction of the probe with the magnetic field. The magnetic sensor will sense the change in the magnetic field and the resulting signal comes out of the system as an electrical response. The signal amplitude depends on the distance of the probe from the magnets, and simulation is critical for understanding this dependence. "When you form the resulting magnetic field, you can calculate the dependency on the distance," Thierauf explains. "From there, you can optimize and apply it to more specialized models based on customer specifications."

ADHERING TO FITNESS REQUIREMENTS

IN ADDITION TO security features, banknotes also need to be sorted based on their adherence to fitness requirements. Banknotes may be ripped or torn; have missing or folded corners, stains, graffiti, or tape; or be stuck together with other banknotes. For example, to help detect banknotes that are stuck together or have tape on them, Domke's team employs arrays of ultrasonic sensors. When a bill arrives at the sensor, a pulsed ultrasonic acoustic signal is sent through it to a receiver on the opposite side of the bill. The major difficulty of this is that only 1% or less of the signal actually travels through the banknote and reaches the receiver; 99% of the acoustic energy is reflected. 24 pairs of transmitters are employed in the system to increase the resolution at the receiver

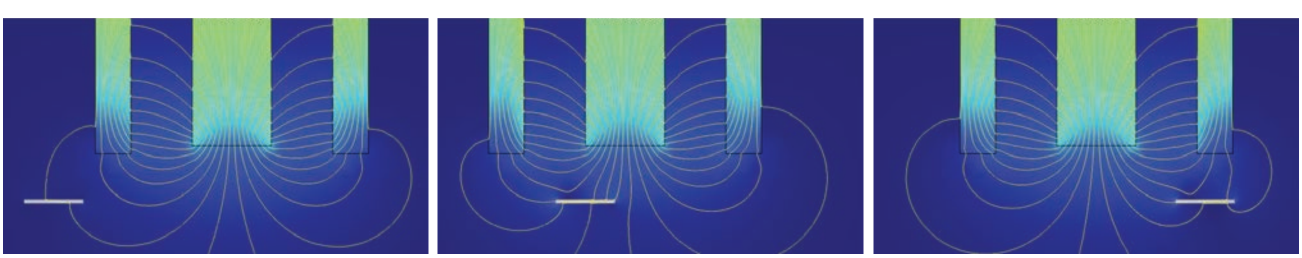


Figure 3. Simulation of a magnetic probe passing the magnetic sensor. Top: Permanent magnet (gray) and iron cores (black) guide the magnetic field of the sensor. A moving mesh is used to model the probe passing by in a virtual transport channel. Bottom: Time sequence of the probe passing by the sensor and deforming the magnetic field.

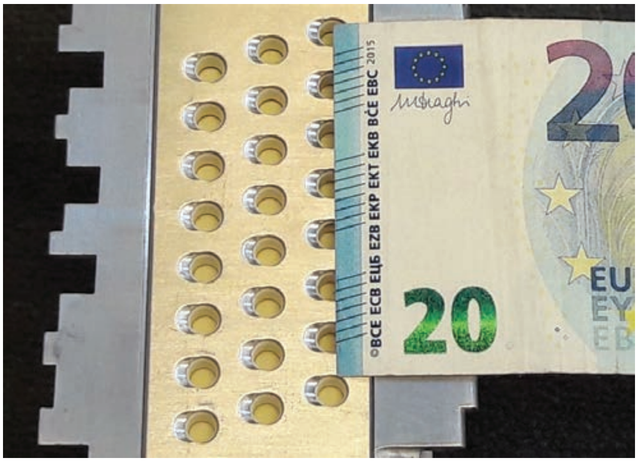


Figure 4. Array of 24 transmitters used to send ultrasonic acoustic signals through banknotes. A 20 euro bill is shown.

(Figure 3). However, with this many transmitters, signal interference becomes a problem and creates a complex and delicate issue of managing signal timing, damping elements, and geometry aspects.

Domke and his team utilize multiphysics simulation to manage these challenges. As the bill passes by and the ultrasonic signal is reflected, parts of the reflected pulse will run around the edge of the banknote due to diffraction and therefore be picked up by the receiver (Figure 4). As this signal would interfere with the weak signal of the transmission, the detection process by the receiver needs to be finished before the diffracted signal arrives. Using multiphysics simulation Domke modeled the addition of acoustic channels to guide the pulsed signal. By simulating both the near and far field characteristics, the maximum amplitude, and the decay of the acoustic field, he was able to prevent the distortion of the transmitted signal. "Simulation is an essential tool here because at such small scales, experimental measurements are impractical," Domke explains. "If we can tune the geometry and timing just right via simulation, we can get really good and undisturbed transmission information from the inception of the design."

FUTURE IMPROVEMENTS

DOMKE AND THIERAUF also use multiphysics simulation for other aspects of sensor development and will continue to expand their simulation capabilities. They employ a multiphysics approach to modeling ultrasonic transducers and conduct heat transfer analyses for thermal management in their printed circuit boards. For these applications, they can also compare their simulations with experimentation, and the agreement has been extremely convincing of the accuracy of their models. They hope that continued use of simulation will yield higher degrees of flexibility for customer specifications, optimal sorting out of potential counterfeit bills, and maximal alignment of fitness inspection with human perceptions.

> *Simulation is an essential tool here because at such small scales, experimental measurements are impractical.*
>
> —JAN DOMKE, PHYSICIST, G+D CURRENCY TECHNOLOGY

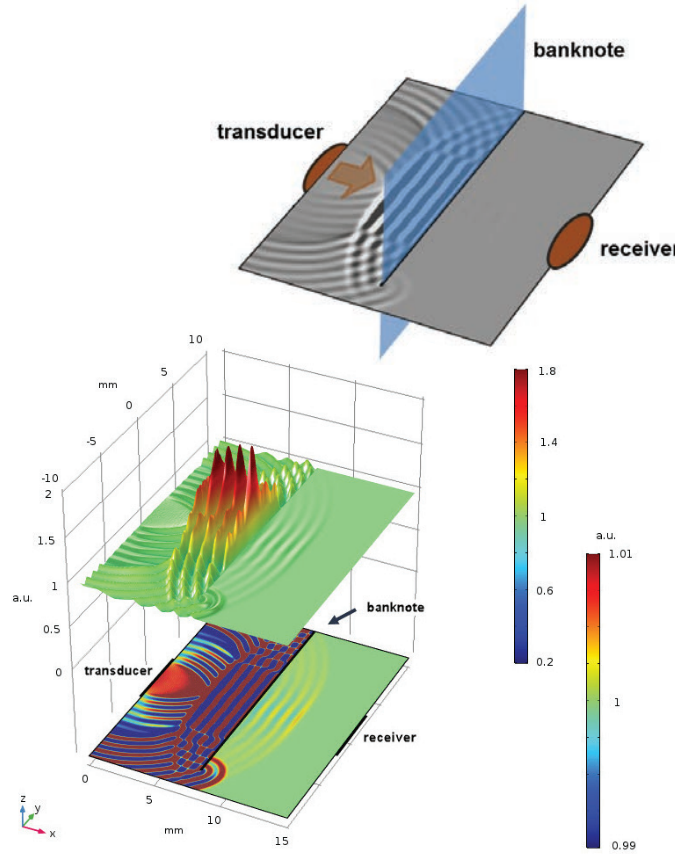


Figure 5. Propagation of an acoustic wavelet from the transducer toward the edge area of a banknote and to the receiver. Top: Sketch of the simulated setup. Bottom: Two different representations of an acoustic wavelet propagation toward a banknote. Here, half of the wavelet already impinged the note. Only a small fraction is transmitted, whereas the major part gets diffracted around the edge of the banknote.

Klaus Thierauf and Jan Domke, physicists at G+D Currency Technology.

NATIONAL GRID MODELS UNDERGROUND CABLE ROUTES

The use of simulation to accurately predict the rating of underground electric cables within clear safety margins is enabling National Grid to maximize output, ensure reliability, and keep costs as low as possible.

By **JENNIFER HAND**

IF HOMEOWNERS PLUGGING IN new entertainment and kitchen devices were asked to describe their expectation of household electricity, the answers might well include the words "safe," "reliable," and "affordable."

Managing the electrical grid, ensuring that it matches demand throughout the day, and keeping voltage and frequency within acceptable limits are fundamental for safety, reliability, and affordability. In England and Wales, this responsibility lies with National Grid, which owns, constructs, maintains, and operates the high-voltage transmission network that provides electricity to homes and businesses. Figure 1 shows a photo of one of the high-voltage underground cable systems.

Challenges faced by National Grid include improving the thermal management of these enormous networks; optimizing routes for laying new cable and ensuring the accuracy of cable ratings, especially in cases where repairs of older sections have led to combinations of different materials in the same cable line. Meeting these needs requires a thorough understanding of the impact of surrounding soil, cable age, repairs, and how the proximity of other cables will affect a given section's performance.

» RATING CHALLENGES

MOST TRANSMISSION and distribution networks use standards issued by the International Electrotechnical Commission (IEC) and supported by the International Council on Large Electric Systems (CIGRE), to work out the rating of a cable — the maximum load it can support while remaining within temperature limits and avoiding potential damage.

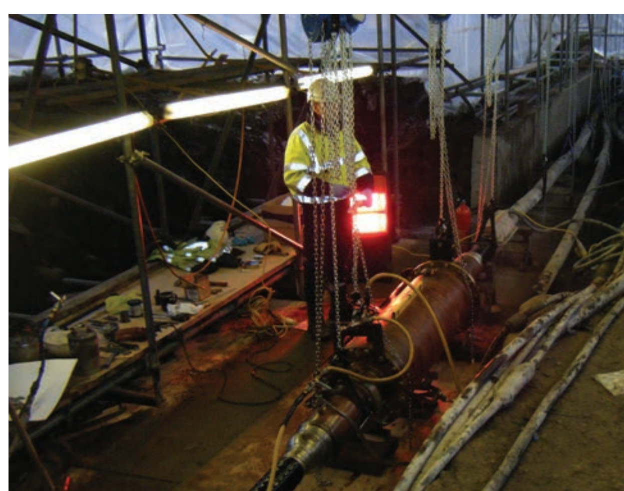


Figure 1. A section of a high-voltage cable system in a tunnel (top) and buried (bottom).

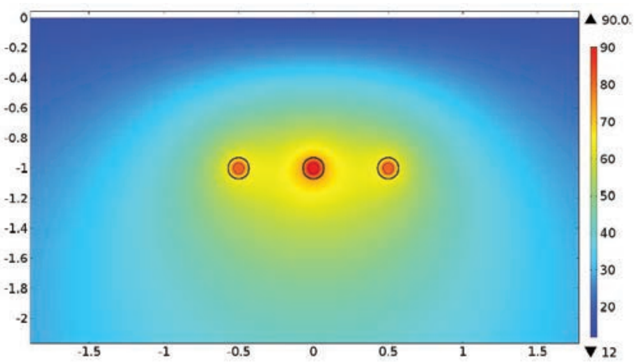


Figure 2. Simulation results in COMSOL® software of the thermal profile of cable laid directly in soil.

David Scott, network mapping engineer, looks after overhead and buried cable capabilities at National Grid's Asset Integrity Department. He explains, "The testing of high-voltage systems is not the easiest business. These cables are up to 165 feet [50 meters] underground and exist in the context of a larger system, not in isolation. The temperature of the earth around a cable may vary along its length, and the thermal load changes where other cables, such as those of distribution or rail power networks, cross or pass close by. It is difficult to validate test results. We are always looking for more accurate cable ratings."

The Tony Davies High Voltage Laboratory (TDHVL) at the University of Southampton, which collaborates with National Grid on innovation projects, has led the way in modeling different cable components and using simulation to better understand the changes in performance that occur as they undergo environmental changes and begin to age.

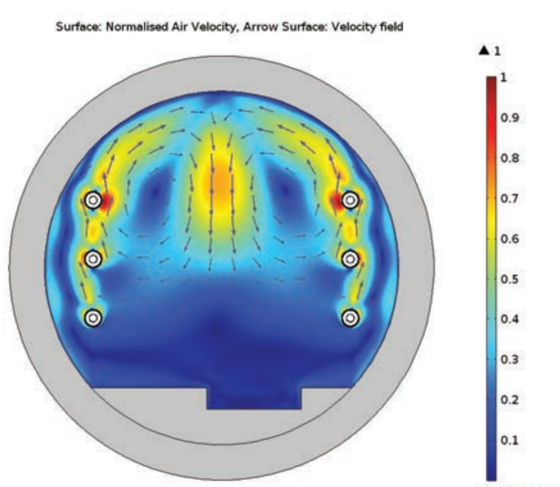
The research partnership between TDHVL and National Grid began with the creation of empirical models. Engineers at TDHVL work closely with National Grid and undertake finite element analysis (FEA) with the COMSOL Multiphysics® software. Focusing primarily on heat transfer, they first validated the ratings of particular types of cables, and then began to analyze cable ratings at specific "pinch points" in isolation and for different environments (see Figure 2).

For example, when soil is wet heat dissipates relatively quickly. Dry soil is more resistant due to the presence of small air pockets, which limits heat dissipation and affects the cable's thermal performance (Figure 3). The team accounts for soil dryness and cracking when modeling the trench in which a cable runs. "There are standards for soil and specialized backfill materials that we populate in the model. Soil does vary, so we tend to adopt a pessimistic assumption of how it will affect a cable," Scott explains.

» THERMAL AND ELECTRICAL PROFILING

FOR NATIONAL GRID the result of this modeling work is a new outlook, particularly for rating cables that lie close together and optimizing the configuration of new cable routes. Close proximity between cables can impede heat loss, lead to a rise in the temperature of both cables, and reduce their current-carrying capacity. However, sometimes assessments are overly cautious and can result in unnecessary costs in the form of extra cable being laid. "We have found that standards-based methods of assessing cable ratings are generally conservative," says Scott. "They have the potential to suggest overheating issues when two cables are actually over 330 feet (100 meters) apart and have very little bearing on each other."

His team uses the relevant COMSOL model



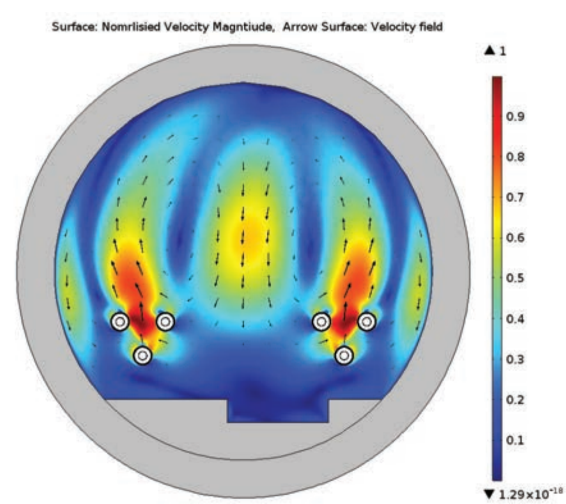


Figure 3. Simulation results of a normalized airflow profile within a cross section of a long horizontal tunnel.

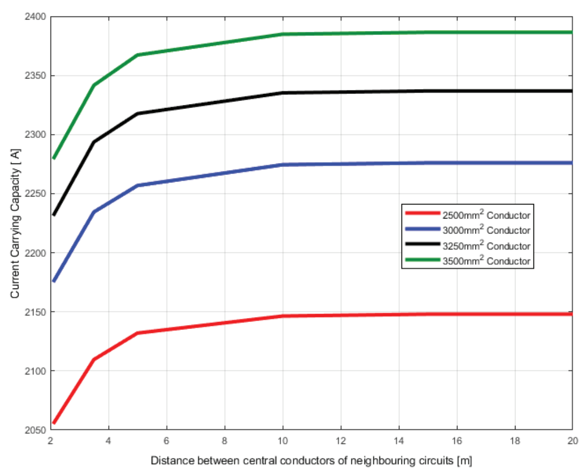


Figure 4. COMSOL® model showing the current-carrying capacity of four identical circuits as the separation between them is varied.

to ascertain whether a new cable can be laid on top of an existing route and still adhere to safety and performance standards, as well as the optimal position (Figure 4). “With modeling, we can now, for example, give precise feedback on the design of the new system and how it impacts the existing network,” says Scott.

“Previously we might have had to ask for specific mitigation, mostly by asking the relevant third party to separate their cables further or bury them more deeply. Deeply buried cables do not perform particularly well, and a widely spread cable is expensive in terms of land required — and in confined urban areas may not be possible. With FEA we gain a clearer understanding of the real situation, the true cable rating, and what is possible.”

Another challenge is the availability of spares for maintaining older systems and repairs that result in mixed materials (see Figure 5). “Many older cables include a lead outer sheath, whereas new cables tend to be aluminum. If we need to do repairs we prefer to replace only the damaged section because of the obvious cost implications. However, many cable systems are designed to minimize induced currents, thus maximizing capacity. By mixing materials in any given repair, this element of the cable design may be compromised. Existing industrial standards do not consider the case of mixed conductors in parallel. COMSOL allows us to calculate cable circuit losses and understand what countermeasures are required when specific materials are combined.”

» RELIABLE RESULTS UNDERPIN DECISION-MAKING

THE REAL VALUE OF SIMULATION becomes clear when Scott discloses the cost of a new transmission cable. “A ballpark figure is 20 million pounds [26 million USD] per kilometer of buried 400-kV cable. Where work that necessitates the installation of a cable is triggered, lean asset design and the maximization of cable capacity are the top priorities for minimizing costs. The knowledge we gain from simulation means we can safely opt for much less deep and convoluted options.” This knowledge is of particular benefit when working in tightly constrained parts of a power transmission system such as in central London, where there is often little scope to extend the footprint of a substation horizontally.

“With FEA we gain a clearer understanding of the real situation, the true cable rating, and what is possible.”

—DAVID SCOTT, NETWORK MAPPING ENGINEER, UK NATIONAL GRID

Figure 5. Photos of field joints being used to connect separate sections of cables together.

There is no shortage of ideas for how to use modeling in the future to inform decision making regarding the life cycle, compatibility, and connectivity of high-voltage equipment, including aboveground cables.

“If we model wind and air temperature around overhead lines and add in the system load for a given time, we'll have a powerful method for identifying potential issues early, such as where pollution may have congealed on the surface of the line,” Scott explains. There is also the potential to search for issues with compression fittings, perhaps as a result of fatigue cycling or mechanical damage, and predict potential failure modes for such fittings.

Scott adds: “It is easy to focus on the physical problem without getting caught up in mathematical complexities. We can use the work of TDHVL and adjust key parameters to explore design options while remaining confident in the results. If we ensure accurate input, the simulation has proven extremely reliable and helps us to make good decisions about cable laying and repairs.” ◎

RELIABLE STRUCTURES AND WEARABLE SYSTEMS CALL FOR MULTIPHYSICS SIMULATION

Engineers at STMicroelectronics use numerical simulation to optimize their semiconductor solutions for a wide range of applications.

By **VALERIO MARRA**

THE INCREASING DEMAND FOR miniaturized electronics and Internet of Things (IoT) devices has created new challenges for the specialists who design microdevices such as actuators, controllers, drivers, sensors, and transmitters. From responsive equipment and wearable monitors to energy efficient lighting in the office and automation in the factory, engineers need to bridge the microscopic components of semiconductors and our macroscopic world with reliable and innovative products. This shift has inspired engineers to find new solutions by exploring their ideas in the virtual world of numerical simulation.

STMicroelectronics, a world leader in designing and manufacturing semiconductor solutions, employs 7500 individuals in the area of research and development (R&D). Lucia Zullino, technology R&D engineer at STMicroelectronics explains their efforts, "In our field we need to analyze very small structures and understand their interaction with large packages in different configurations over a wide range of environments and applications."

For semiconductor manufacturers, the choice of material and design is critical. This is where simulation plays an important role in the evaluation of materials and performance parameters. "Much of our work is done through the COMSOL Multiphysics® software, which we use to validate hypotheses and to optimize products," explains Zullino. "There are about 30 users within STMicroelectronics, and although we belong to different departments and work in various locations, we are continually building and sharing knowledge about mathematical modeling techniques used in several projects."

» MULTIPHYSICS SIMULATION FOR RESEARCH AND PRODUCT DESIGN

SIMULATION IS USED TO understand multiphysics interactions at every stage of the development process for several products. A few examples include: optimizing an epitaxial reactor for faster wafer production, controlling reactant flow distortion in the wet etching process, and investigating the interaction between die and package at the microscopic level. In addition to design and manufacturing of microchips, engineers at STMicroelectronics work on the design of miniaturized actuators such as micromirrors used in recognition technologies that require optics and cameras. Simulation was also used in another actuator-related project to investigate printheads and compare the effectiveness of two different working principles: displacement of ink through pressure-generated bubbles or using a membrane actuated by a PZT a ceramic material made of lead zirconate titanate. Through this work the researchers were able to determine that the thin-film piezo printhead offers better compatibility with a wide variety of inks, higher printing speed, superior print output quality, and extended printhead lifetime.

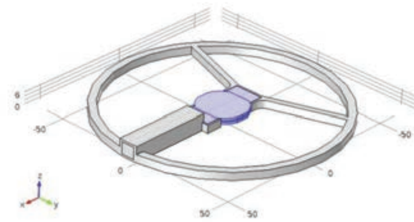


Figure 1. Geometry of the embedded structural health monitoring sensor. The sensing part is highlighted in blue.

» SENSING CONCRETE HEALTH

GOVERNMENTS AND BUSINESSES have been implementing various sensor technologies to monitor the performance of concrete for years. In one development project simulation was used to analyze the properties of concrete and predict the capacity of an embedded sensor (Figure 1) to monitor age-related changes and relay a signal to the surface. This structural

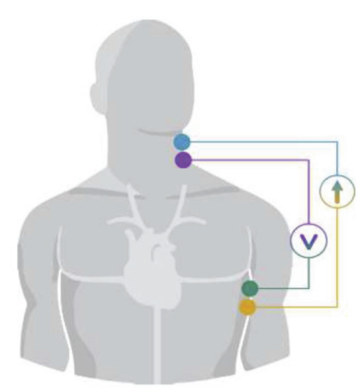


Figure 2. Technique used to measure the bioimpedance of an organ.

> “We can assess materials and structures more quickly and screen for the best ones, which means less time spent on trials, better technical decisions and quicker business decisions.
>
> —**LUCIA ZULLINO, TECHNOLOGY R&D ENGINEER AT STMICROELECTRONICS**

health monitoring (SHM) system has already been deployed in Italy. It is being used on various structures to assess the health of concrete and log damage following any unexpected stress that may impact the structural integrity and reliability of the system.

» *WEARABLE MEDICAL MONITORING*

OVER THE YEARS, STMicroelectronics has developed many healthcare applications. In one prototype project, a patch was designed to measure the bioimpedance of an organ, such as the heart, inside the human body (Figure 2). Working from medical imaging of human organs, researchers created a 3D model (Figure 3) to run an AC/DC simulation in the frequency domain (Figure 4) and assess the effect of the electrode shape and position on the measured physiological parameters. The simulation results they obtained (Figure 5) correlated closely with real-life measurements and enabled the development of a wearable configurable patch capable of indicating physiological changes. These sensors will enable doctors monitoring various heart conditions to get real-time data to provide patients with the best care using the latest technology.

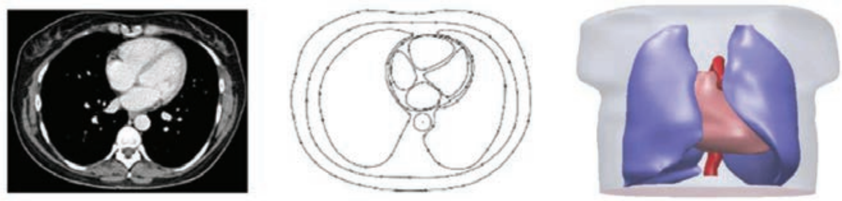


Figure 3. 3D model created from computed tomography (CT) images (left), postprocessed with CAD tools (middle), and then interpolated to generate the volumes (right) needed for the analysis.

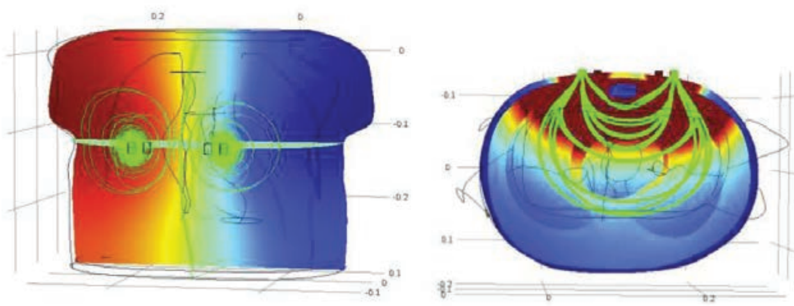
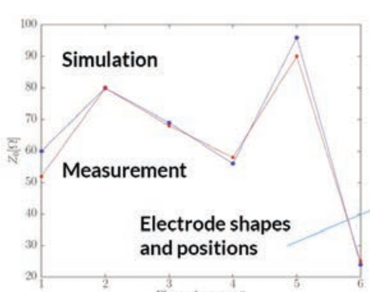


Figure 4. Simulation results showing the electric voltage and current distribution in a human torso.



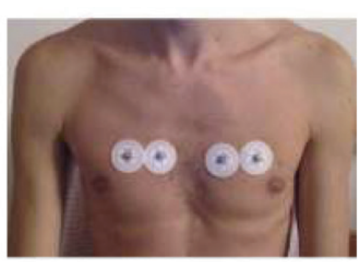


Figure 5. Comparison between measured and simulated bioimpedance values (left) for different electrode shapes and positions (bottom).

» *TACKLING MORE AND MORE COMPLEXITY THANKS TO SIMULATION*

“THROUGH SIMULATION we have learned a lot about potential problems and we have gotten better at optimizing semiconductors for the outside world. Simulation now drives product design, both for internal and external customers,” comments Zullino. She and her colleagues see opportunities to continue using multiphysics simulation in all aspects of development. She shared that studies on humidity inside packaging and the potential for corrosion are already in progress.

“We can assess materials and structures more quickly and screen for the best ones, which means less time spent on trials, better technical decisions and quicker business decisions,” concludes Zullino. “Compared to physical testing, we can implement new solutions and verify them at zero cost. Simulation is one of the key tools that drives innovation.”

HELICON ANTENNA SUPPORTS NUCLEAR FUSION

Engineers and scientists at General Atomics share how they use multiphysics simulation to achieve magnetically confined fusion in the DIII-D tokamak.

By **GEMMA CHURCH**

FUSION IS AN ENERGY PRODUCTION process where two deuterium atoms are accelerated to the point where they overcome the Coulomb force and fuse into one helium atom and a neutron, releasing a tremendous amount of energy as a result. It is the Holy Grail of energy production since it is carbon-free, low waste, and has almost a limitless source of fuel. Nuclear fusion powers the Sun and could unleash a clean energy revolution, if only we could harness its power here on Earth.

KEEPING THE DIII-D TOKAMAK IN TOP SHAPE

THE TOKAMAK IS a promising design that relies on magnetic fields to confine hot plasma. Plasma is an ionized gas. It is made up of both positive ions and free electrons that have no charge. Usually, plasma is created at low pressures.

Tokamak fusion devices use a series of magnetic coils to create, shape, and stabilize the plasma within a doughnut-shaped (or toroidal) chamber (Figure 1). External heating systems are then used to heat the plasma to extremely high temperatures of the order of 150 million °C to achieve nuclear fusion.

In San Diego, USA, General Atomics (GA) operates the DIII-D National Fusion Facility on behalf of the U.S. Department of Energy as part of an ongoing effort to achieve magnetically confined fusion. As a user facility (Figure 2), the DIII-D tokamak hosts over 650 researchers from around the world to carry out cutting-edge fusion research.

The DIII-D tokamak operations group has performed multiphysics simulation to help optimize and validate the operations and diagnostics equipment to keep the facility running optimally. GA's Humberto Torreblanca, DIII-D tokamak chief operator, said: "We do not need to use simplified models for engineering analysis anymore thanks to COMSOL Multiphysics®, nor do we have to assume we are working with perfect scenarios. We can look at the complicated geometry of the tokamak and work out a range of complex multiphysics models."

"As a result, we can design and push our ideas without damaging our machine. It gives us very accurate results instead of having to make simplifying assumptions to do the calculations," Torreblanca added.

For example, while the internal magnetic fields in the DIII-D tokamak had already been mapped, the operations team had to rely on simplified magnetic field maps for the external fields (Figure 2). Torreblanca explained: "The tokamak is surrounded by many components and systems and the magnetic field can generate forces and currents that can affect and damage these systems. Analysis and simulation helps avoid potentially costly damage and delays in the research program."

Torreblanca imported the tokamak geometry using LiveLink™ *for* SOLIDWORKS® to study the external magnetic field at certain locations and to see how it would affect specific systems.

"This saved me a lot of time because the model was easy to set up and it also replaced our previous methods, which were more time

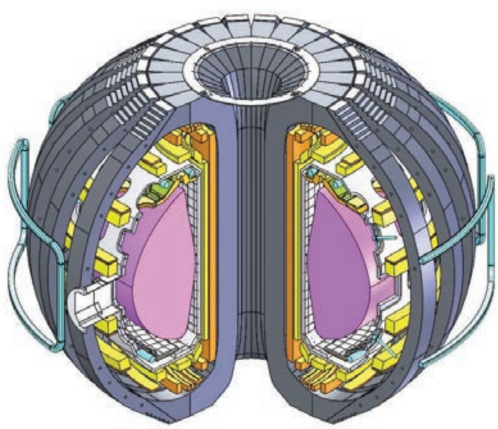


Figure 1. The interior of the DIII-D tokamak nuclear fusion device.

Figure 2. The DIII-D tokamak is surrounded by complex systems and components, which are exposed to strong magnetic fields.

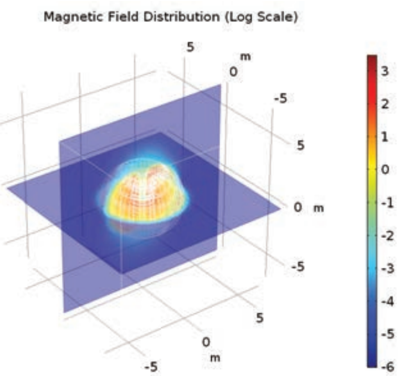


Figure 3. Simulation results of the magnetic field distribution inside and outside the tokamak vessel.

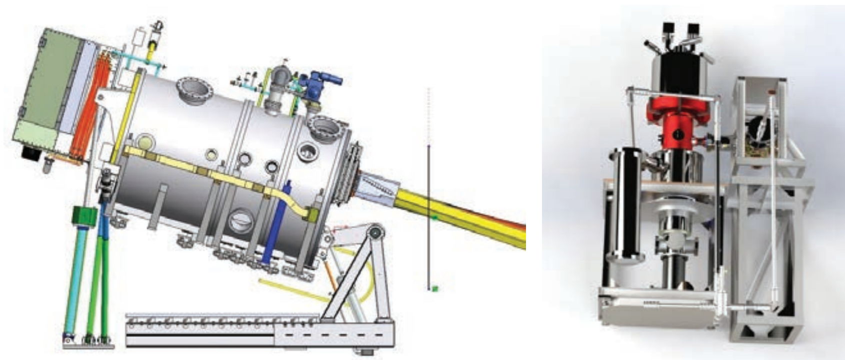


Figure 4. Current DIII-D external heating systems: neutral beam (left) and gyrotron (right).

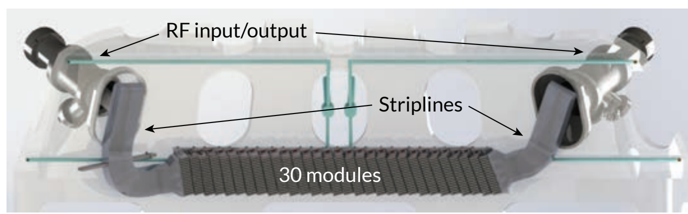


Figure 5. The helicon antenna featured on the DIII-D tokamak.

intensive," Torreblanca said.

For example, static, slow, or fast varying magnetic fields have damaged some of the tokamak's vacuum turbo pumps, which are vital for both main and subsystems on the tokamak. The team used multiphysics simulation to significantly improve analysis of the time-varying magnetic field distribution outside the tokamak vessel to find the best location to fit these pumps to improve reliability (Figure 3).

» *A HELICON ANTENNA TO HARNESS THE SUN'S POWER*

THE DIII-D TOKAMAK needs to achieve temperatures that are ten times hotter than the core of the Sun to achieve nuclear fusion. Currently, two systems (Figure 4) are used to achieve this: a neutral beam system (which injects 20 MW of power in the form of high-energy deuterium atoms) and the electron-cyclotron heating (ECH) system (where gyrotrons are used to inject up to 4 MW of microwave power to heat electrons). A novel heating system using a helicon antenna (Figure 5) that can inject 1 MW of radio frequency (RF) power is being designed and built.

Multiphysics simulation has been fundamental to optimizing the design of the helicon antenna. DIII-D will be the first tokamak to use such an antenna at MW power levels to couple RF power to the plasma to drive current and heat the plasma as predicted by specialized physics codes.

The helicon antenna consists of a 1.7 m array of 2 end modules and 28 center modules. Power can be injected from either end of the antenna through two striplines connected directly to the end modules, which then couple power inductively to each of the passive center modules in succession. DIII-D plasmas are on for up to 10 seconds with 10 to 15 minutes between pulses to allow the support systems to cool down to room temperature. The antenna is being designed to follow the same operation cycle.

Torreblanca explained: "Multiphysics gave us the ability to try new materials and allowed us to work out which material gives the best results. The antenna needs to survive the strong electromagnetic forces due to plasma disruption events that induce large currents on its structure. In order to reduce this current, a material with low electric conductivity is required. However, at the same time, a material with high thermal conductivity is needed to dissipate the high temperature that the antenna is exposed to from the plasma. A hybrid design made of CuCrZr and Inconel gave us the best of two worlds. Simulation made our work easier because we could look at many different materials with a few clicks."

Torreblanca said: "It was easy to compute the antenna's electromagnetic fields and visualize them. We coupled the electromagnetic analysis with heat transfer to model the RF loss distribution and get a map of the hot spots, which helped us refine the antenna design."

The antenna is excited at its resonant frequency (476 MHz), and the GA team needed to know how the temperature would affect this frequency. Torreblanca said: "We need to understand if there is a drift in the antenna resonant frequency due to temperature so we can compensate for it in the antenna design or its operation parameters so it can operate reliably for 10 seconds."

"Multiphysics simulation helped us to model the temperature distribution across a range of physical scenarios. This means we can work out whether it is possible to use the antenna for 10 seconds without damaging it, or we can calculate whether the antenna could operate for a few seconds and still be able to drive current and heat the plasma," Torreblanca added.

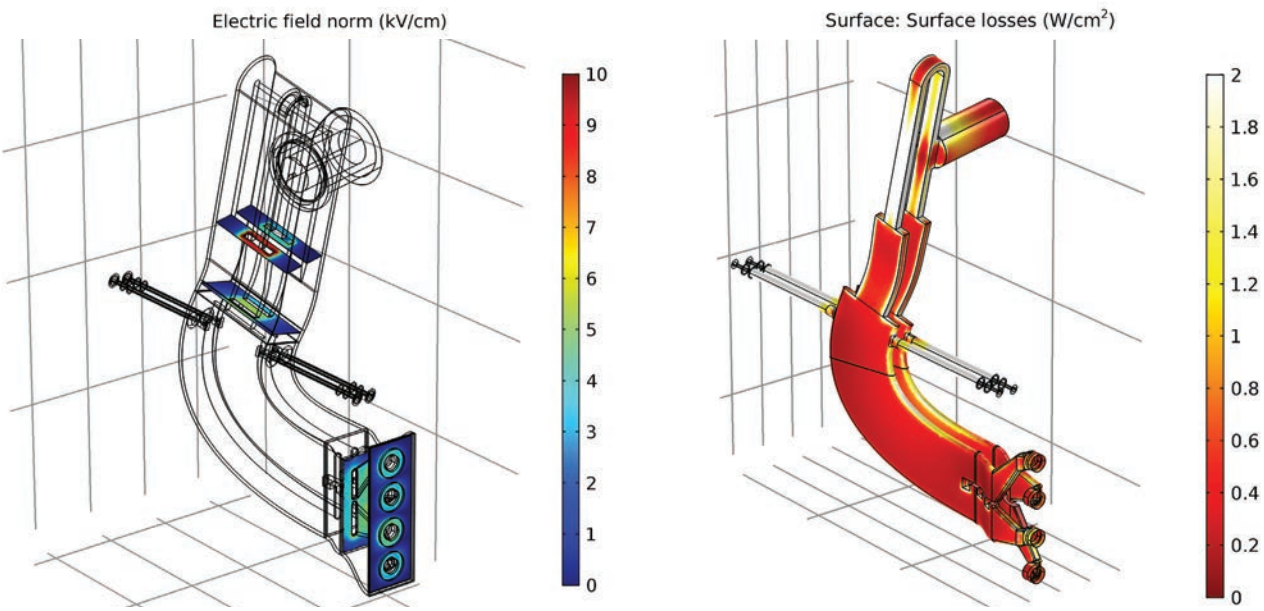


Figure 6. The antenna's stripline, showing the electric field distribution (left) and the RF losses (right).

SMALL-SCALE TESTS FOR BIG INSIGHTS

THE DIII-D GROUP built scaled-down test versions of key antenna components, allowing the team — in combination with multiphysics simulation — to test the parameters and conditions of these components of the full-scale antenna before they are built. Their tests included a one-quarter scale model and an RF resonator enclosure designed to replicate the electric field values of a full-scale antenna module and its stripline to find out whether arcing or multipacting phenomena will adversely affect the system (Figure 6). "We are validating these scaled versions of the antenna components, and simulation is providing a good match with the experimental results. This gives us even more confidence with the parameters and geometry of the antenna," according to Torreblanca.

"The insights from the simulation are always illuminating. We think that we know how the field will work and then we look at the visualization and we understand the design or performance better. As a result, we can be confident that the system will work the way we want," Torreblanca added.

The DIII-D research program is a key part of the worldwide effort to develop a viable nuclear fusion device in large part due to its highly collaborative approach among institutions and the integration of simulation and modeling to optimize its work.

Torreblanca concluded: "We are working on a global energy problem. If we can get good results in a timely fashion using COMSOL software, then that's a step forward to achieving nuclear fusion."

> *"We do not need to use simplified models for engineering analysis anymore thanks to COMSOL Multiphysics®, nor do we have to assume we are working with perfect scenarios. We can look at the complicated geometry of the tokamak and work out a range of complex multiphysics models."*
>
> —**HUMBERTO TORREBLANCA, DIII-D TOKAMAK CHIEF OPERATOR, GENERAL ATOMICS**

Acknowledgement:

This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Fusion Energy Sciences, using the DIII-D National Fusion Facility, a DOE Office of Science user facility, under Awards DE-FC02-04ER54698.

SIMULATION ADVANCES THE DESIGN OF A MICROFLUIDIC THERAPEUTIC CELL SORTER

Researchers at The Technology Partnership (TTP) in Cambridge, UK, used multiphysics simulation to help create a novel cell sorting device for the treatment of cancer.

By **GEMMA CHURCH**

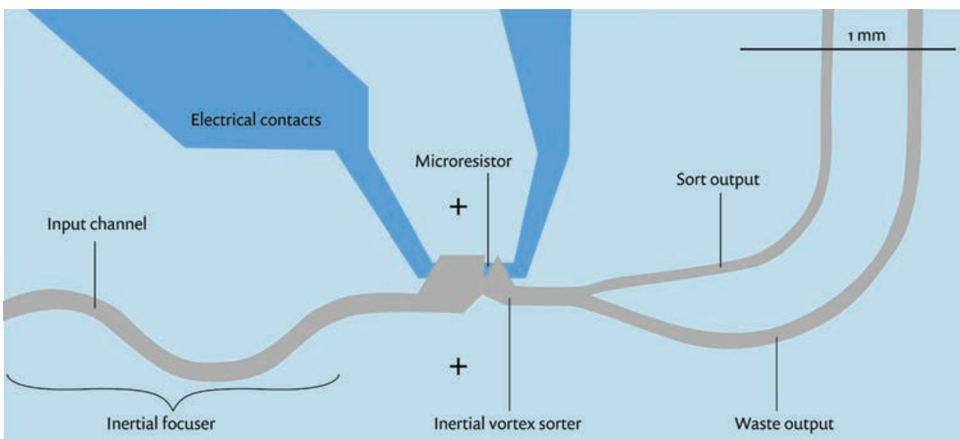


Figure 1. Geometry and components of the vortex-actuated cell sorter.

RESEARCHERS AT The Technology Partnership (TTP plc) in Cambridge, UK, have created a novel cell sorting device that could provide a manufacturing process for cell therapies to treat a range of diseases, including cancer, with many other applications in basic research, diagnostics, and bioproduction.

Current cell sorting systems can isolate rare cell phenotypes or subpopulations of cells that behave differently for biological research. However, cell sorting does not translate well to the clinic. Robyn Pritchard, a life sciences consultant at TTP, explained: “While a lot of exciting new developments in the field of cell therapy need better cell separation technology, current cell sorters are not capable of producing cell therapies.”

The primary traditional method of cell separation is known as jet-in-air sorting, or by its trademark fluorescence-activated cell sorting (FACS). Cells are first measured individually by a laser and subsequently stream through the air in droplets to be individually deflected by high-voltage electrodes. Commercially available jet-in-air systems are not suitable for therapeutic use due to relatively low cell processing rates, the need for highly skilled operators, and the risks to both patient and operator from nonsterile fluid handling and the production of droplets in the air, which may carry pathogens.

» BEYOND JET-IN-AIR: THE VORTEX-ACTUATED CELL SORTER

TTP HAS INVENTED a new microfluidic cell sorting technology, the Vortex-Actuated Cell Sorter (VACS). Similar to jet-in-air sorting, fluorescently labeled cells are measured optically, and cell sorting decisions are made in real time.

VACS consists of an input channel and uses a novel geometry to sort cells into two output channels, one for the waste cells and one for the cells of interest (Figure 1).

The new sorter could address many of the issues associated with existing cell sorters, as Pritchard explained: “For cell therapy, the key challenge is to sort fast enough. Any single-stream sorter, including jet-in-air, reaches a speed limit caused by killing the cells. To go faster requires multiplexing: operating many cell sorters in parallel. To create a multiplex cell sorter without making the measurement and control system too complicated, the best approach is by minimizing the size of the individual sorters. This is so that enough of them fit under just one microscope objective lens. The team was looking to process about half a billion blood cells with high purity and yield in an hour; in other words, about 10 to 20 times than what conventional cell sorters can manage.”

Pritchard added “The biggest challenge to making a faster cell sorter is to make a much smaller cell sorter that can operate at similar speeds to conventional instruments.”

VACS will be a safer option because it is enclosed and does not produce hazardous aerosols, unlike the jet-in-air systems. The new sorter is also disposable, which mitigates the risk of contamination and cross-contamination across

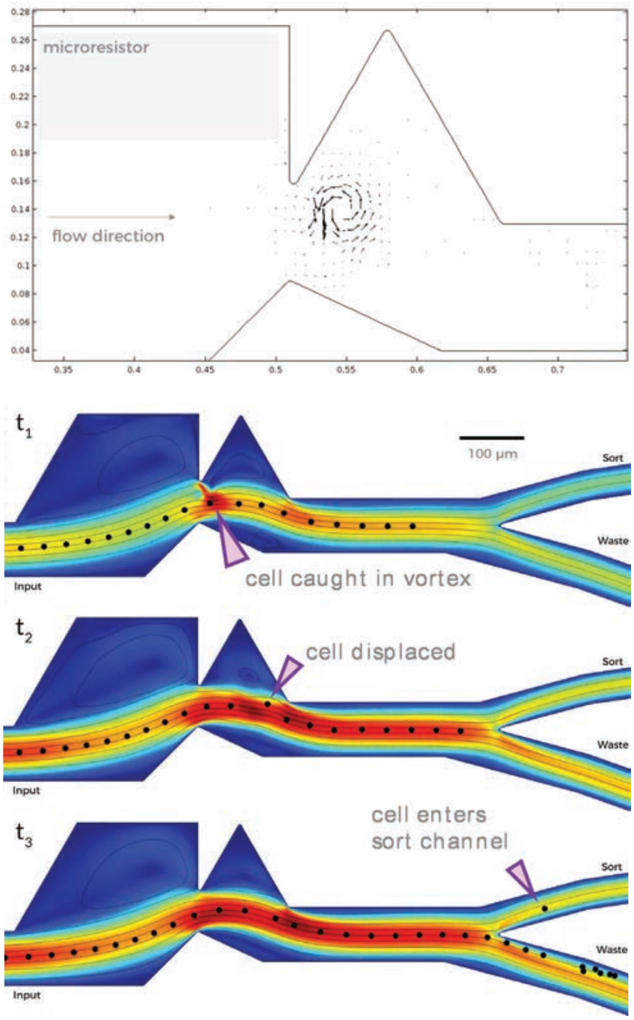


Figure 2. Simulation results showing the working of a VACS device. Plot showing the position of the microresistor actuator, which produces the thermal vapor bubble, and a vector plot of the vortex according to the simulation (top). The time slices (bottom) show the cell caught in the vortex, causing the displacement of the cell across the streamlines, before the cell eventually enters the sort channel.

samples. Finally, the sorter is highly practical and portable, easy to automate, and a cost effective solution for good-manufacturing-practice (GMP) cell therapy production.

» HIGH SPEED IN SMALL PLACES

THE VACS DEVICE measures 1 mm by 0.25 mm, including the actuators, and can be arrayed on a chip with a pitch of ~1 mm, including all plumbing. "We believe this makes our design the smallest high-speed cell sorter technology in the world," Pritchard asserted.

"The team started with a short list of actuators that were small enough to fit inside the VACS device. One notable mention was a thin-film microheater, which could create thermal vapor bubbles and was both small (~0.1 mm wide) and easy to manufacture. However, the experiments and COMSOL Multiphysics® simulations quickly showed that the listed actuators were too fast and weak to move a cell on their own."

Pritchard said, "Then we had a moment of inspiration. What if we could amplify the displacement caused by the actuator by using the ideas of inertial microfluidics?" This is currently a hot new research field, utilizing inertial effects to manipulate cells on tiny length scales. "We postulated that if we could use the actuator to generate a tiny vortex, that vortex could flow downstream with a cell of interest, gradually moving it from the waste stream to the sort stream. The idea of VACS was born."

» CLOSING THE LOOP WITH MULTIPHYSICS SIMULATION

"IT WAS UNTHINKABLE to design VACS devices without multiphysics simulation," according to Pritchard. Not only were these microfluidic effects very far from everyday experience, until recently, nobody believed that inertial effects were important in microfluidic devices. Moreover, each iteration of the device was expensive and time consuming to make and test experimentally.

Multiphysics simulation was instrumental in the conception of this design. Using a fluid dynamics model, the TTP team simulated the effect of the expansion and collapse of the thermal vapor bubble using a "moving wall technique": moving the boundary locally by a realistic amount to simulate the bubble.

Pritchard said: "This mimicked the edge of the bubble and the effect of the 10-µs pulse of the thermal vapor bubble but without the need to simulate the complicated physics of the large deformation a bubble would create. As a result of this novel modeling approach, we could iterate between 20 to 30 designs to rapidly get the inertial vortex concept working with enough confidence before we built the real device." After many iterations of the simulation (Figure 2), the prototype worked as designed for the first time in real life.

Within VACS, when a cell of interest is identified, the actuator creates a thermal vapor bubble, which expands and collapses within 10 µs. This creates an inertial vortex, which persists for 200 µm and permanently deflects the cell by around 20 µm.

> *This pace of development would not have been possible without the modeling and simulation tools we have used.*
>
> —ROBYN PRITCHARD, LIFE SCIENCES CONSULTANT, TTP

The cell then travels to a separate sort channel where it is collected. All other cells automatically flow into a waste channel. A composite image of the sort and waste trajectories is shown in Figure 3.

VALIDATING THE FINAL PRODUCT

THE TEAM HAS ALSO USED multiphysics to validate their designs. Pritchard explained: "We faced various teething issues with chip fabrication, and simulation was often our best tool to work out what was causing the issue and fix it. In particular, the quality of several important features came out differently from our microfabrication processes than specified in our design. We used simulation to tweak the design to improve performance based on features that we could build."

The team is now building the multiplex version of the chip (Figure 4). Multiphysics simulation is being used to test several aspects of this chip. Pritchard explained: "With 16 input channels and 16 individual sorters, we are working with a highly complex microfluidic system where we have to ensure that equal amounts of fluid and cells flow down each channel."

The team predicts that the single-channel inertial vortex sorter will be commercially available in the near future, with the multiplex design expected to follow shortly thereafter. Pritchard added: "We hope to prove the multiplex design in the coming months and have a full proof of concept machine working shortly after this to demonstrate the technology. This pace of development would not have been possible without the modeling and simulation tools we have used." ◎

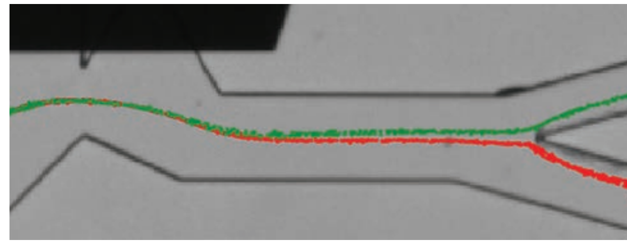


Figure 3. Trajectories of cells going to sort (green) and waste (red) in the VACS device.

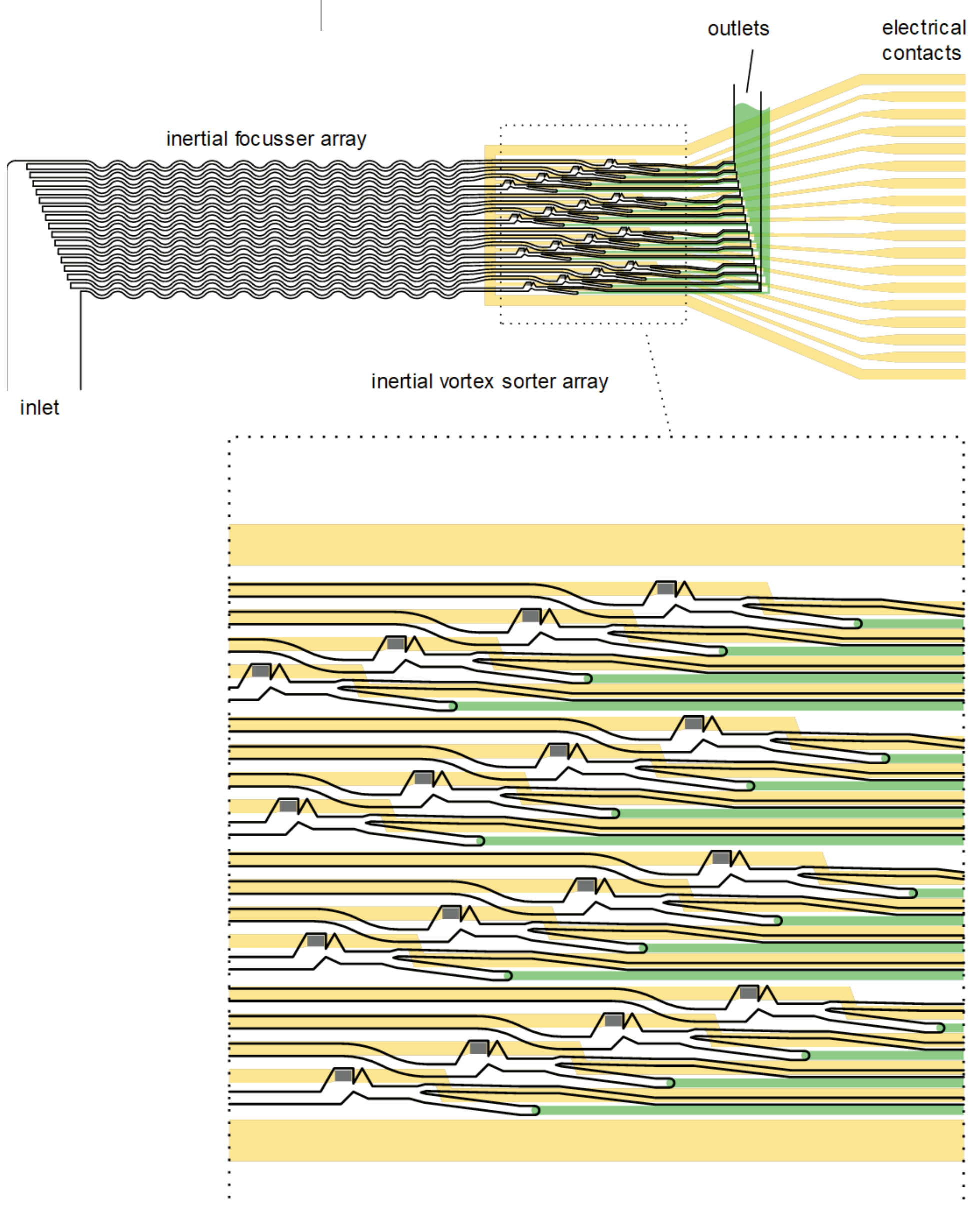


Figure 4. Inertial vortex sorter with 16 input channels and 16 individual sorters.

EFFICIENT GRID OPERATION AND MAINTENANCE WITH SIMULATION APPS

Engineers at NARI Group developed a customized Cable Condition Analysis Expert System App based on their multiphysics model to accurately predict cable faults and improve troubleshooting efficiency.

By **ZHANG QIQI**

ELECTRIC CABLES AND WIRES are hailed as the “blood vessels” and “nerves” of China’s national economy, providing the foundation for electric power infrastructure construction, the smart grid, and new energy industries.

The demand for cable lines increases as China’s economy continues to grow. Increased power load can cause parameter fluctuations of electrical systems or momentary interruptions. This may lead to grid equipment malfunction, or, in extreme cases, fires and explosions. Routine maintenance of cable systems helps to keep the economy growing and customers happy, while failure protocols allow for speedy electrical recovery.

Electrical equipment needs regular assessment to prevent sudden power outages, where testing equipment such as infrared, ultraviolet, and partial discharge are used. However, these routine “health tests” are not able to fully reflect a cable’s condition or determine failure types in many situations. Additionally, cables are installed in different environments, such as underground, within tunnels, or up in the air, adding unique challenges to detection work.

ACCURATE CABLE HEALTH ASSESSMENT REQUIRES SIMULATION

TO KEEP POWER RUNNING, in addition to relying on traditional testing equipment, engineers must take other factors into consideration, for example, cable structure and material, impurities in the cable,

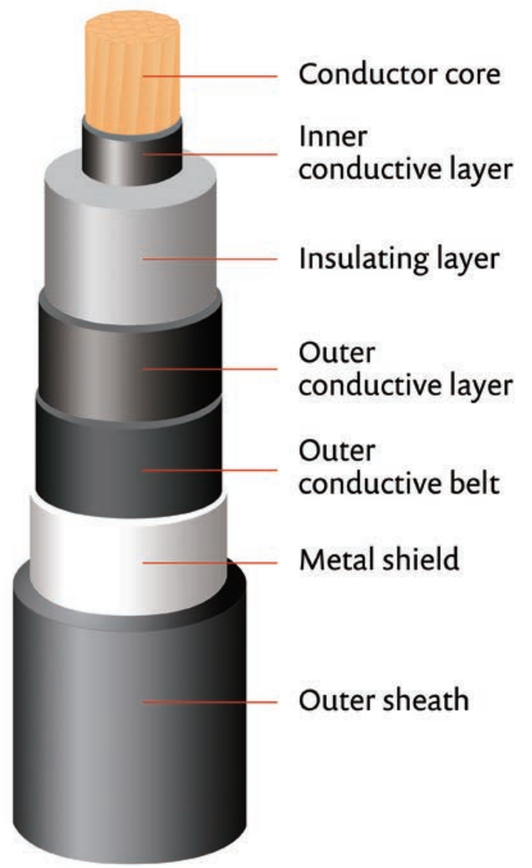


Figure 1. Schematic of a standard cable structure.

Figure 2. Left: Water tree caused by the interaction between the electric field and moisture. Right: Close-up of the mechanical damage to the insulation layer.

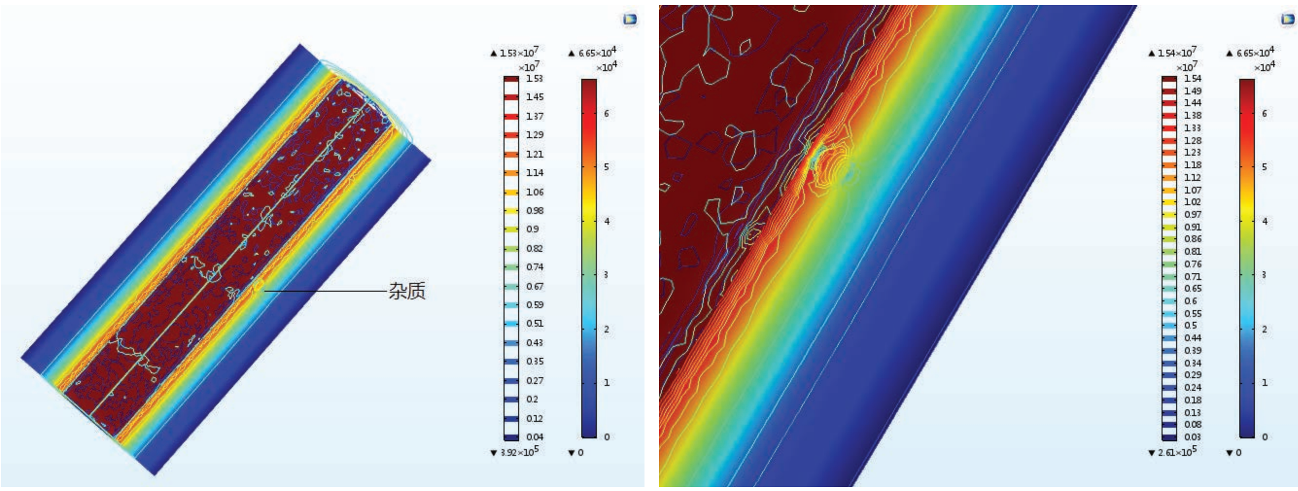


Figure 3. Left: Simulation results of a cable with impurities included, showing potential distribution and electric field norm contours. Right: Detailed view of the electric field.

voltage fluctuation, and operating conditions and environments.

Wuhan NARI Group Corporation (NARI) of the State Grid Electric Power Research Institute is affiliated with State Grid Corporation of China. NARI focuses on research and development, design, manufacturing, and engineering services for power transmission and transformation products. NARI also works with local power companies on equipment maintenance and failure analysis. Given the many parameters and physical phenomena involved, a team of engineers led by Jing at NARI used simulation to investigate changes in electrical fields due to factors, such as health of the cable system, and failure causes.

HOW WATER TREES AFFECT CABLE HEALTH

CABLES ARE MADE UP of a complex multilayer structure. The wire core consists of one or several sets of mutually insulated stranded wires, wrapped in a highly insulating layer (Figure 1). When inducing factors such as moisture, impurities, protrusions, or space charge, occur in the insulating layer, part of the insulation material will develop tree-like microchannels as a result of the combined action of moisture and an electric field. In operating cables, the electric field forces moisture to displace in such a way that it continuously accumulates at the fault spots. This results in mechanical damage to the insulating layer and expanded damage to the insulator. This phenomenon, known as "water tree" is regarded as the main cause of damage in high-voltage cables used for power transmission (Figure 2).

To understand the impact on cable health, NARI's engineers used multiphysics simulation to create a cable model. "COMSOL Multiphysics® features a user-friendly interface and predefined physics interfaces that make modeling easy to adopt organizationally" said Jing Zhang, engineer at NARI.

Simulating the cable fault required two steps. First, they set the radius and electrical properties of the materials in each layer of the cable and calculated the normal electric field when a high voltage is applied. The next step was to introduce parameters representing impurity and the presence of a water tree layer. "Assessment of cable health entails analyzing its behavior when deteriorating material properties and the formation of water trees are considered, and the COMSOL® software makes this easy to do," Zhang explained.

In comparing the results of the electric fields under normal and abnormal conditions, the engineers were able to reach an accurate understanding of the impact of the impurities and water trees on the cable's performance. The electric field of standard cables only involves lines of electric force that point to the shielding layer along the radius of wire; therefore, the electric field distribution is uniform. Once impurities are added, as shown in Figure 3, the uniform electric field is disturbed. Once a local electric potential difference exceeds the maximum allowable voltage in the insulating layer, the

> *"The simulation app plays a key role in cable maintenance. It makes the work of our field technicians more efficient by empowering them to confidently assess and repair faults."*
>
> — JING ZHANG, NARI GROUP CORPORATION

layer is compromised and will break down in a relatively short time.

BRINGING A DIGITAL TWIN TO THE FIELD

SIMULATION OFFERS a vast landscape of knowledge of cables to engineers at NARI. However, when cable failure occurs in the real world, troubleshooting personnel are not trained to use the digital twin provided by a multiphysics model to analyze failure causes based on real-time data. In remote areas, it may take days or even weeks to invoke an expert to conduct a site survey and remove the fault. If on-site troubleshooting personnel are able to understand what condition led to the failure through simulation, the troubleshooting work is greatly simplified. To enable maintenance personnel to respond in real time, Zhang developed a simulation app featuring relevant parameters that the troubleshooting personnel can modify. A simulation app can be created from any multiphysics model using the Application Builder in COMSOL Multiphysics.

The Cable Condition Analysis Expert System app (Figure 4) allows the field technicians to directly enter data from the cables and select the type of fault, thus modifying the underlying multiphysics model on the fly, to calculate and output the data necessary to understand what caused the fault. The app quickly yields a reported potential and electric field, which guides the technicians to determine whether it is necessary to replace or repair the cable. “The simulation app plays a key role in cable maintenance. It makes the work of our field technicians more efficient by empowering them to confidently assess and repair faults,” Zhang said.

The Cable Condition Analysis Expert System App developed by NARI is adopted by a subordinate unit of Guangxi Power Grid Co., Ltd. Repair personnel, who use it to predict cable faults and maintain the normal operation of the power grid system in southwest China. ◎

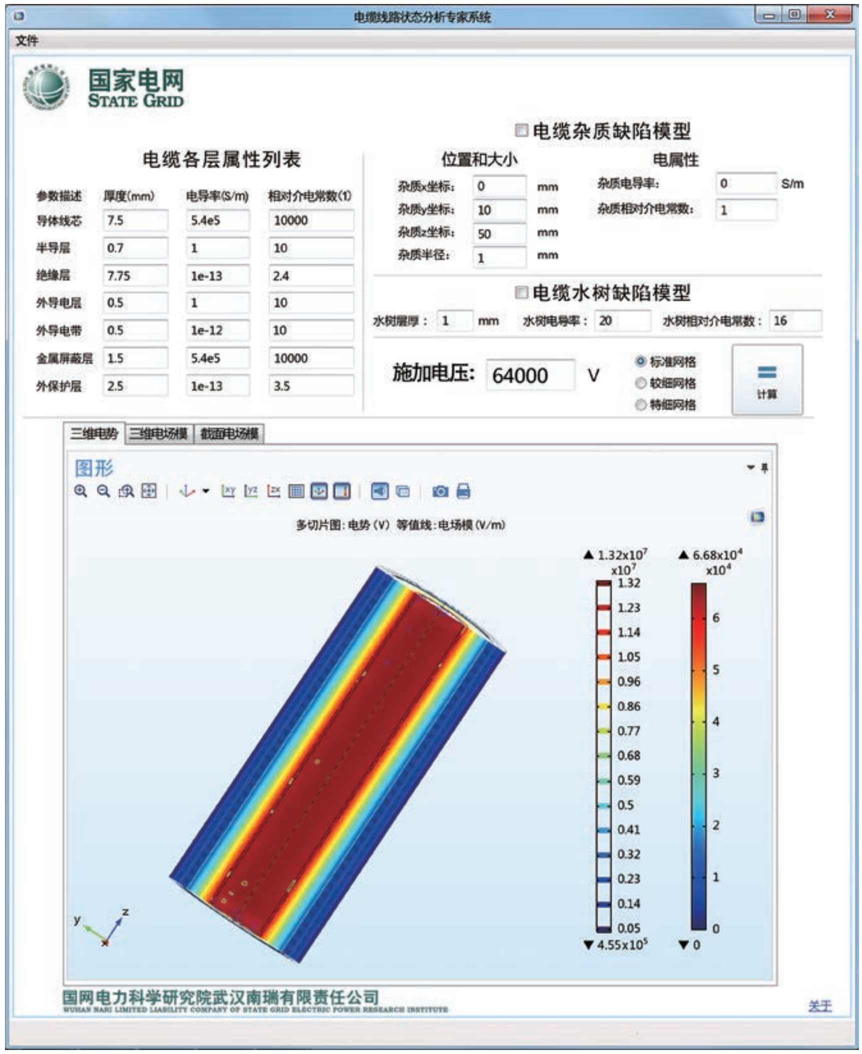
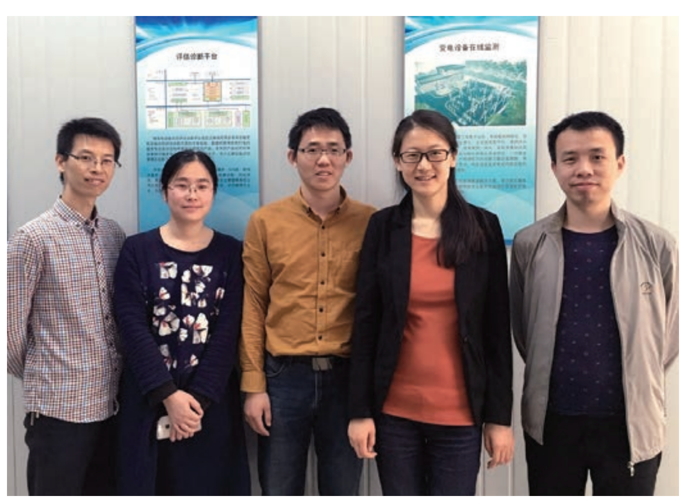


Figure 4. The Cable Condition Analysis Expert System app.



Members of the simulation research team, part of the Shipment Inspection Services Division at NARI Group Corporation. Left to right: Zhao Chen, Ting Hu, Tiyou Fang, Jing Zhang, and Hao Wang

ILLUMINATING COMPLEX MATERIAL BEHAVIOR WITH MULTIPHYSICS SIMULATION

At Canadian Nuclear Laboratories, multiphysics simulation is used to shed light on the complex material behavior of nuclear fuel.

By **SARAH FIELDS**

WHAT HAPPENS WHEN ENGINEERS explore the possibility of replacing tried-and-true but cumbersome in-house code with multiphysics simulation software? Nuclear engineers began to ask this question at the Computational Techniques Branch of Canadian Nuclear Laboratories (CNL), Canada's premier nuclear science and technology organization.

In the field of nuclear engineering, where research focuses on improving the safety, efficiency, and economics of reactors, mature and robust in-house computer codes are frequently used for modeling studies. Unfortunately, the need to comb through many lines of code to investigate the potential effect of a minor adjustment to a system is a real barrier to innovation. As an alternative to modifying mature or legacy codes, a multiphysics platform provides an environment that allows engineers to explore changes in data and modeling methods without the complications of adapting lengthy code.

Andrew Prudil, fuel safety scientist at CNL, is at the center of research that enlists simulation software to find ways to improve the established, seemingly immutable design of nuclear reactors.

"Essentially, nuclear science is material science, but with additional considerations for the effects of radiation," Prudil explains. "The materials we study include the nuclear fuel, as well as the constituents of some of the surrounding components."

›› NUCLEAR FUEL: A COMPLEX MATERIALS SCIENCE PROBLEM

ULTIMATELY, PRUDIL ENLISTED multiphysics software to create a awe-inspiring mathematical model that includes a staggering number of physical phenomena. His modeling work includes a representation of a nuclear fuel pellet including heat transport, structural mechanics deformation, mechanical contact, pressure buildup due to fission gas release, and microstructural changes due to grain growth, radiation damage, and burnup. He also modeled the behavior of the cladding around the nuclear fuel.

In a nuclear reactor, pristine nuclear fuel pellets (Figure 1) are placed inside the cladding, or sealed metal tube. Upon irradiation, these fuel pellets increase in temperature, and transfer heat to the sealed metal tube, which in turn transfers heat to water. This hot water is eventually used to produce steam in order to generate electricity, mirroring the process that takes place in conventional power plants.

Upon irradiation, a fission reaction drives heat production within the fuel pellets, resulting in high temperatures, high thermal gradients, and thermal expansion. There are also nuclear-specific phenomena to consider, as the products of fission accumulate in the fuel pellets.

Figure 1 shows the complicated microstructure of a nuclear fuel pellet after sustained high-temperature operation. The initial as-fabricated grain structure remains only on the outside closest to the coolant where the temperature is the lowest. At slightly higher temperatures, the grains grow (coarsen), forming a region of equiaxed grain growth. At the highest temperatures, a vapor transport mechanism enables the porosity in the fuel to migrate following the temperature gradient (toward the center) forming a central void and leaving long columnar grains in its wake.

Of these effects, cracking occurs inside the ceramic fuel. There is also contact between the ceramic and the metal cladding. Radiation damage to consider, as high energy fission products such as gamma and neutron radiation change the microstructure

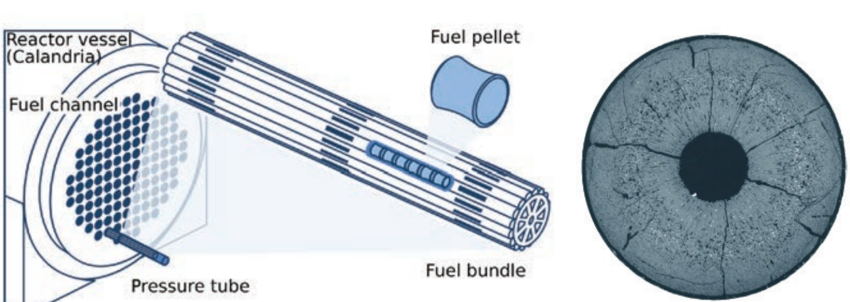


Figure 1. Left: Diagram showing the location of fuel pellets in a fuel bundle. Right: Transverse micrograph of a fuel pellet showing the microstructure produced during operation.

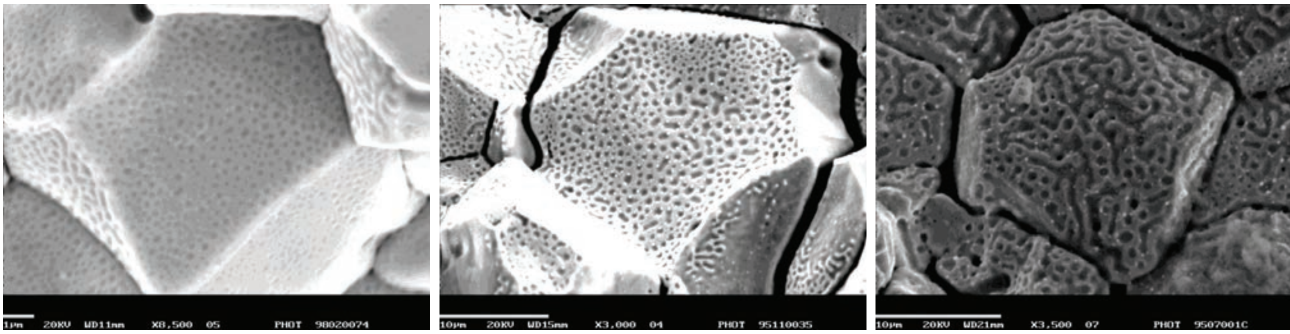


Figure 2. Micrographs showing the development of fission gas bubbles on the grain boundaries of uranium dioxide fuel. With increasing burnup, left to right, the bubbles become larger and more interconnected. White, *Development of grain-face porosity in irradiated fuel*, J. Nuc. Mat. 325, 2004, www.sciencedirect.com/science/article/pii/S0022311503004616.

of all materials. There is also macroscopic swelling, since fission is the splitting of one atom into two, and two atoms take more space than one.

Furthermore, two fission products, the noble gases xenon and krypton, are inert and form bubbles inside the fuel pellets (Figure 2).

There are also corrosion issues to consider as high-temperature water in a radiation environment leads to the formation of radiolysis products, which cause corrosion on the outside of the cladding.

PREVENTING FUEL FAILURE

BECAUSE THE PROPERTIES of nuclear fuel pellets change dramatically as they are irradiated, engineers rely heavily on models to predict fuel performance parameters like peak temperature, gas pressure, and cladding strain to interpolate between available experiments. Similarly, knowing how any design change could manifest in a radiation environment requires extensive modeling work and validation with physical measurements.

One of the primary motivations for Prudil's research was to model the deformation of the cladding and obtain a better estimate of cladding strain, as it is a significant mechanism of fuel failure. Once a model for strain of the cladding was created, the system could be optimized virtually. Optimization strategies include making a direct change to the fuel, the fuel to cladding gap, or how the fuel is treated once in the reactor.

"It's relatively straightforward to build a model," Prudil says, "but less straightforward to know what the

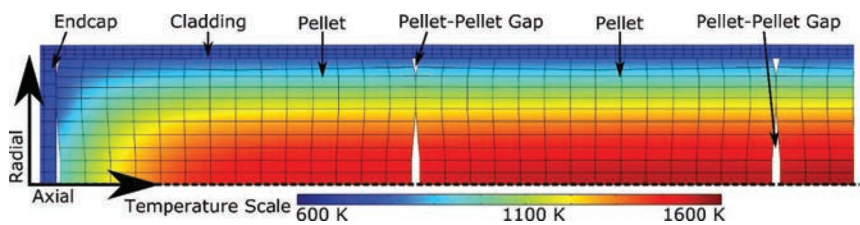


Figure 3. Simulation results from the 'Fuel and Sheath Modeling Tool (FAST)' showing temperature throughout the cladding, fuel pellets, and pellet-pellet gaps.

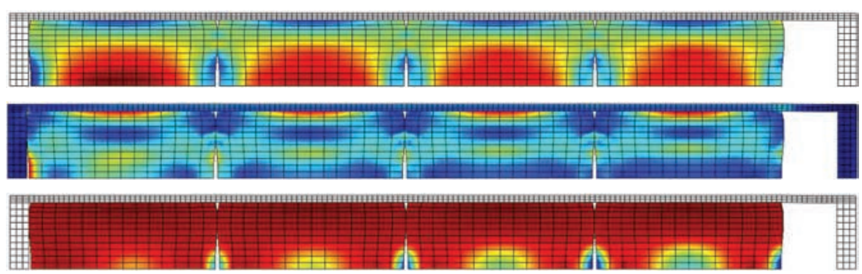


Figure 4. Simulation results from FAST showing hydrostatic pressure (top), von Mises stress (middle), and axial creep (bottom) throughout the cladding, fuel pellets, and pellet-pellet gaps.

correct material properties are to put in that model, especially when they evolve with time and radiation exposure." After completing a new model, he compares the simulation results to experimental results to assess the quality of his predictions.

Changing the fuel itself is an attractive approach to improving a nuclear reactor, as nuclear fuel is designed to be replaced. This is cost effective, as no parts of the reactor would need to be updated: The engineers could simply feed the system the new fuel when it is time to refuel the reactor.

"Therefore," Prudil says, "our top challenge is accurately describing the materials in question."

COUPLING SEVERAL PHYSICAL PHENOMENA IN ONE MODEL

USING THE COMSOL MULTIPHYSICS® software, Prudil created the Fuel and Sheath Modeling Tool (FAST) to capture the complex heat transport, solid mechanics, and material behavior of the nuclear fuel, cladding, and the gap between the fuel and the cladding. Figure 3 shows an example of the temperature profile generated for the pellets and cladding.

"Using the COMSOL® software," Prudil says, "I don't have to worry as much about the numerics and programming – I'm able to directly approach the math and the physics rather than worry about the solution process and the post-processing.

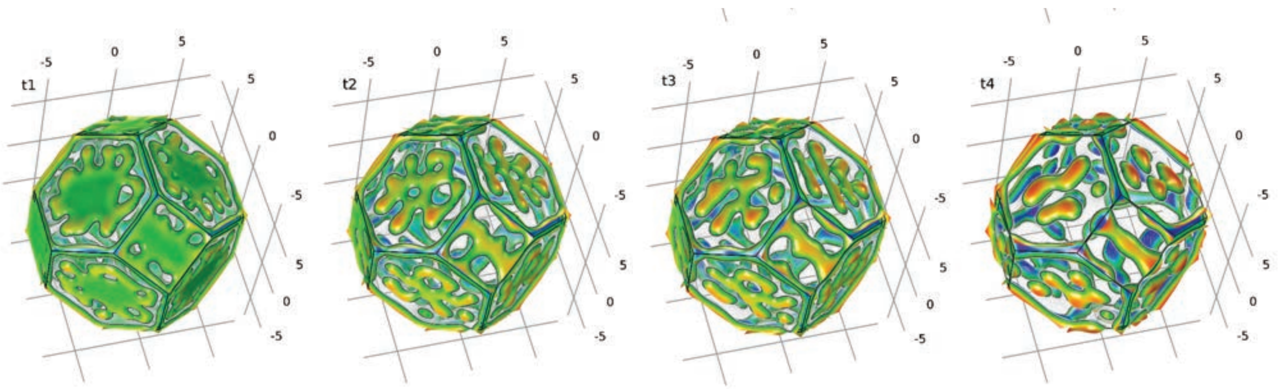


Figure 5. Simulation, left to right, of formation, movement, and coalescence of gas bubbles on the grain boundaries.

There's less overhead than what's usually associated with numerical modeling using an in-house code."

Prudil also obtained simulation results from FAST the show hydrostatic pressure, von Mises stress, and axial creep throughout the cladding and fuel pellets (Figure 4). The distribution of these fields is the result of design parameters such as the length-to-diameter ratio and chamber dimensions as well as operational considerations like power level and coolant temperature.

» *SIMULATING THE EVOLUTION OF GRAIN BOUNDARY POROSITY*

TO EXTEND THE MODELING TOOL and shed light on the performance of the reactor in a different way, Prudil modeled the diffusion of gas out of the fuel grains, and then the formation and movement of bubbles on the grain boundaries (Figure 5) using the equation-based modeling functionality available in COMSOL®.

Upon irradiation and the chemical change of the nuclear fuel, gas seeps out of the fuel grain, forming bubbles. These bubbles then move around and coalesce (Figure 5). In a traditional phase field, the volume of the fuel grains would be modeled. The novelty and power of this technique comes from ignoring the solids and only modeling the moving surface between the solids and gas. This turns a 3D problem into 2D and significantly reduces the computational resources required.

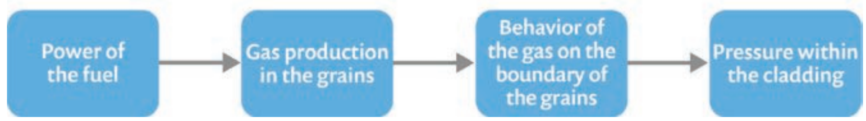


Figure 6. The fuel degradation process.

The model uses two coupled weak form equations on the surface of the grain, one for the distance to the bubble surface, and the other for the chemical potential. Knowing how much gas comes out of the fuel allowed Prudil to calculate the thermal conductivity and gas pressure inside the fuel element. The results from this analysis allowed Prudil to determine other key indicators of fuel performance. This set of calculations serves as a nonlinear representation of fuel degradation (Figure 6).

From the simulation, it is possible to approximate if the pressure is sufficiently low, such that the fuel can continue being irradiated — an insight with great implications for safety.

» *SIMULATION DRIVES INNOVATION IN FUEL TECHNOLOGY*

BY USING MULTIPHYSICS SIMULATION, engineers at CNL were able to create a useful tool, and clear the way for faster design iteration and innovation. Prudil sees multiphysics simulation informing other areas of development in nuclear engineering, such as the development of accident-tolerant fuel. The interest in designing fuel that is resistant to severe accident scenarios represents an opportunity for engineers to completely rethink fuel.

In the long term, Prudil also sees simulation software playing a role in the development of small module reactors, which would represent a paradigm shift in nuclear reactor design toward smaller, easier to build reactors and potentially reduce the high capital costs of reactors. Small module reactors could be made of new materials and have new geometries and safety paradigms, a departure from the decades-long trend of ever-larger nuclear reactors.

Meanwhile, the complex representation of existing reactors Prudil has already created continues to lend valuable insight into the many layers of complexity of the nuclear reactor. ◎

Andrew Prudil, fuel safety scientist at CNL.

HATS OFF TO THE BOUNDARY ELEMENT METHOD

Engineers at GN Resound used the boundary element method for acoustics to create a simulated version of a physical Head and Torso Simulator (HATS), a critical tool in evaluating the performance of acoustic devices that interact with the human body, including headsets, hands-free communication devices, and hearing aids.

By **ZACK CONRAD**

REPRESENTING THE HUMAN BODY'S influence on airborne sound signals is no straightforward task, but in order to evaluate the performance of acoustic devices that interact with humans, it is a necessary challenge to undertake. In situ electroacoustic testing is a standard method of performance evaluation, but the irregular shapes and extensive variations of the torso, head, pinna, and ear canal often pose quite the headache for acoustic engineers.

To make acoustic data collection as accurate as possible, sound and vibration measurement equipment manufacturer Brüel & Kjær developed HATS, the Head and Torso Simulator, a manikin that accurately reproduces the geometric features and acoustic properties of an average adult head and torso (Figure 1). Composed of built-in mouth and ear simulators, the manikin is ideal for performing electroacoustic tests on headsets, headphones, hands-free communication devices, hearing aids, helmets, and hearing protectors. Usually, the ear simulator is a half-inch microphone connected to a preamplifier, while the mouth simulator is a high-compliance loudspeaker with a sound pressure distribution that simulates a talking average adult human mouth.

GN Resound has been using a HATS for many years in their measurement setup to investigate the effects of the geometry of ears on the perceived sound at the eardrum and to determine directionality characteristics due to the scattering by the ear and head geometry. Recently, a mathematical model for HATS has been constructed in the COMSOL Multiphysics® software. The task was carried out by Senior Engineer René Christensen, using the boundary element method (BEM) functionality. Once the model was complete, several colleagues saw an opportunity to utilize this simulation tool instead of a manikin for their respective purposes.

» WHY THE BOUNDARY ELEMENT METHOD?

THE COMBINED INFLUENCE of the torso, head, pinna, and ear canal on airborne sound signals and the acoustic field around the head is known as the Head-Related Transfer Function (HRTF). "For a given point in space away from the head, you can describe how a sound originating from that point will arrive at the eardrum," explains Christensen. This is a deterministic approach that allows the simulated sound to be visualized for different microphone placements (example points of interest shown in Figure 2), aiding engineering decisions and enabling the exploration of how the head and torso affect the total sound pressure (Figure 3). The challenge with acoustics simulations that take place over meter-scale distances is that the commonly used finite element method (FEM) is computationally expensive and requires considerable amounts of RAM.

For Christensen, who performs most of his simulation work on a laptop, this was a severe constraint. But with the COMSOL Multiphysics® software he was able to choose which method to use and, in this case, he took advantage of the BEM functionality available for acoustics to run much more efficient simulations. While BEM demands more computation per degree of freedom than FEM does, BEM usually requires significantly fewer degrees of freedom to obtain the same level of accuracy over large volumes. BEM allows you to extract sound pressure values at any point in the domain while only meshing and performing calculations on a surface, providing a substantial computational advantage.

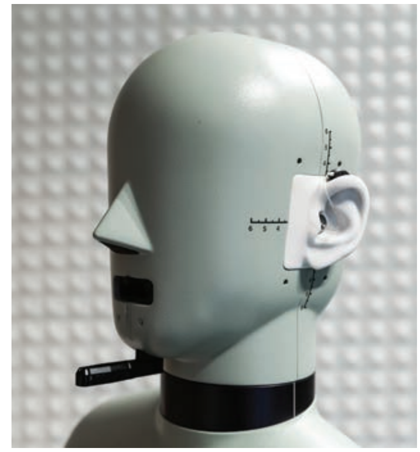


Figure 1. HATS (Head and Torso Simulator) being used to test an integrated helmet system.

> *"The software is very beneficial to someone like me who tries out physics described by mathematics not necessarily already available in it. I like to ask myself, 'Can you give me an equation that describes this problem?' And if so, then you can probably set it up and solve it in COMSOL."*
>
> —RENÉ CHRISTENSEN, SENIOR ENGINEER, GN RESOUND

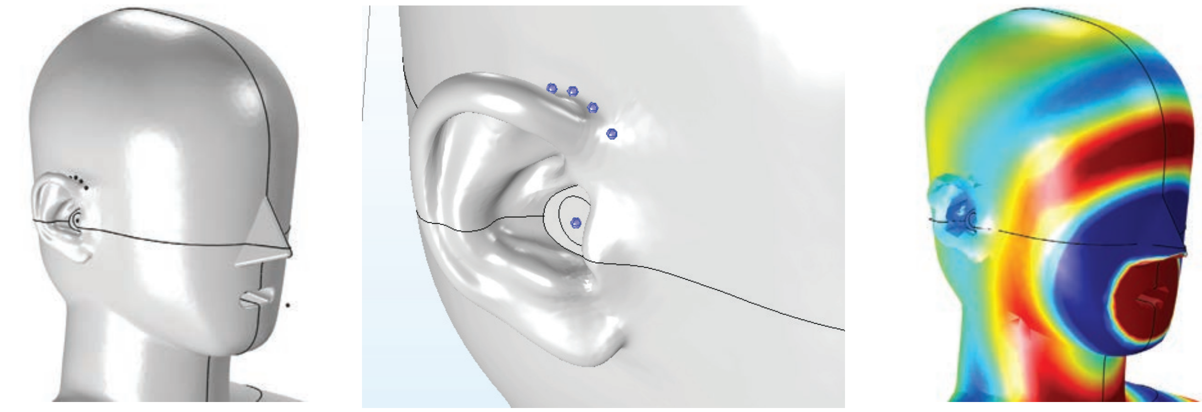


Figure 2. Left and middle: "Near-ear" points where the mouth-to-point near-ear transfer function is evaluated. The mouth-to-point near-ear transfer function is a more specific type of head-related transfer function. Right: Sound pressure distribution at 3200 Hz. The red corresponds to high, positive pressures, while the blue corresponds to high, negative pressures.

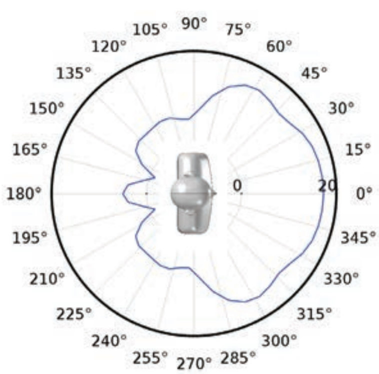


Figure 3. Polar plot of total sound pressure for 1 m radius at 3200 Hz.

The entire volume needs to be meshed instead with FEM, which is be feasible when the near-field is of interest. With the use of BEM, Christensen could now keep his simulations within his computational resources and perform them on his laptop. "It's a lot easier to set up with the boundary element method," Christensen says. "If you have a good geometry, you can just create a surface mesh which is such a luxury. Usually you would use a volume mesh and have to do things like resolve the air and apply radiation conditions to limit reflection, but this is all implicitly incorporated in BEM."

» TALKING AND LISTENING

THE BEAUTY OF HATS is that it can be used to model situations with several sources, an example being if a user speaks and additional sounds are present, as is often the case with a headset user talking in a busy office environment. Hearing aids are especially complicated because they consist of both microphones and loudspeakers, and this can lead to feedback. "There is an extra layer of complexity because there are two microphones in a typical hearing aid, and both of them pick up sound and vibration," Christensen explains. "Some of this stems from the hearing aid itself, and so there is a potential for feedback, something that will often result in a horrible noise."

With BEM, the simulation is relatively straightforward because of how little physics needs to be set up. In such instances, an acceleration boundary condition is applied on the mouth to mimic a loudspeaker. HATS itself is assumed to be rigid, and any radiation conditions that would ensure acoustic waves are not reflected are automatically fulfilled with BEM. From there, the sound pressure field around the head and torso is calculated, and once the simulation has been run, several microphone positions can be investigated with postprocessing. If a hearing aid geometry is present, mechanical designers can indicate all feasible positions, and the optimal one can be determined with the information extracted from the simulations. "With BEM, there is really not much physics to set up," Christensen says. "Since we are interested in mouth-to-ear relations, I apply an acceleration in the mouth and extract pressure at points in front of the mouth or in and on the ear, and that is it. The only physics is acoustics."

» FUTURE USE

CHRISTENSEN'S HATS MODEL is of supreme value to him and his colleagues because once it has been solved, there is a tremendous amount of information available to extract using various postprocessing tools. Different configurations such as domes that help aids fit snugly or ports that connect the inner ear to the exterior, can be investigated, new transfer functions can be derived for assorted points, and it can be prepared for use with other software.

Christensen also says that as he continues to improve his acoustic models, not just for HATS but vibroacoustics in general, he will continue to use COMSOL Multiphysics®. "I like the software because it has a very familiar and intuitive feel, and you can add or modify equations to accommodate your needs, which I often take advantage of," he explains. "The software is very beneficial to someone like me who tries out physics described by mathematics not necessarily already available in it. I like to ask myself, 'Can you give me an equation that describes this problem?' And if so, then you can probably set it up and solve it in COMSOL." ◎

DESIGNING SUPERIOR PRODUCTS WITH CONFIDENCE

By DAN ANAGNOS, CHIEF TECHNOLOGY OFFICER, WARWICK AUDIO TECHNOLOGIES

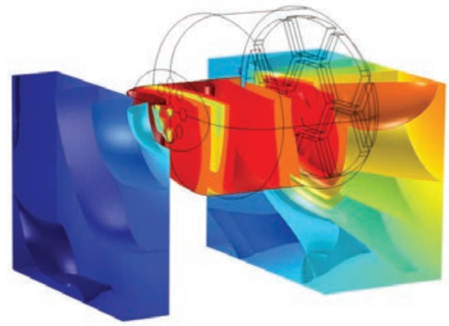
ELECTROACOUSTIC SYSTEMS R&D ENGINEERS have applied traditional simulation methods such as lumped parameter modeling and distributed element modeling for many years. While these modeling techniques have proven useful for some applications, they are limited in terms of accuracy and effectiveness. Often, results have relatively poor correlation to acoustical measurements and misrepresent underlying mechanisms, which can lead to false conclusions or compromised designs. When developing novel, cutting-edge technologies for reproducing sound, a more comprehensive, accurate, and efficient simulation technique is essential.

At Warwick Audio Technologies (WAT), we have utilized multiphysics modeling to dramatically shorten design cycles, reduce the costs of prototyping, and quickly converge on optimal solutions for a wide range of applications. Two years ago, we collaborated with Xi Engineering Consultants, a COMSOL certified consultant to assist in developing our first-generation high-precision electrostatic laminate (HPEL) transducer. Following its success, we've continued working with Xi Engineering to develop a second-generation HPEL planar transducer, along with specialized drive electronics. This new design offers significant performance improvements and scalability to different sizes, shapes, and power levels for applications ranging from headphones to automotive sound systems.

With multiphysics modeling, we predicted very accurate sound pressure levels, sensitivity, linearity, and various types of distortion over a frequency range of 10 Hz to 60 kHz, at differing power input levels. Numerical simulation enabled us to parameterize different geometries and materials to arrive at a fully optimized design prior to prototyping. We were even able to add manufacturing-related assembly features to the design and gauge their impact on performance.

We have also extended our modeling to include the surrounding acoustical environment. By combining the boundary element method (BEM) and the finite element method (FEM), we were able to specify the optimal design of materials and acoustical loading conditions surrounding a self-powered automotive headrest speaker system. Furthermore, the transducer and electronics have been scaled and optimized for specific locations throughout the vehicle.

Multiphysics simulation is an extremely powerful and effective tool for mission-critical R&D tasks, saving time, cost, and resources that are often constrained and limited. It also reduces risk during research and development and is beneficial in all these ways for mature, established corporations as well as early-revenue, venture-funded companies like ours. Our investors can view compelling evidence of progress quickly with a high level of confidence, and then reap the benefits of superior designs and products that reach their intended markets rapidly. ◎



Sound pressure level (SPL) contours of an HPEL transducer in an automotive headrest.

The ultrahigh performance Sonoma Headphone System, using the HPEL transducers and fully integrated audio drive electronics developed by WAT.

DAN ANAGNOS *is the chief technology officer at Warwick Audio Technologies Ltd., a UK-based technology venture developing state-of-the-art electrostatic planar transducers and proprietary drive electronics for premium audio applications. Dan has managed electroacoustic research and product development in the consumer electronics, professional audio, and OEM audio segments for various companies over the last 30 years. He has 14 patents in the field of electroacoustics.*