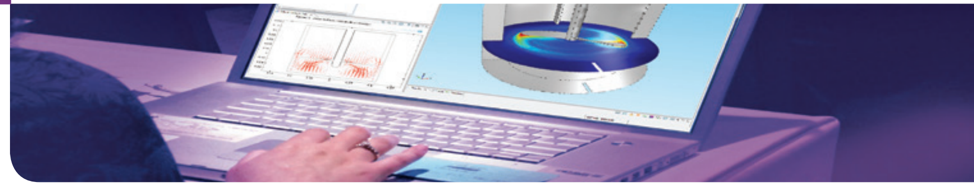
COMSOL MULTIPHYSICS®

PRODUCT BOOKLET



VERSION 4.3b

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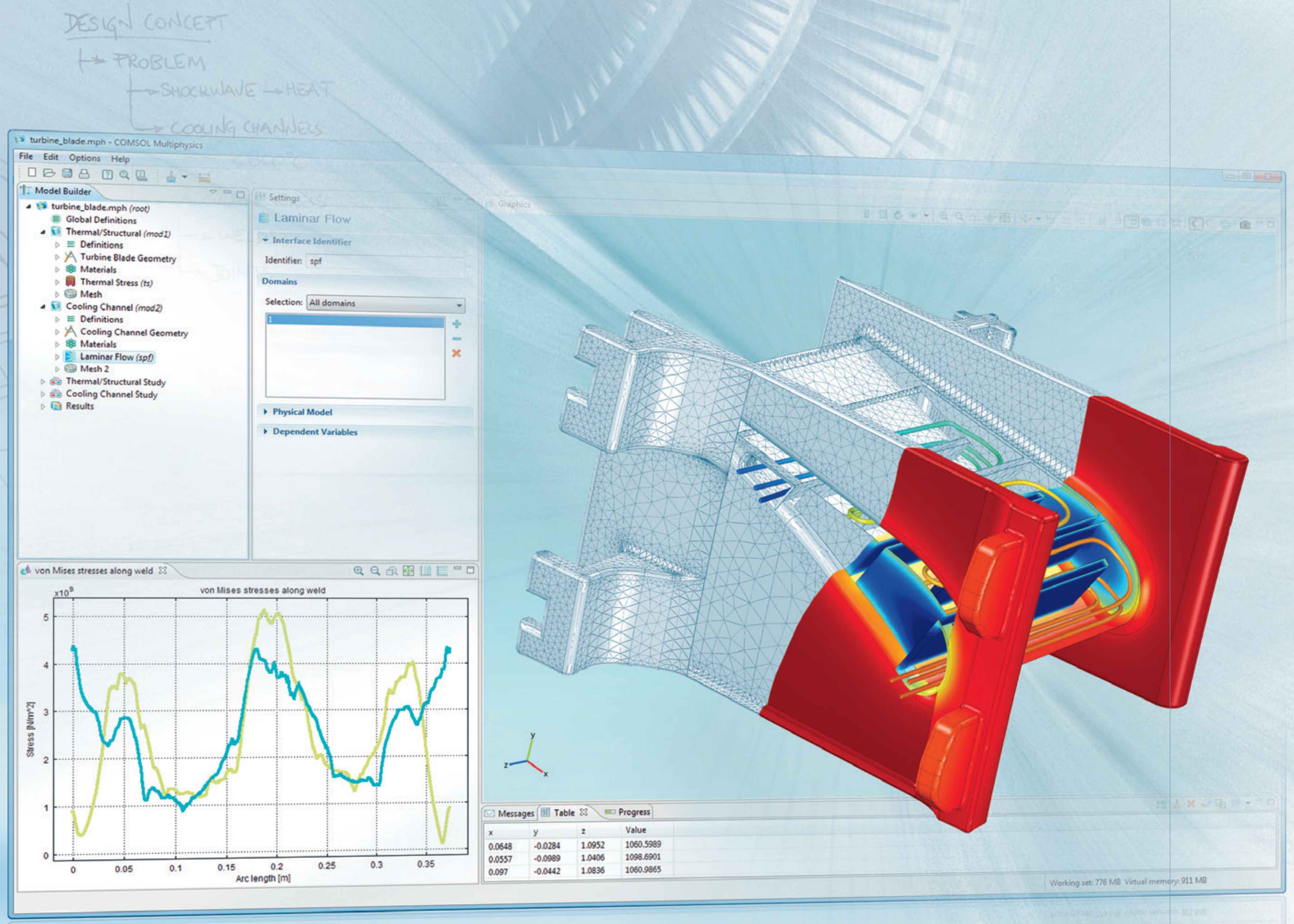

TURBINE STATOR BLADE

A stator blade in the turbine stage of a jet engine is heated by the combustion gases. To prevent the stator from melting, air is passed through a cooling duct in the blade. The resulting temperature gradients introduce significant stresses.

Multiphysics Simulation.

In today's fast-paced research and development culture, simulation power gives you the competitive edge. COMSOL Multiphysics® is the ideal tool to build simulations that accurately replicate the important characteristics of your designs. Its unparalleled ability to include all relevant physical effects that exist in the real world is known as multiphysics.

This approach delivers results—tangible results that save precious development time and spark innovation. COMSOL Multiphysics brings you this remarkable technology in an easy-to-use, intuitive interface, making it accessible to all engineers including designers, analysts, and researchers.

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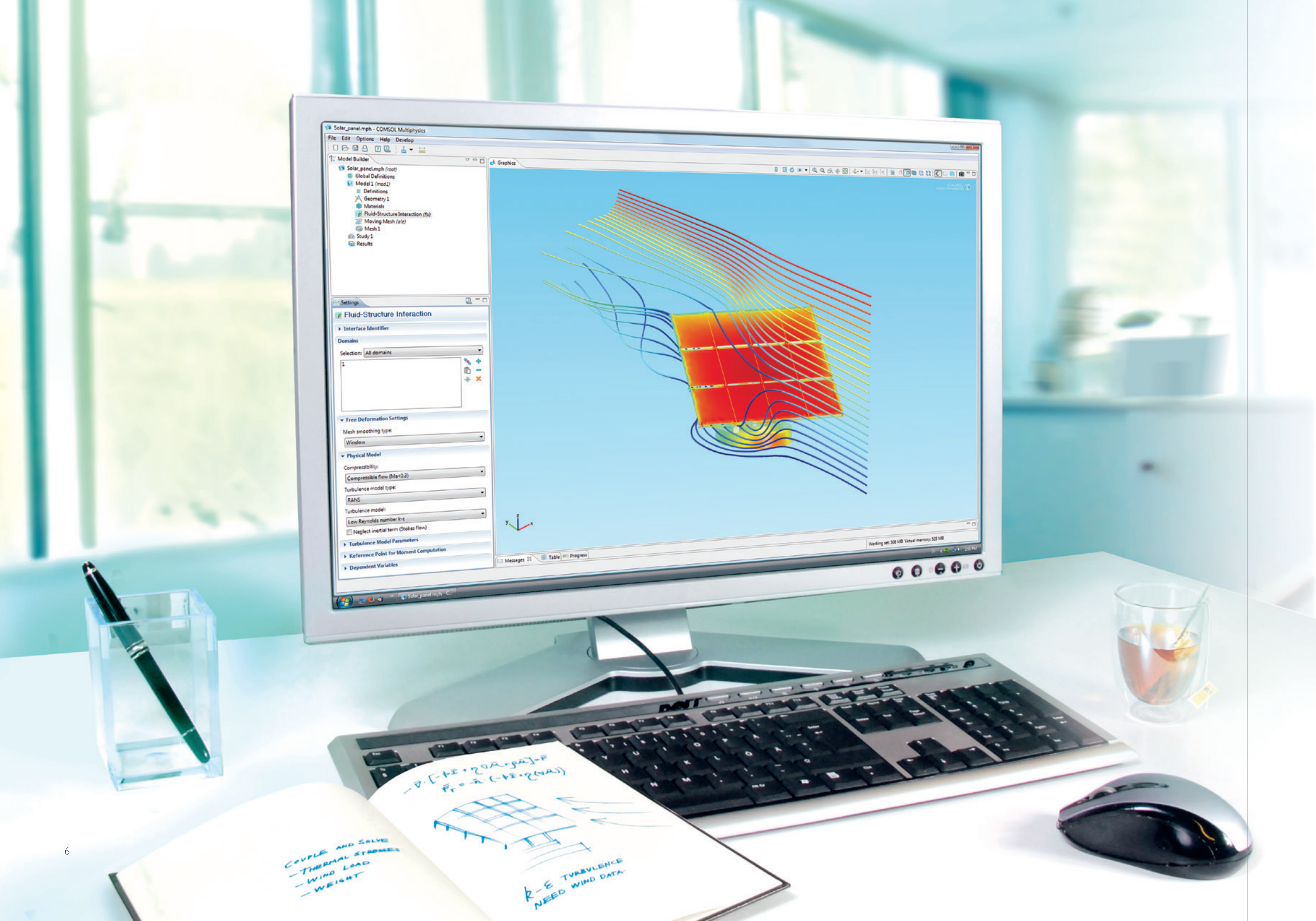
How do you verify and optimize your design?



"COMSOL Multiphysics provides an excellent platform that allows us to examine all physics within one easy-to-use environment and optimize system operation before we start building prototypes."

Karl-Anders Weiss, Fraunhofer Institute for Solar Energy Systems, Freiburg, Germany.

Through powerful simulation tools.

Companies are gravitating toward using simulation to drive the design. What is being realized are the advantages of simulation not simply to verify design decisions, but to explore and develop these new, innovative ideas; come up with viable concepts; and investigate all of their "what-ifs" in terms of use of materials or manufacturing methods.

A critical feature of these processes is making sure that the necessary tools are provided that let you quickly create and test new ideas. This is what COMSOL Multiphysics is offering: a single, integrated solution that can address the widest range of applications.

HEARING IMPLANT

Over the years, Cochlear Ltd. has helped more than 250,000 people in over 100 countries connect to a world of hearing. A new type of hearing implant, Codacs™, provides mechanical stimulations directly to the cochlea. Shown is a simulation of the electromagnetic fields within the balanced armature.

Model and pictures courtesy of Patrik Kennes, Cochlear Technology Centre, Belgium.

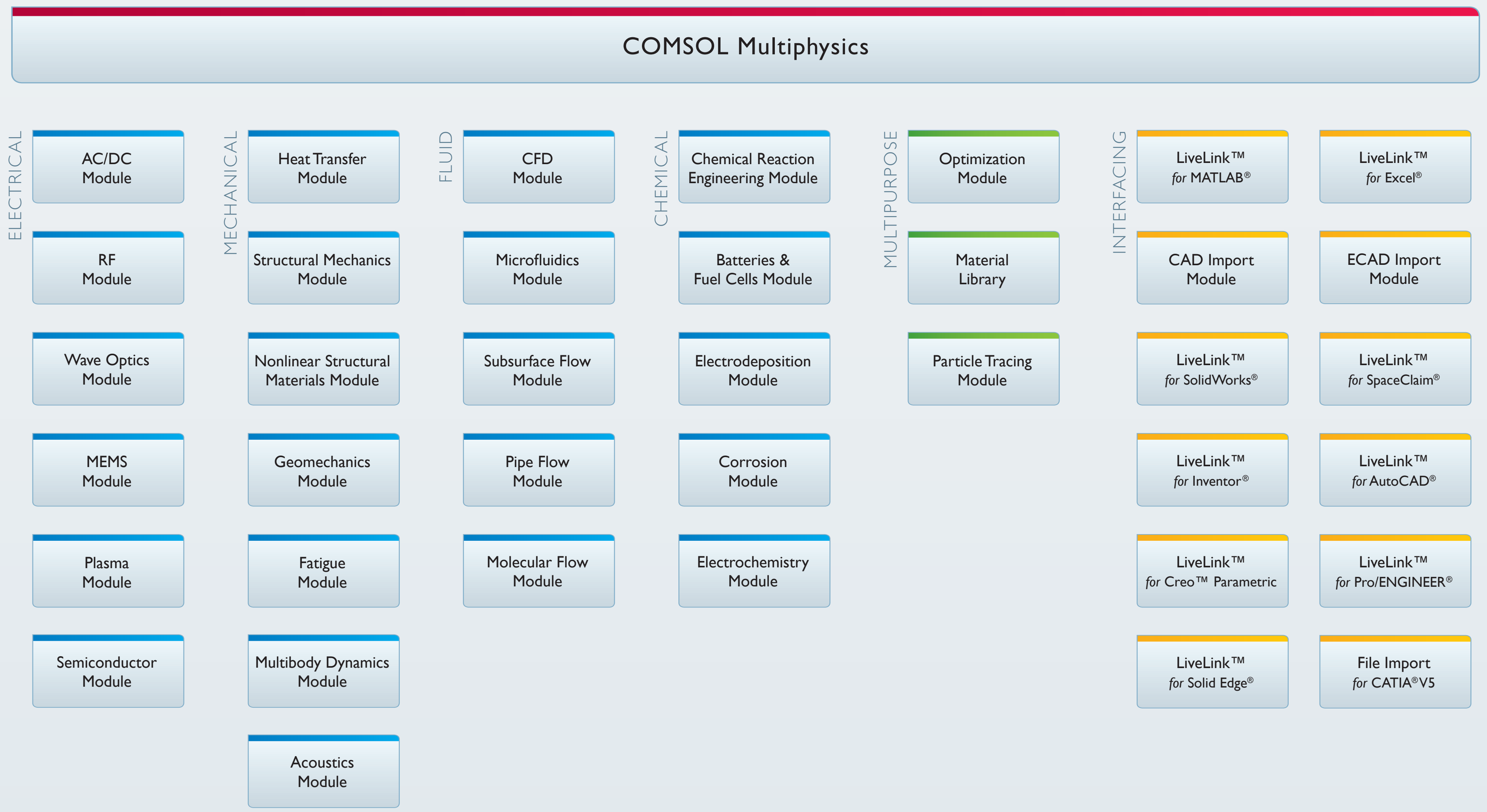
"The Direct Acoustic Cochlear Implant was developed from the ground up using COMSOL Multiphysics. Through COMSOL, we were able to avoid a time-consuming and costly trial-and-error design approach whereby we would have to build many prototypes to determine the appropriate part dimensions."

Patrik Kennes, Cochlear Technology Centre, Belgium.

With real world precision.

From its inception, the COMSOL® system was designed to address multiphysics problems to help you predict what will happen to a desired level of accuracy. The software starts with first principles like transport phenomena, electromagnetic field theory, and solid mechanics as basic fibers. Then, in a practical and flexible user interface, you can weave these fibers together in a self-consistent way to solve your particular simulation needs. The end result is a model you can trust, because you control every aspect of the underlying physics.

Our suite of best-in-class solvers comes standard and includes automatic detection of your model's characteristics. Mesh generation is also an automated process. Powerful tools like parametric sweeps, interactive meshing, and custom solver sequences together with materials and other model properties help you quickly adapt to the ebbs and flows of your requirements.



PRODUCT SUITE

COMSOL Multiphysics

The COMSOL Multiphysics simulation environment facilitates all the steps in the modeling process – defining your geometry, meshing, specifying your physics, solving, and then visualizing your results. It also serves as a platform for the application specific modules.

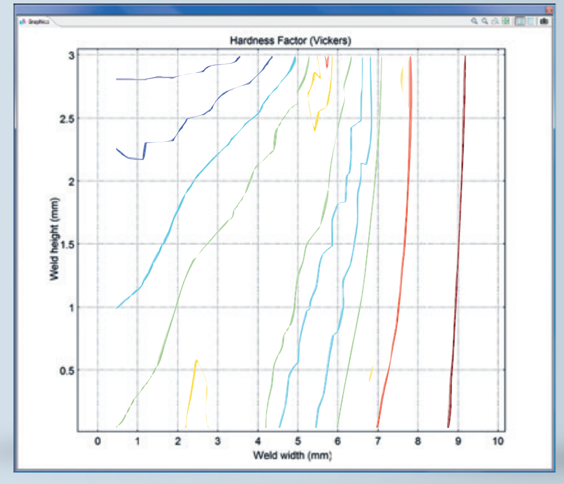
Model set-up is quick, thanks to a number of predefined physics interfaces for applications ranging from fluid flow and heat transfer to structural mechanics and electrostatics. Material properties, source terms, and boundary conditions can all be spatially varying, time-dependent, or functions of the dependent variables. You can freely mix physics interfaces into new multiphysics combinations as well as couple with any application specific module.

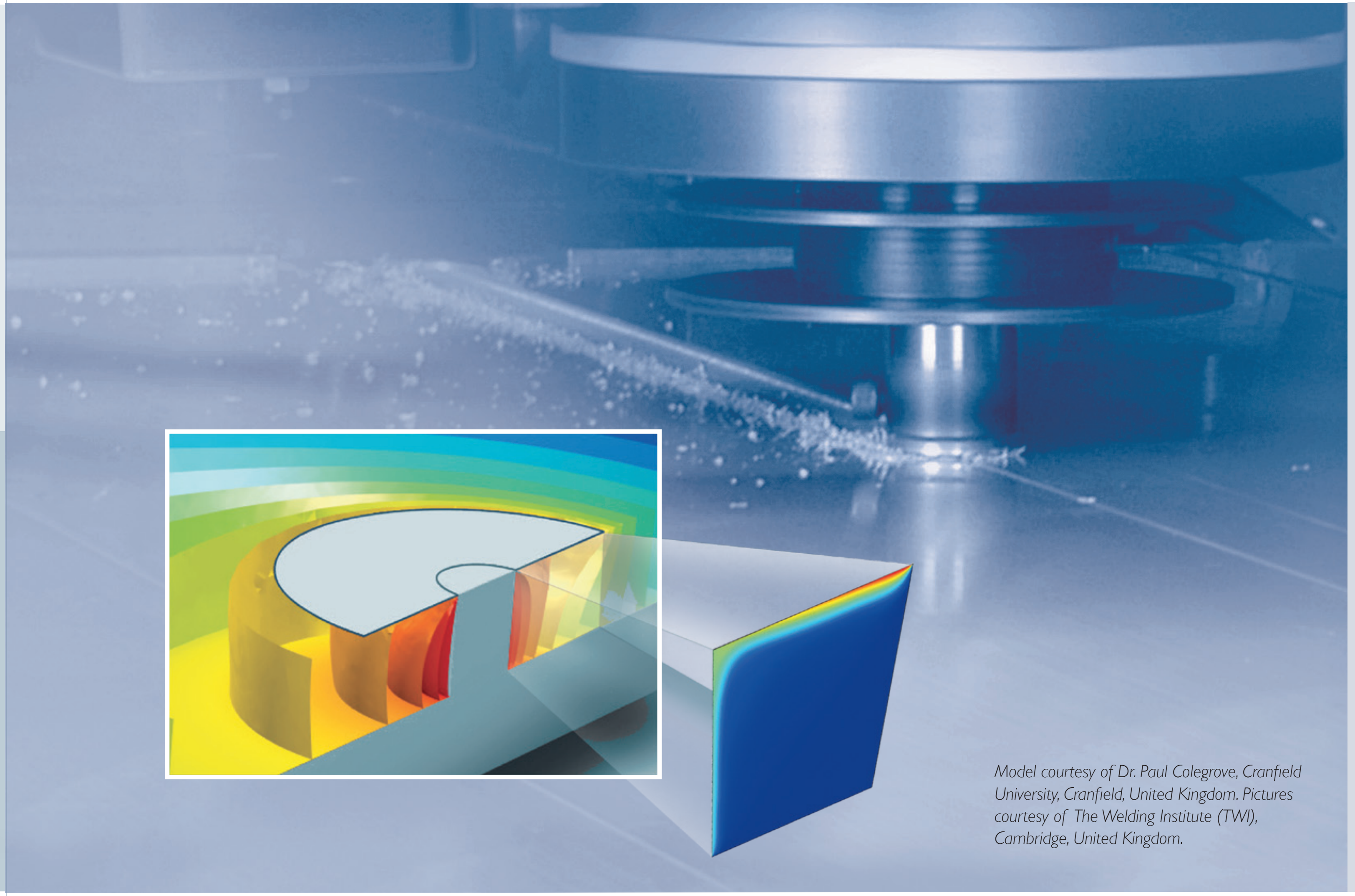
As an alternative to writing your own simulation code, the COMSOL Multiphysics user interface gives you the option to specify your own partial or ordinary differential equations (PDEs or ODEs) and link them with other physics interfaces. When combined with the CAD Import Module or one of the LiveLink products, this enables you to run custom simulations on CAD models from industry-standard formats.

WELDING

Friction stir welding is a solid phase welding process which was developed and patented by The Welding Institute in the 1990s. Since its invention, the process has received worldwide attention and today many companies are using the technology in production, particularly for joining aluminum alloys.

This model shows temperature distribution in a model that couples fluid with friction and heat transport. The graph shows the hardness factors in the weld as calculated from the model.

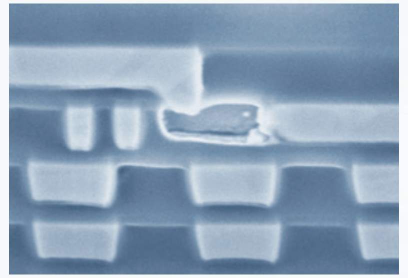




Model courtesy of Dr. Paul Colegrove, Cranfield University, Cranfield, United Kingdom. Pictures courtesy of The Welding Institute (TWI), Cambridge, United Kingdom.

HIGHLIGHTS

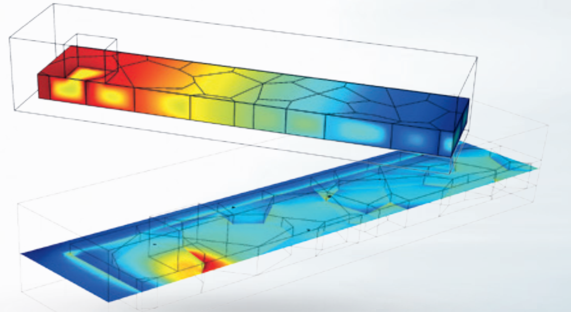
- Parameterized geometry modeling
- Automatic, swept, and boundary-layer meshing
- Mesh import
- Linear and high-order finite elements
- State-of-the-art multicore solvers
- Visualization tools
- Particle tracing, streamlines, and probe plots
- Animation, image, and data export
- Boundary and volume integration
- Fast-fourier transform (FFT)
- Interpolation table import for 1D, 2D, and 3D data sets
- Partial and ordinary differential equations user interfaces
- Entry level physics user interfaces
- Moving and deformable meshes
- Model couplings for linking 1D, 2D, and 3D models
- User-defined linear and nonlinear materials
- Space- and time-dependent expressions for physical properties and boundary conditions

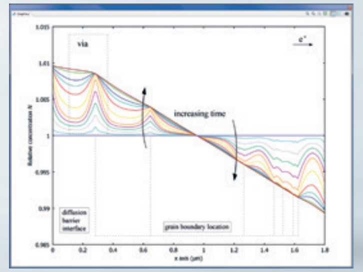


ELECTRONICS

Model predicting a copper line interconnect failure. Model results show vacancy concentrations, and the resulting von Mises stresses these produce. The graph shows the evolution of the vacancy accumulation over time where peaks occur near the via and at the grain boundaries.

Model courtesy of F Cacho and V Fiori, STMicroelectronics, Crolles, France.





All inclusive.

Practical simulation software—the kind that gets results—must be straightforward to use regardless of your modeling experience, while being constructive and powerful enough to achieve your objectives. We've incorporated these qualities into the all-inclusive COMSOL Desktop® environment.

This sleek interface gives you full insight and control over the modeling process as it concisely reflects the COMSOL Multiphysics architecture. The modeling process is integrated and intuitive, guiding you quickly through the building of your simulations. The COMSOL Desktop structure is uniform throughout, no matter which physics or application is being simulated. This encourages cross-discipline collaboration so engineering teams can develop better models faster.

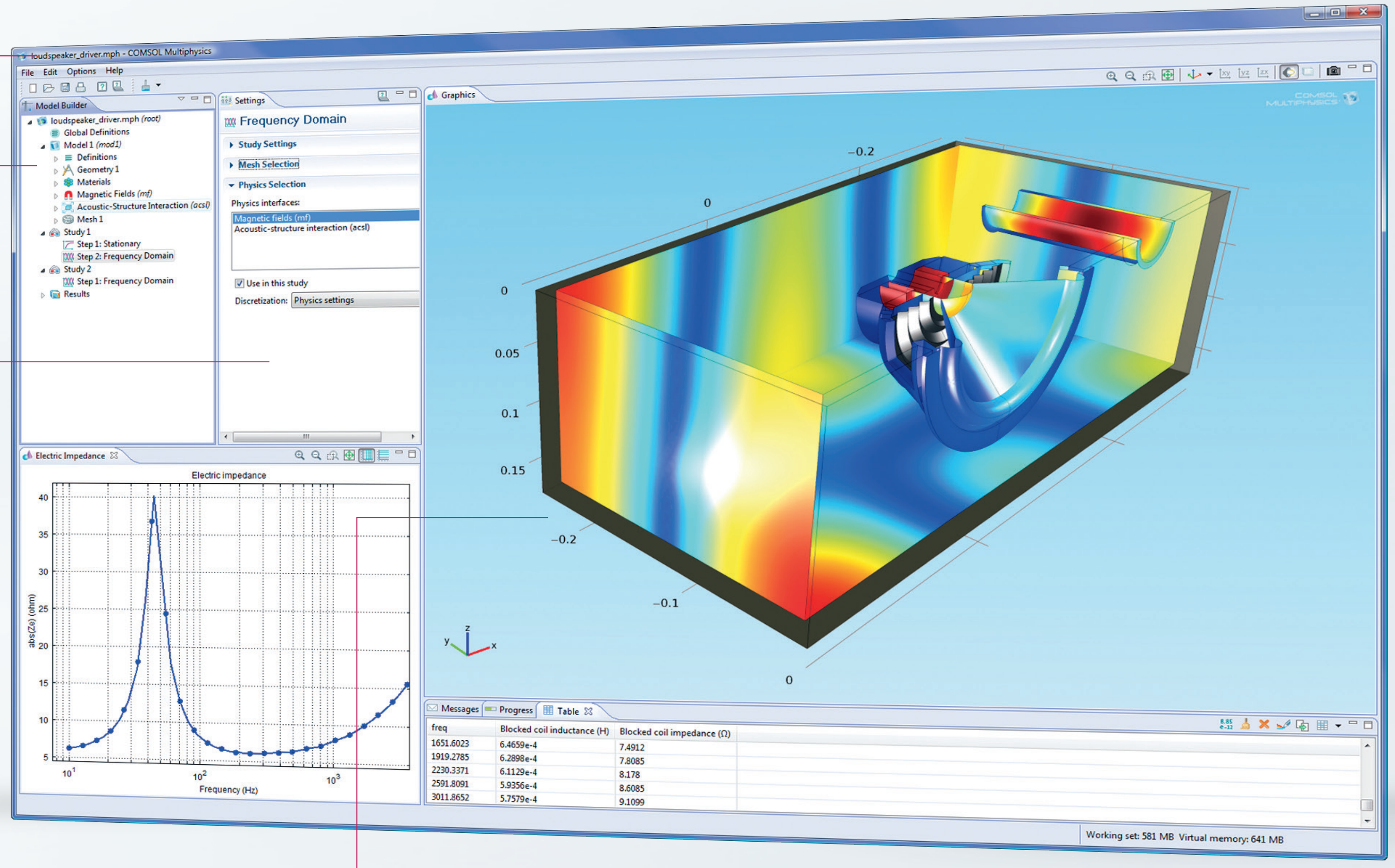
"COMSOL Multiphysics version 4 is a significant advance of simulation power with its fresh, new interface and insightful approach to the overall management of [simulation] data,"

Bill Vetterling, ZINK Imaging, Bedford, Massachusetts.

COMSOL DESKTOP
Customize the appearance by positioning the docked windows to your liking.

MODEL BUILDER
The Model Builder provides instant access to any part of the model settings.

SETTINGS
Through its integration with the Graphics window, you can control and update model properties in the Settings window.



GRAPHICS
Ultrafast graphic presentation, stunning visualization, and multiple plots.

Structured.

Building a model in COMSOL naturally follows your line of thinking, from concept to realization. The entire model workflow is controlled from the Model Builder, which brings a dynamic, yet logical structure to your simulations.

A model can be built by following the branches in the tree structure, from parameter definition and geometry creation to visualization of the simulation results. Nodes are added on demand to refine and improve your model as it evolves into a true description of your application.

"The COMSOL Multiphysics environment is so easy to understand and use, it didn't take long before several of us could model with it and collaborate."

Jan Hoffman, Amsterdam Water Supply, Amsterdam, The Netherlands.

MATERIALS

Define equations, and functions to describe your Material properties in the Materials Browser branch or use those provided in the Material Library.

GEOMETRY

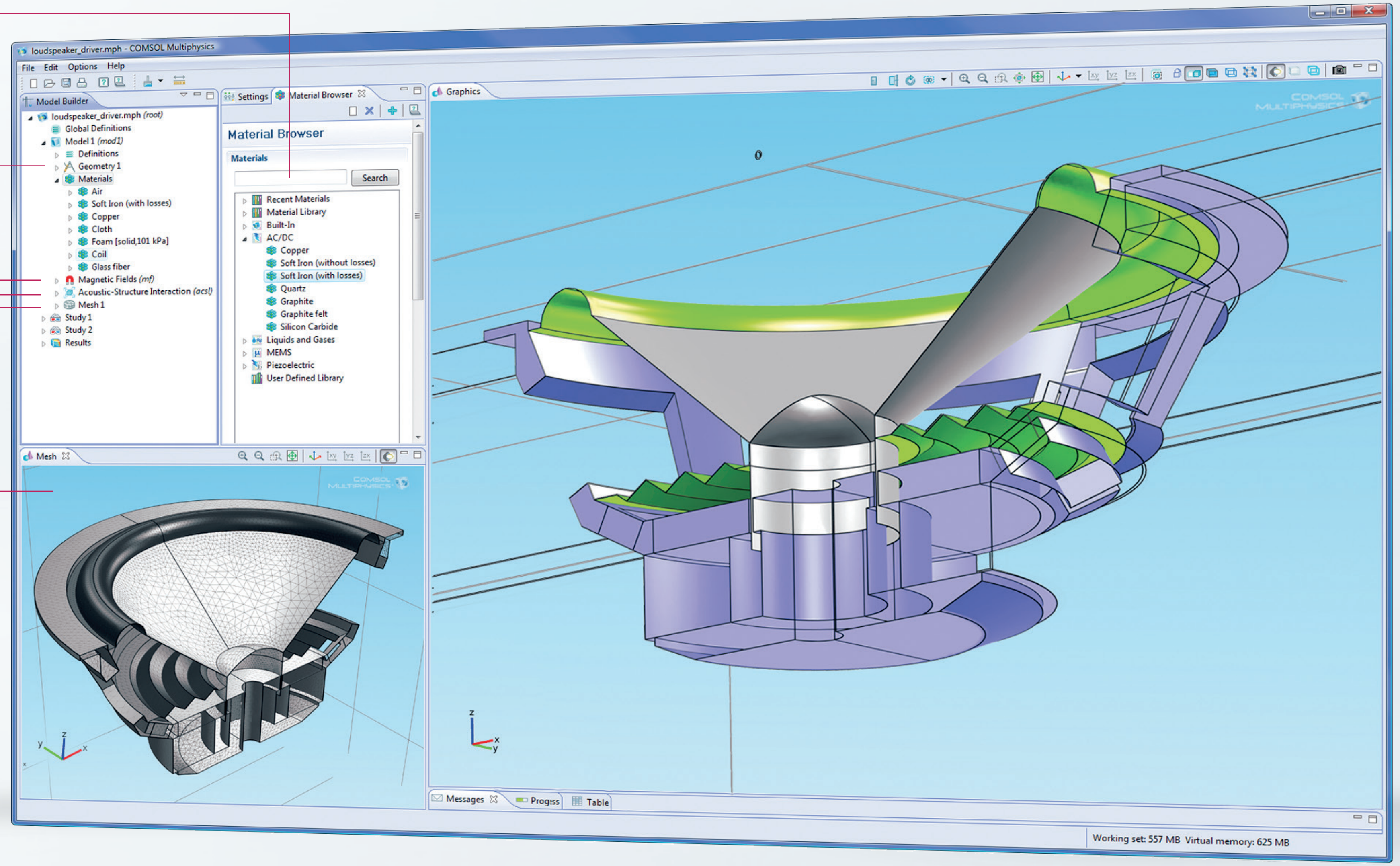
Use the built-in drawing tool or import files from a CAD package to create your geometries in the Geometry branch.

PHYSICS

Couple your physics, and manipulate your equations and functions in the Physics Interface node and setting windows.

MESH

Automatically generate and customize your Mesh for optimal resolution and solving.



In control.

The Model Builder allows instant access to any part of the model settings—changes in one node will update all others. You can even record the steps of your set-up as a sequence of nodes, pausing the process at any stage to investigate, refine and optimize a modeling feature.

This makes the Model Builder the versatile graphical programming tool for parametric analysis, optimization, and customized simulation routines.

"COMSOL allows us to couple mechanisms in a very nice and simple way, allowing us to understand their combined effect. This is the true power of simulation."

Dr **Roberto Suarez-Rivera**, Schlumberger, Salt Lake City, Utah.

MODEL WIZARD
Quick set-up of your modeling is done in the Model Wizard by selecting ready-made multiphysics couplings or creating your own.

DEFINITIONS
Easy control of your parameters, functions, and even lighting from the Definitions branch.

STUDY
Configure parametric studies and other sequences of Solvers.

MODEL LIBRARY
The Model Library consists of documented examples from all fields of engineering and science.

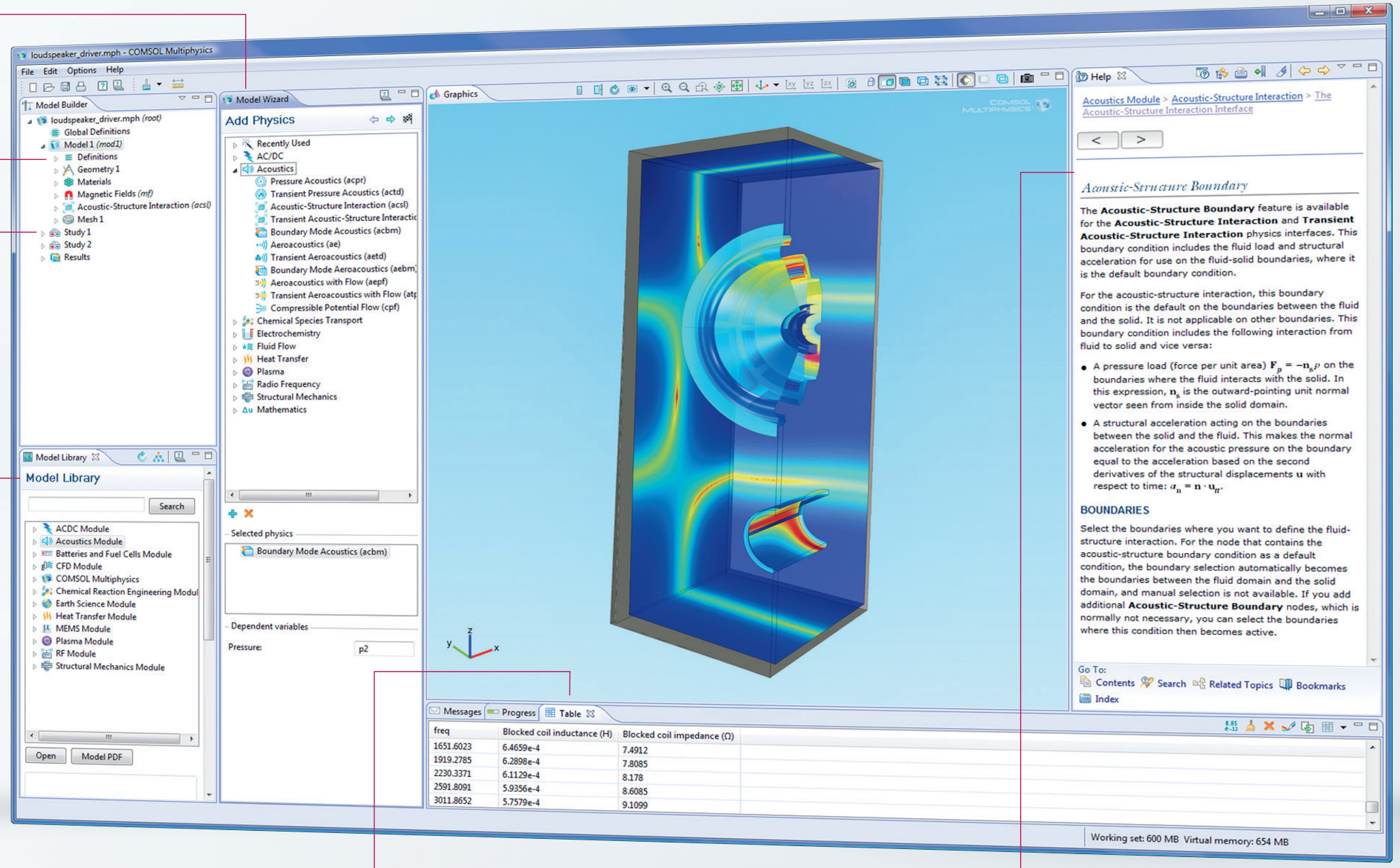


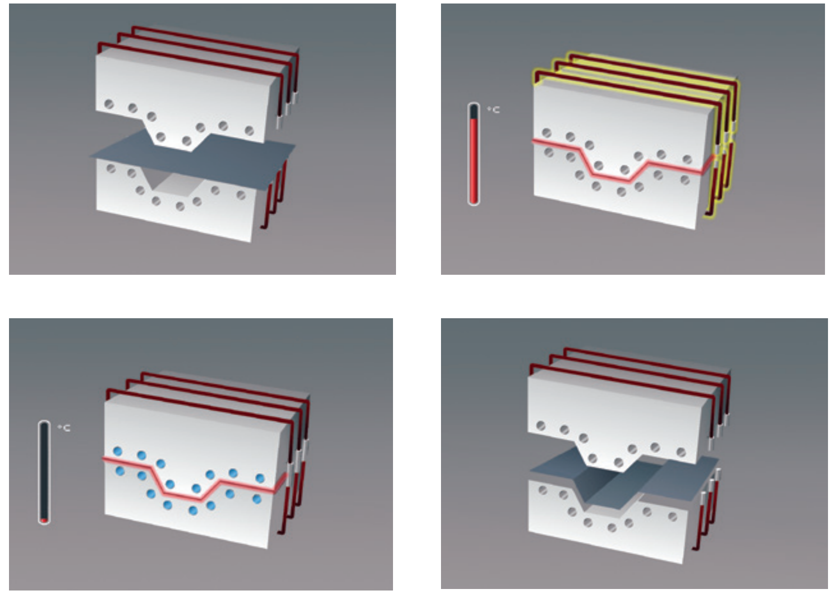
TABLE
Displays tables with results from integral and variable evaluations defined in the Results branch.

DYNAMIC HELP
Continually updated with online access to the Knowledgebase and Model Gallery, the Help feature enables easy browsing with extended search functionality.

AC/DC Module

The AC/DC Module sets the stage for modeling the performance of capacitors, inductors, motors, and microsensors. Although these devices are principally characterized by electromagnetics, they are also influenced by other types of physics. Thermal effects, for instance, can change a material's electrical properties, while electromechanical deflections and vibrations in generators need to be fully understood during any design process.

The capabilities of the AC/DC Module span electrostatics, magnetostatics, and electromagnetic quasi-statics with access to any derived field quantities and unlimited couplings to other physics. When considering your electrical components as part of a larger system, the AC/DC Module provides an interface with SPICE circuit lists where you choose circuit elements for further modeling. Then you can take your analysis beyond the conventional by running a single simulation of a mixed system of lumped and high-fidelity component models.



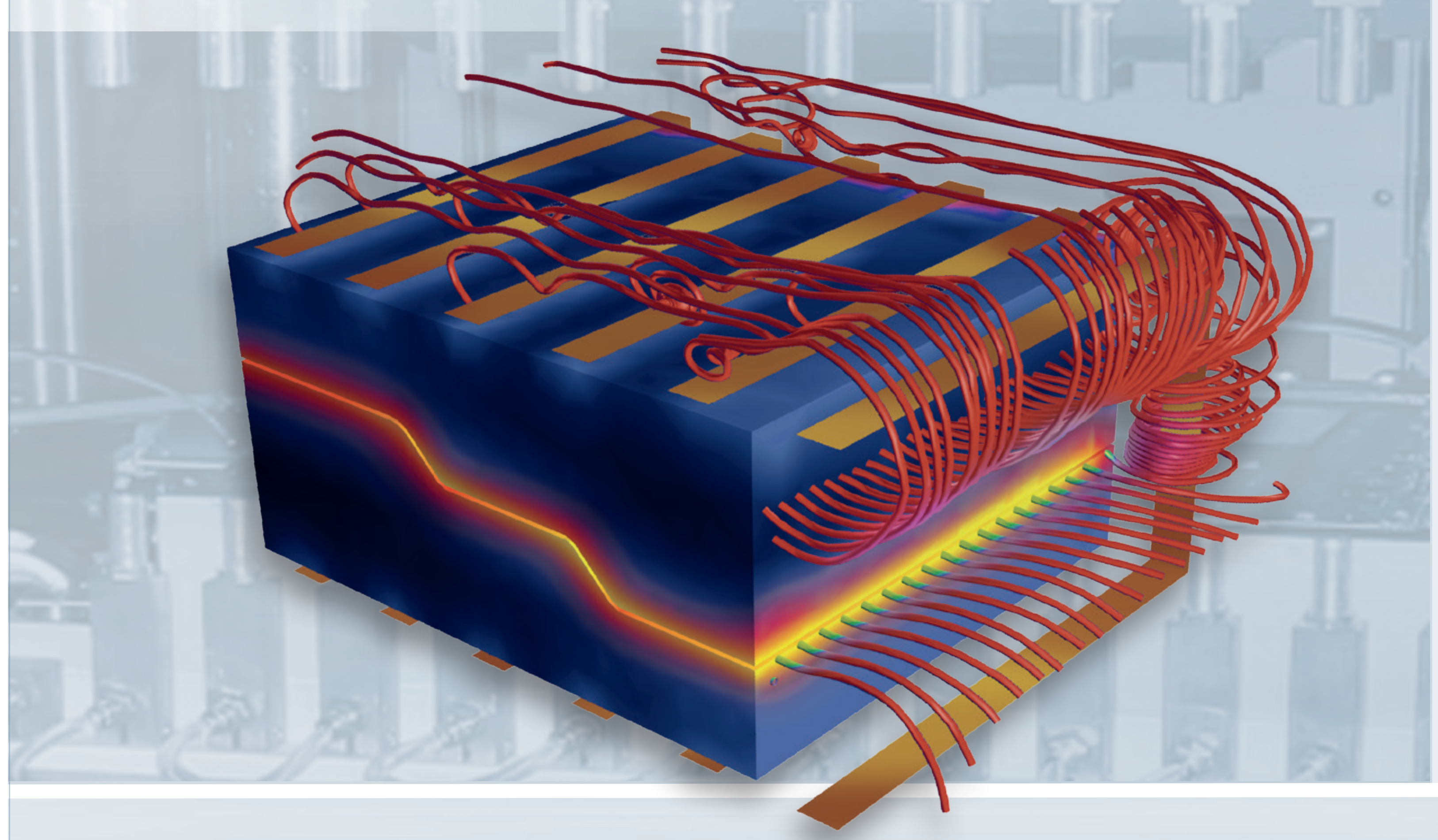
COMPOSITES MANUFACTURING

A sheet of composite material is placed within a mold that then presses down on the material while induction currents heat the two surfaces of the mold. When the final shape has been taken, water flows through pipes to cool down the material, which is then released.

Model, drawing, and pictures courtesy of José Feigenblum, RocTool, Le Bourget Du Lac, France.

INDUCTION HEATING

The model shows the magnetic flux (streamlines) and temperature distribution (color plot) in the electromagnetic induction molding apparatus and composite material.

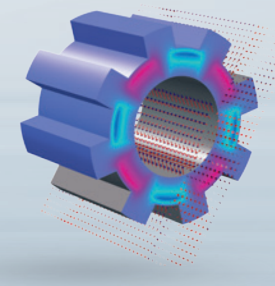


HIGHLIGHTS

- AC/DC current and field distribution
- Bioheating
- Coils and solenoids
- Combined SPICE circuit and field simulations
- Contact resistance
- Electromagnetic compatibility (EMC) and interference (EMI)
- Electromagnetic force and torque
- Electromagnetic shielding
- Electromechanical deformation
- Insulators, capacitors and dielectrics
- Motors, generators, and other electromechanical machinery
- Nonlinear materials
- Parasitic capacitance and inductance
- Permanent magnets and electromagnets
- Porous materials
- Resistive and induction heating
- Sensors
- Transformers and inductors

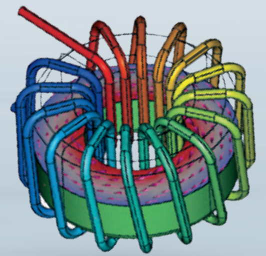
POWER ENGINEERING

Static 3D simulation of a generator with a rotor consisting of annealed medium carbon steel, which is a nonlinear ferromagnetic material that is saturated at high magnetic flux densities. Shown is the magnetic fields inside and around the generator.



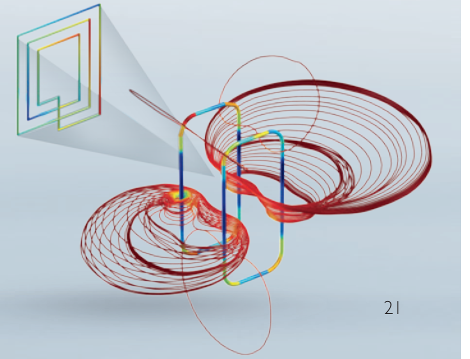
ELECTROMAGNETIC INDUCTOR

An inductor consisting of a wire wrapped around a ferrite core is modeled, and the device inductance is calculated. The current flow, due to an applied voltage, induces a magnetic field. The magnetic flux density is shown.



RFID TAGS

An RFID system consists of a tag or transponder with a PCB antenna (left) and a much larger reader antenna (right). This generates an electromagnetic field to energize the IC-circuit inside the tag. Shown is the magnetic flux density.



RF Module

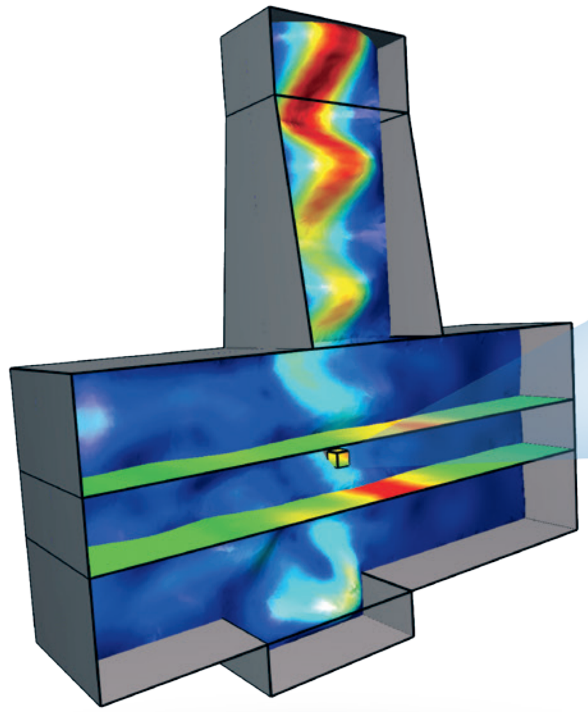
Modeling in the RF, microwave, and optical regimes requires modeling the propagation of electromagnetic waves in and around structures that can be metallic, dielectric, gyromagnetic, or even metamaterials with engineered properties. The RF Module offers you the tools to meet this challenge by including port and scattering boundary conditions, complex valued, spatially varying, anisotropic material models, perfectly matched layers, and the best solvers available. As a result, you can easily model antennas, waveguides, microwave, and optical components.

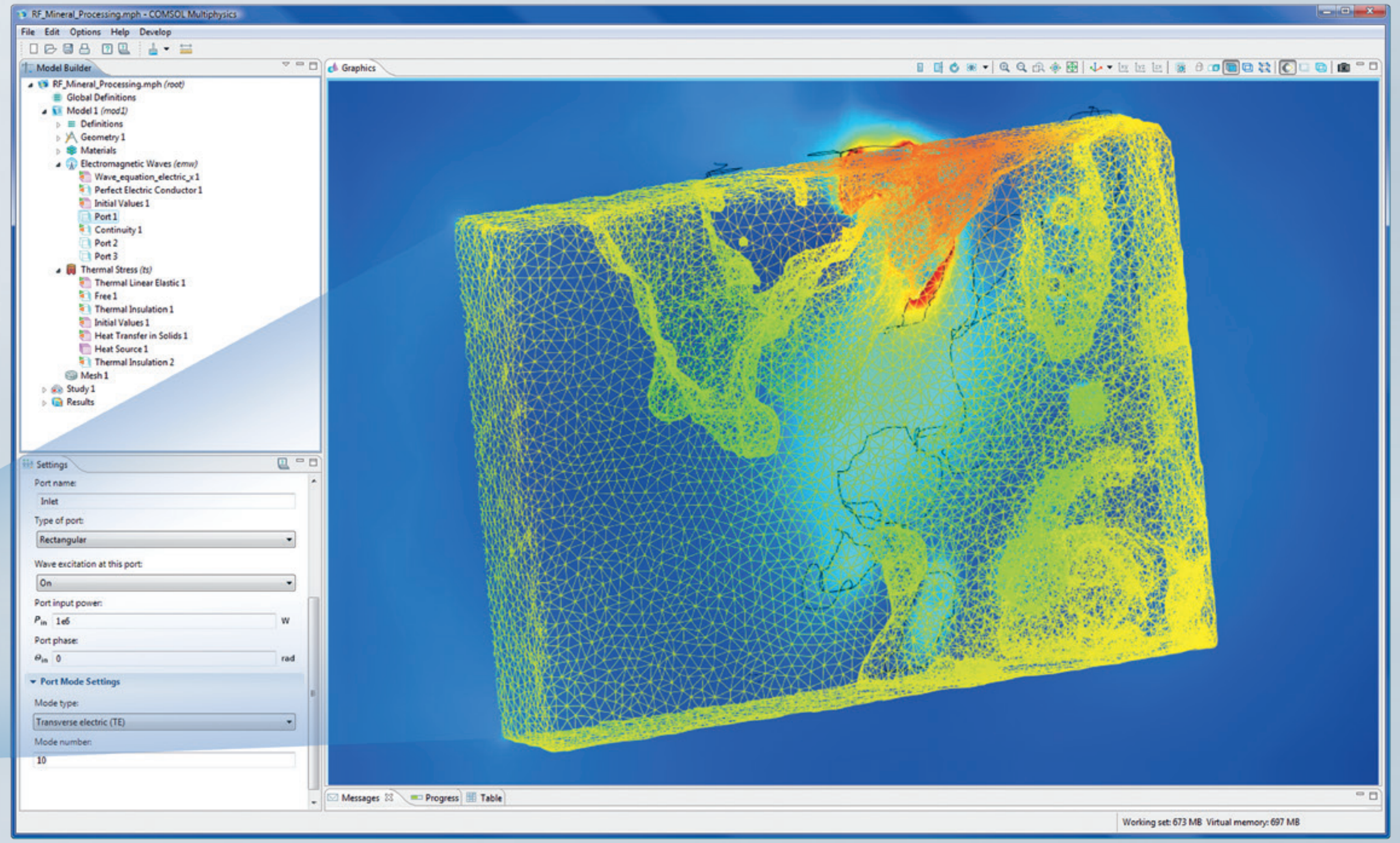
The RF Module completes the modeling experience by providing S-parameter computation and far-field analysis. Taken together with the unsurpassed ability of COMSOL Multiphysics to couple to other physics, such as electromagnetic RF heating, stress, and deformation effects, you have the industry's leading multiphysics solution for electromagnetic waves.

MINERAL PROCESSING

By applying microwave radiation, mineral particles in an ore are selectively heated, which causes local thermal expansion and liberation of the particles. This process requires significantly less energy than the conventional method of crushing the rock and separating the minerals. The model resolves the microwaves in applicators, which are several cubic meters in volume, together with those that heat the mineral particles, which are only tens of microns in size.

Model courtesy of Jan Przybyla, e2v, Chelmsford, UK.



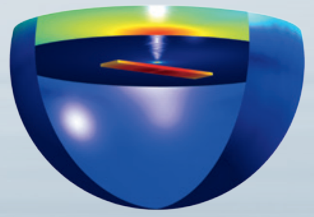


HIGHLIGHTS

- Antennas, waveguides, and cavities
- Bloch-Floquet periodic arrays and structures
- Circulators and directional couplers
- High speed interconnects
- Metamaterials
- Microwave and RF heating
- Microwave devices
- Microwave sintering
- Oil exploration and controlled source electromagnetic (CSEM) surveys
- Plasmonics
- Porous materials
- Resonant coil design
- RF and microwave bioheating
- Scattered field formulation for RCS and scattering problems
- S-parameter analyses of antennas
- Stress-optical effects
- Thermo-structural effects in antennas and waveguides
- Transmission lines

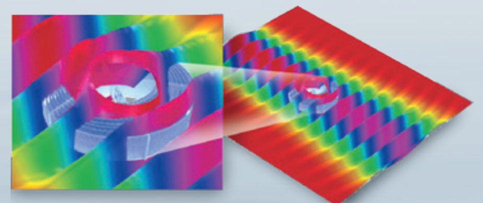
OIL PROSPECTING

The CSEM method has become popular within oil prospecting. Here, a horizontal 1 Hz electric dipole antenna is towed 150 m above the sea floor, where receivers measure the electrical field generated by the source and the reflected or guided transmitted energy resulting from the resistive reservoir.

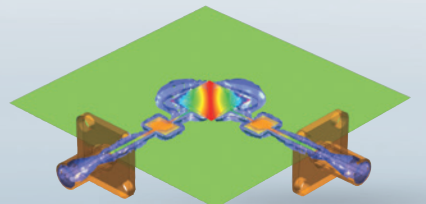


MATERIALS SCIENCE

Electromagnetic metamaterials have a spatial resolution that is below that of an electromagnetic wavelength, so as to create a form of 'invisibility' over a narrow wave band. In this model, an object located in the center of this structure is invisible to microwave radiation.



Model courtesy of Cummer and Schurig, Duke University, Durham, North Carolina.

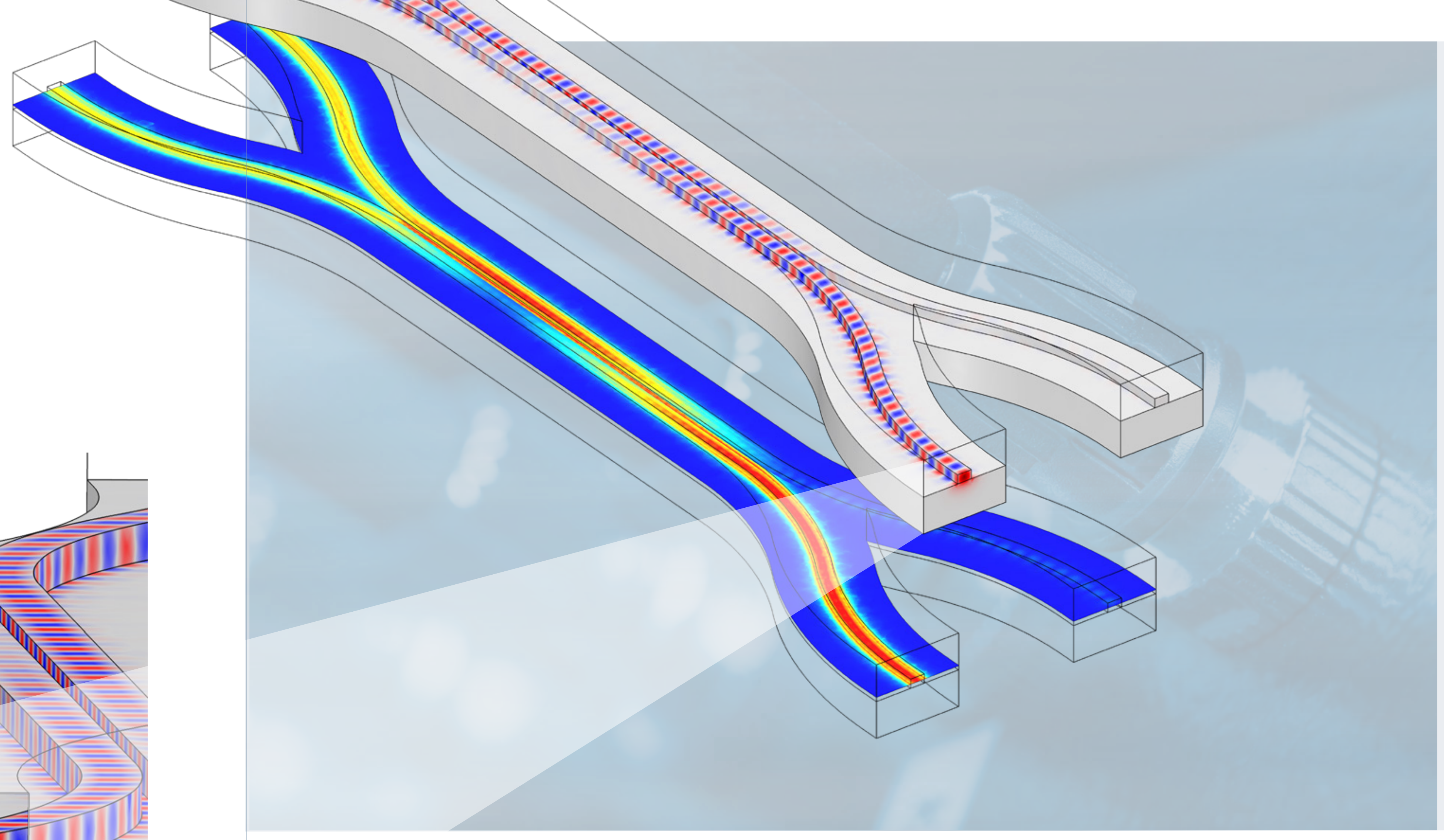


ANTENNAS

Two coaxial cables work together to create a balanced feed to a patch antenna. The model computes the antenna efficiency to find the optimal operating frequency, 6.3 GHz.

DIRECTIONAL COUPLER

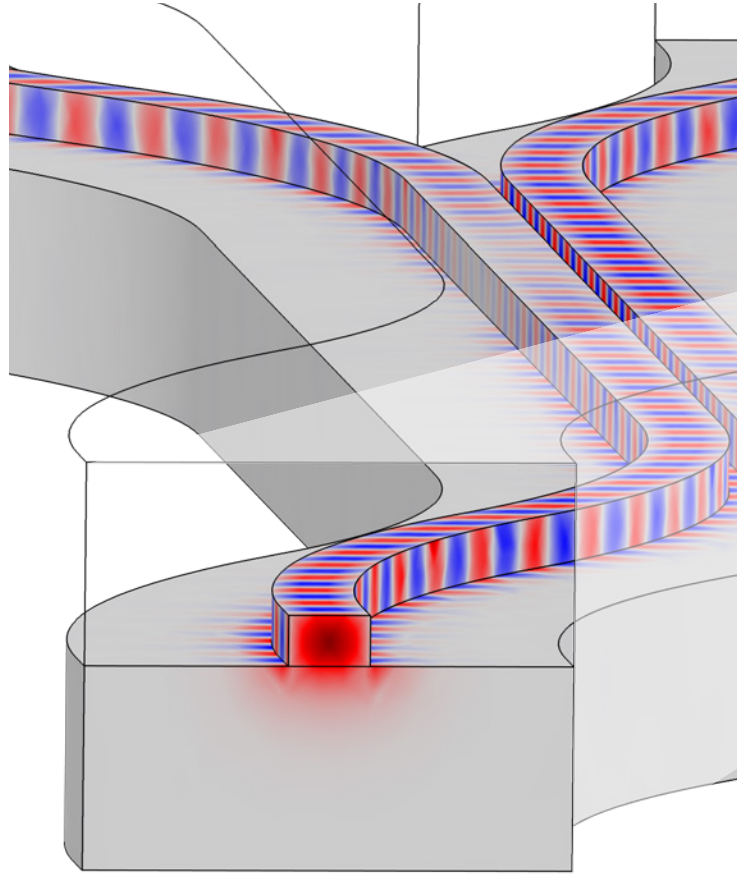
Model of a directional coupler formed from two interacting waveguides. The left waveguide is excited and the simulation results reveal the optical coupling between the waveguides through visualization of the electric field.



Wave Optics Module

The Wave Optics Module provides dedicated tools for electromagnetic wave propagation in linear and nonlinear optical media for accurate component simulation and design optimization. The innovative beam envelopes method for electromagnetic full-wave propagation overcomes the need for traditional approximations, by direct discretization of Maxwell's equations. This allows for accurate simulation of optically large systems where the geometric dimensions can be much larger than the wavelength, and where light waves cannot be approximated with rays. Conventional electromagnetic full-wave propagation methods are also featured in the module.

Support for generic anisotropic refractive index, permittivity, or permeability tensors allows for optical media that includes gyromagnetic materials or metamaterials with engineered properties. Several 2D and 3D formulations are available in the Wave Optics Module for eigenfrequency mode analysis, frequency-domain, and time-domain electromagnetic simulation.

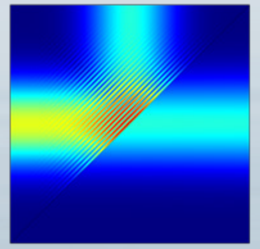


HIGHLIGHTS

- Couplers
- Fiber Bragg gratings
- Fiber optics
- Harmonic generation with frequency mixing
- Integrated optics
- Lasers and amplifiers
- Laser heating
- Nonlinear optics
- Optical lithography
- Optical scattering
- Optical sensors
- Optoelectronics
- Photonic crystal fibers
- Photonic devices
- Rod, slab, and disk laser design
- Scattering from nanoparticles
- Semiconductor lasers
- Surface scattering
- Waveguides

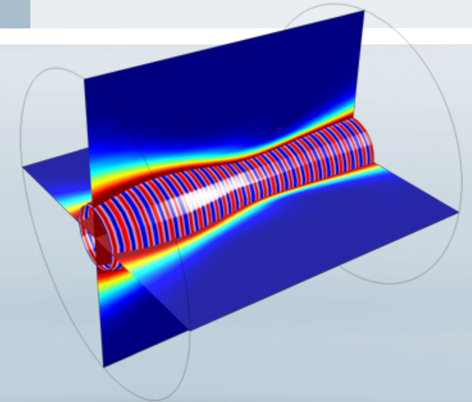
BEAM SPLITTER

A beam splitter is used to split a beam of light in two. One way of making a splitter is to deposit a thin layer of metal between two glass prisms. The beam is slightly attenuated within the layer, and split into two paths. The thin metal layer is modeled using a transition boundary condition which reduces the memory requirements. Losses in the metal layer can be also computed.



SELF-FOCUSING

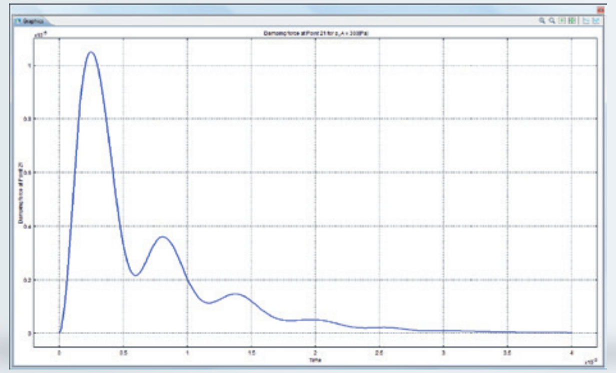
A Gaussian beam is launched into a BK-7 optical glass. The material has an intensity-dependent refractive index. For the center of the beam, the refractive index is the largest. This induced refractive index profile counteracts the diffractive effects and actually focuses the beam. Self-focusing is important in design of high-power laser systems.

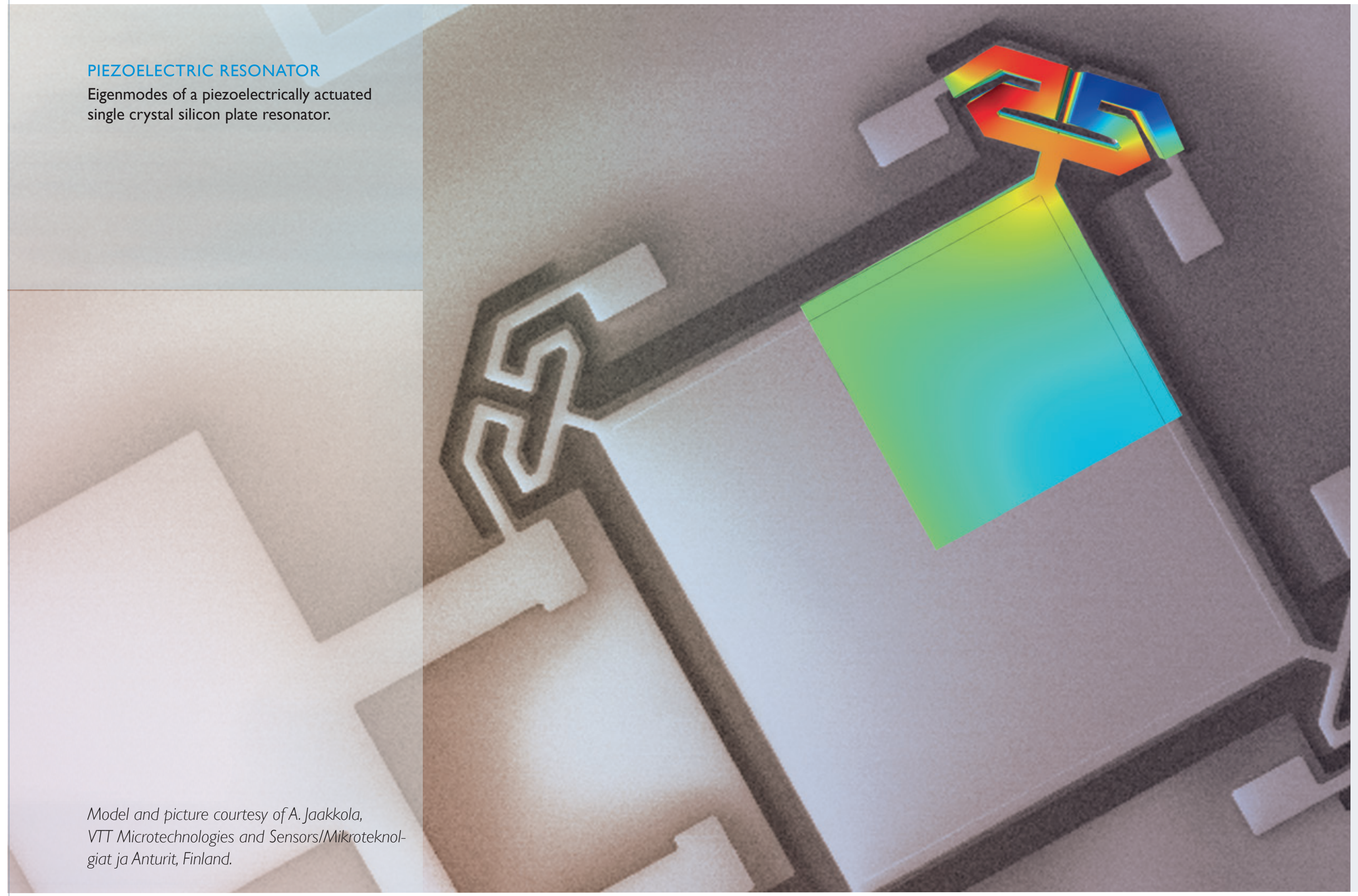


MEMS Module

The design and modeling of microscale electro-mechanical systems (MEMS) is a unique engineering discipline. At small length scales, the design of resonators, gyroscopes, accelerometers, and actuators must consider the effects of several physical phenomena. MEMS devices and sensors may even utilize multiphysics phenomena for its very function or for increased sensitivity. To this end, the MEMS Module provides user interfaces for electromagnetic-structure, thermal-structure, or fluid-structure interactions. A variety of damping phenomena can be included in a model: thin-film gas damping, anisotropic loss-factors for solid and piezo materials, as well as anchor damping. For elastic vibrations and waves, perfectly matched layers (PMLs) provide state-of-the-art absorption of outgoing elastic energy.

Best-in-class piezoelectric and piezoresistive tools allow for simulations where composite piezo-elastic-dielectric materials can be combined in any imaginable configuration. The module includes analyses in the stationary and transient domains as well as fully-coupled eigenfrequency, parametric, quasi-static, and frequency response analyses. Lumped parameter extraction of capacitance, impedance, and admittance and connections to external electrical circuits via SPICE netlists are made easy. Built upon the core capabilities of COMSOL Multiphysics, the MEMS Module can be used to address virtually any phenomena related to mechanics at the microscale.





PIEZOELECTRIC RESONATOR

Eigenmodes of a piezoelectrically actuated single crystal silicon plate resonator.

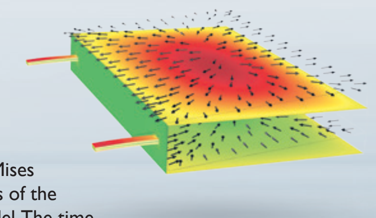
Model and picture courtesy of A. Jaakkola, VTT Microtechnologies and Sensors/Mikroteknol-giat ja Anturit, Finland.

HIGHLIGHTS

- Accelerometers
- Actuators
- Bulk Acoustic Wave (BAW) devices
- Cantilever beams
- Fluid-structure interaction (FSI)
- Hall sensors
- MEMS capacitors
- MEMS gyroscopes
- MEMS resonators
- MEMS thermal devices
- Piezoelectric devices
- Piezoresistive devices
- RF MEMS devices
- Sensors
- Structural contact and friction
- Surface Acoustic Wave (SAW) devices

ACCELEROMETERS

This example depicts the coupling of squeezed film gas damping to the mechanical displacements in a MEMS accelerometer. The direction of the gas flow and the von Mises stresses on the face and arms of the sensor are shown in the model. The time series plot to the left shows the gradual reduction of the damping force.



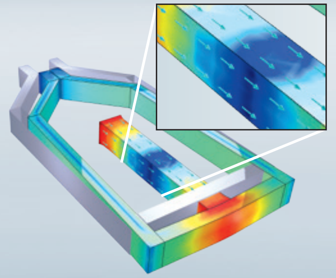
ACTUATORS & SENSORS

A two arm thermal actuator is activated through thermal expansion, where the temperature profile is plotted on the resulting deformed shape. Relative visco-elasticity changes during the clotting of blood are then measured through deflections of the micro-cantilevers.

Model courtesy of Slava Djokov / Neal McLoughlin, Microvisk Technologies, North Wales, UK.

PIEZOELECTRIC MICROGRIPPER

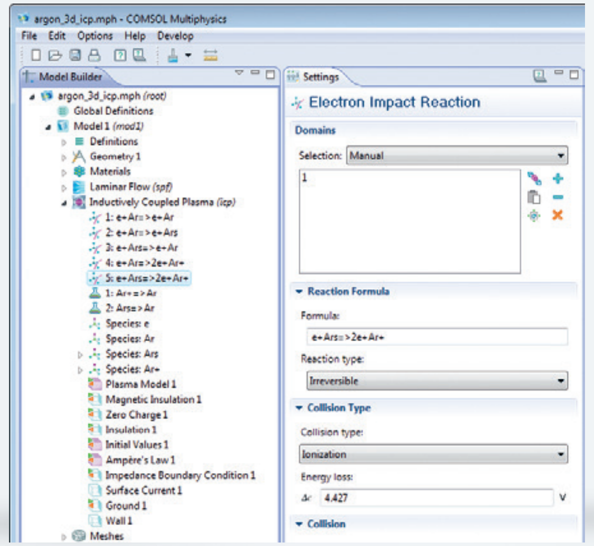
Made up of a stacked piezoactuator, simultaneous contraction in the transversal direction and elongation in the longitudinal direction closes this microgripper. Shown is the von Mises stresses and deformation.

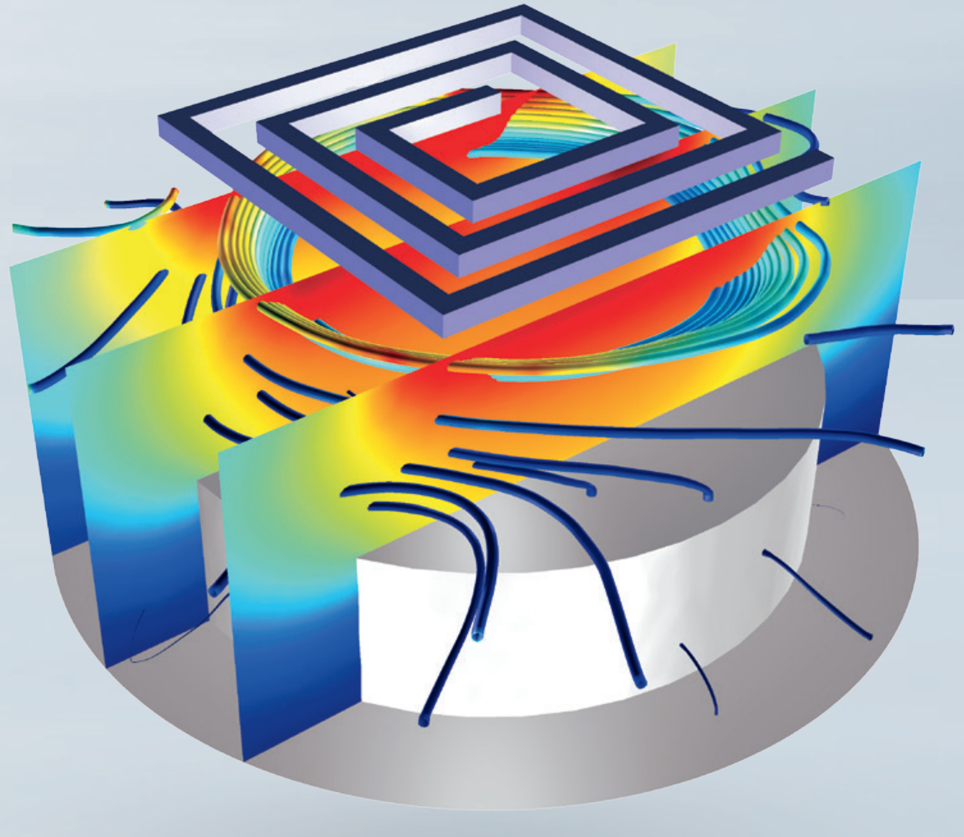


Plasma Module

Low temperature plasmas represent the amalgamation of fluid mechanics, reaction engineering, physical kinetics, heat transfer, mass transfer, and electromagnetics. The Plasma Module is a specialized tool for modeling non-equilibrium discharges that occur in a wide range of engineering disciplines. There are specialized modeling interfaces for the most common types of plasma reactors including inductively coupled plasmas (ICP), DC discharges, wave heated discharges (microwave plasmas), and capacitively coupled plasmas (CCP). Modeling the interaction between the plasma and an external circuit is an important part of understanding the overall characteristics of a discharge. The Plasma Module provides tools to add circuit elements directly to a 1D, 2D, or 3D model, or to import an existing SPICE netlist into the model. The plasma chemistry is specified either by loading in sets of collision cross sections from a file, or by adding reactions and species to the Model Builder. The complicated coupling between the different physics that constitute a plasma is automatically handled by the physics interfaces.

The Plasma Module is designed for researchers, engineers, and experimentalists in the field of plasma science. The module is accompanied by a suite of tutorial and industrially relevant models, which serve as both instructional examples and a foundation for future work.





3D MODEL OF AN ASYMMETRIC ICP REACTOR

The plot shows the mean electron energy (slice) and the electron current density (streamlines).

HIGHLIGHTS

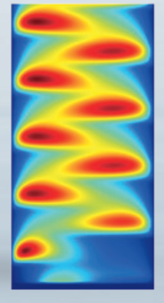
- Capacitively coupled plasmas (CCP)
- CVD and PECVD
- DC discharges
- Dielectric barrier discharges
- ECR sources
- Etching
- Hazardous gas destruction
- Inductively coupled plasmas (ICP)*
- Ion sources
- Materials processing
- Microwave plasmas**
- Ozone generation
- Plasma chemistry
- Plasma display panels
- Plasma sources
- Power systems
- Semiconductor processing
- Thrusters

* *Together with the AC/DC Module*

** *Together with the RF Module*

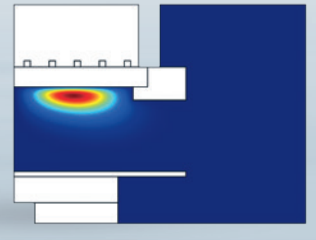
DIELECTRIC BARRIER DISCHARGE

Excited argon atoms can spontaneously decay back to the ground state releasing a photon in the ultraviolet spectrum. The plot to the right shows the concentration of excited argon atoms in a dielectric barrier discharge.



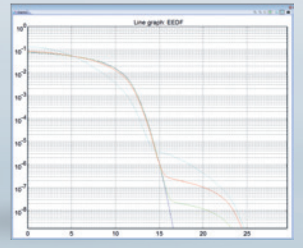
INDUCTIVELY COUPLED PLASMA

This plot displays the power deposition into a GEC ICP reactor with argon chemistry. The power deposition is shielded towards the top of the reactor due to the skin effect.



ELECTRON ENERGY DISTRIBUTION FUNCTION

The two-term Boltzmann equation computes the EEDF for different mole fractions of excited species. A high energy tail in the distribution function is formed as the mole fraction increases.

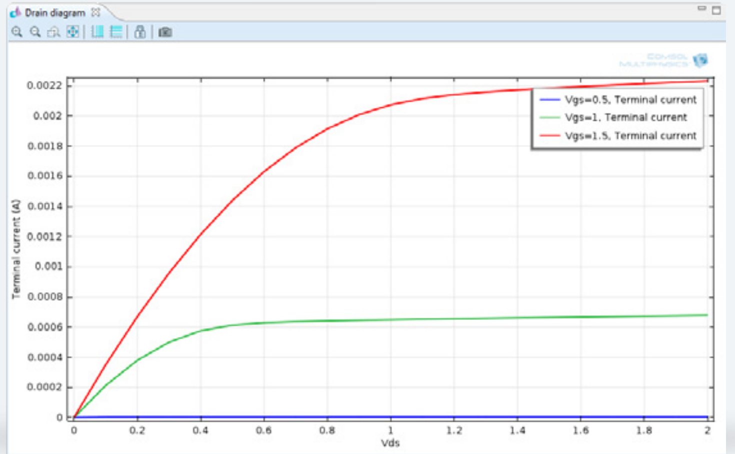


Semiconductor Module

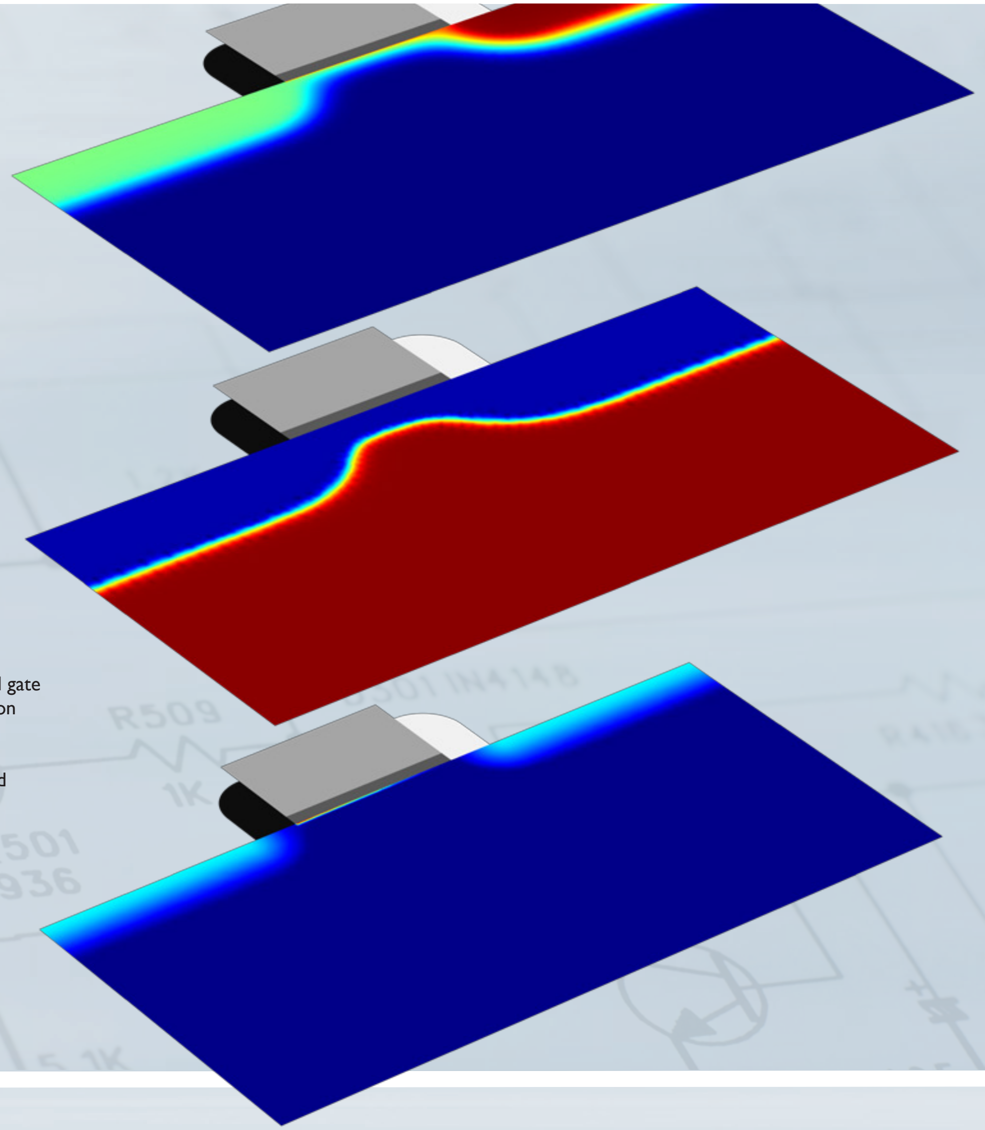
The Semiconductor Module allows for detailed analysis of semiconductor device operation at the fundamental physics level. The module is based on the drift-diffusion equations with isothermal and non-isothermal transport models. Two numerical methods are provided: the finite volume method with Scharfetter-Gummel upwinding and a Galerkin least-squares stabilized finite element method. The module provides an easy-to-use interface, greatly simplifying the task of semiconductor device simulation on the COMSOL platform.

Models for semiconducting and insulating materials in addition to boundary conditions for ohmic contacts, Schottky contacts, and gates are provided as dedicated features within the Semiconductor Module. Enhanced functionality for modeling electrostatics. System level and mixed device simulations are enabled through an interface for electrical circuits with SPICE import capability.

The Semiconductor Module is particularly relevant for simulating transistors including bipolar, metal semiconductor field-effect transistors (MESFETs), metal-oxide-semiconductor field-effect transistors (MOSFETs), Schottky diodes, thyristors, and P-N junctions.



DC characteristics of the simulated MOSFET transistor.



SEMICONDUCTOR DESIGN

2D model of a MOSFET transistor. Simulation results demonstrate the transistor operation where an applied gate voltage turns the device on and then the drain saturation current is determined.

From top to bottom: electric potential, hole density, and electron density are shown.

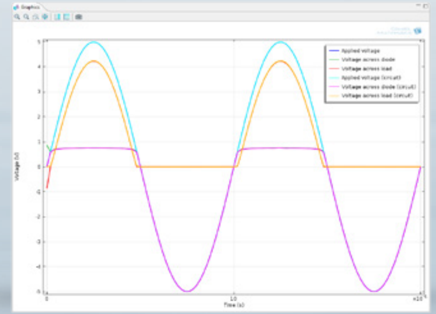
HIGHLIGHTS

- Bipolar transistors
- Metal-oxide-semiconductor field-effect transistors (MOSFETs)
- Metal semiconductor field-effect transistors (MESFETs)
- P-N junctions
- Schottky diodes
- Thyristors

ELECTRICAL

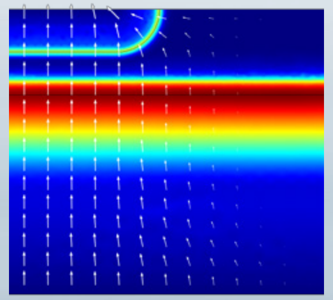
HALF-WAVE RECTIFIER

Input and output waveforms for a full and lumped model simulation of a semiconductor diode.



BIPOLAR TRANSISTOR

Simulation of a bipolar transistor. The current (arrows) and the electric field (color) are shown.

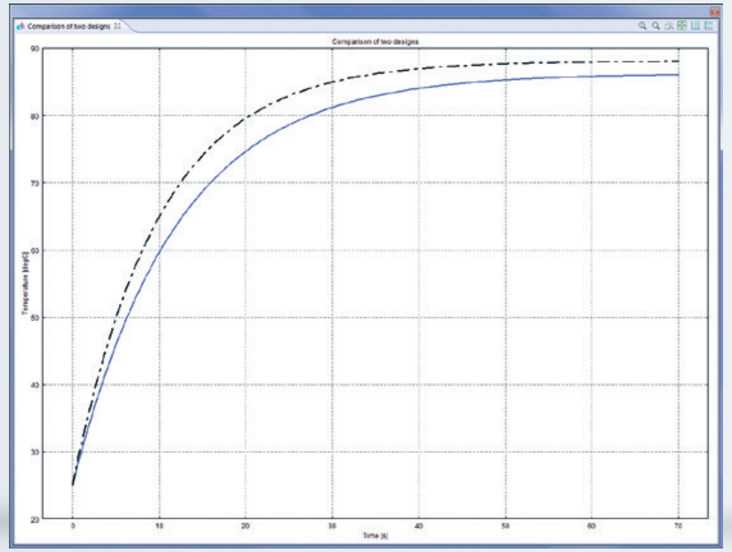


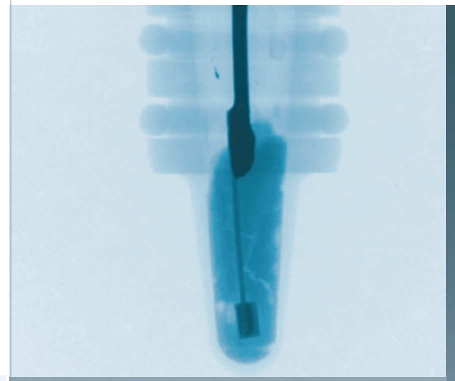
Heat Transfer Module

Almost every manufacturing process and product design must consider thermal effects. The Heat Transfer Module provides a combination of capabilities to model heat transfer via conduction, convection, and radiation, as well as the ability to couple these to other physics.

The Heat Transfer Module has modeling interfaces that are specifically written for the user interested in free and forced convection, process design, phase change modeling, radiative heat transfer through both transparent and semi-transparent participating media, as well as couplings between all of these effects. Specialized formulations are included for users who are interested in the heating of living tissue. With boundary conditions for describing convective and radiative effects, contact resistance, and thin highly-conductive shells, you can simulate anything from a simple "back of the envelope" model to a full model with all effects explicitly described.

Since all material properties are functions of temperature, you can conceivably couple a thermal model to any other physical model. Moreover, COMSOL allows you to include heat generation from any other physics into a thermal model.



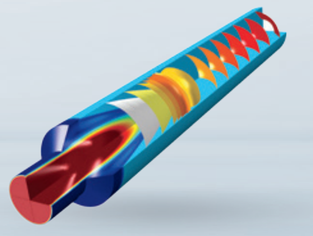


TEMPERATURE SENSOR
A photograph, X-ray picture, and model plot of the temperature distribution in a temperature sensor and on the sensing element inside the cap. The graph compares the temperature versus response time for two different designs of the cap.

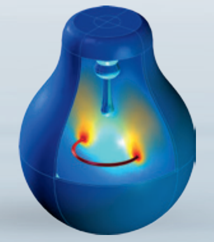
Model courtesy of Martin Šós, Continental Corporation, Frenstat, Czech Republic.

HIGHLIGHTS

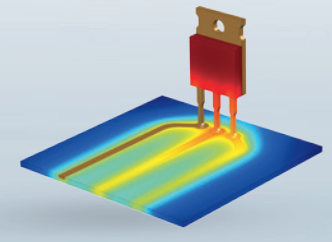
- Arc welding
- Bioheat treatment and thermal therapy
- Casting and thermal processing
- Conjugate heat transfer
- Disc brakes
- Drying and freeze drying
- Electronic cooling
- Food processing, cooking, and sterilization
- Friction stir welding
- Furnace and burner design
- Heat and moisture transport
- Heat exchangers and cooling flanges
- Heat radiation
- Heat transfer in porous media
- Laser welding and laser heating
- Material heat treatment
- Resistive and induction heating
- Solidification



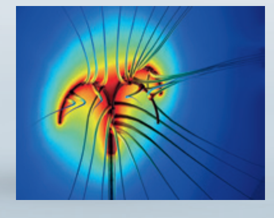
CONTINUOUS CASTING
Simulation of heat transport and the fluid-to-solid flow, including the phase transfer from melt to solid.



LIGHT BULB
Temperature distribution as influenced by the natural convection created within a light bulb.



POWER TRANSISTOR
Temperature distribution in a power transistor and the lines leading from it.



TUMOUR ABLATION
Temperature field and the heat flux emanating from a tumor ablation unit.

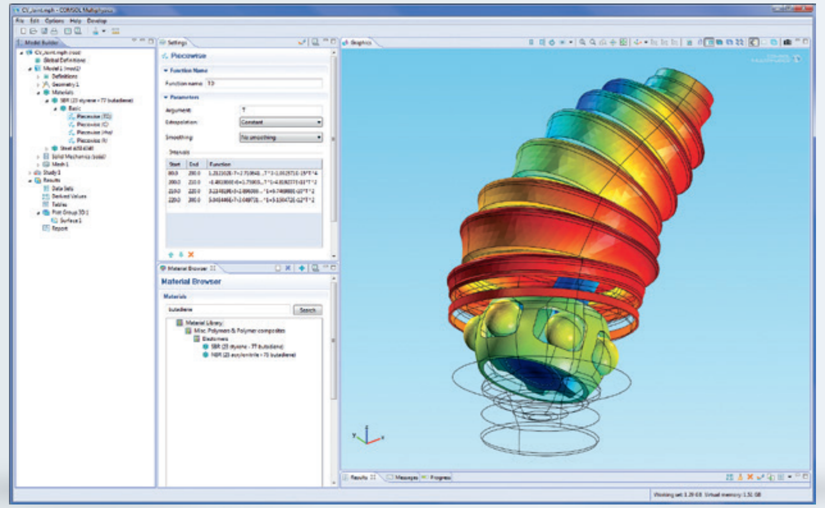
Structural Mechanics Module

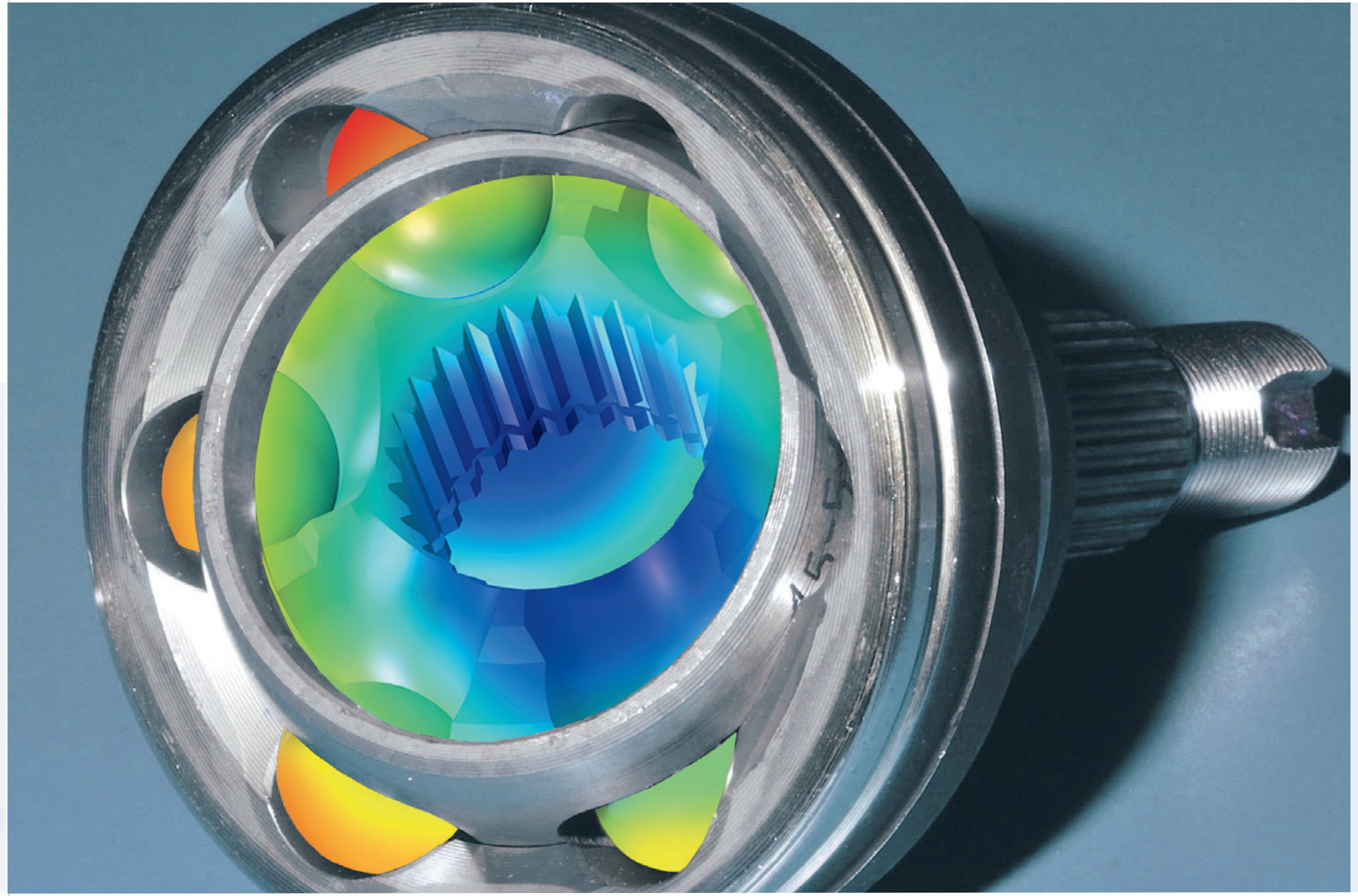
The Structural Mechanics Module is dedicated to the analysis of components and subsystems where it is necessary to evaluate deformations under loads. It also contains special user interfaces for the modeling of shells, membranes, beams, and trusses.

The Structural Mechancis Module is used for a wide range of analysis types including: stationary, eigenmode, parametric, quasi-static, frequency-response, and prestressed. Its user interfaces allow for large deformation analysis with geometrical nonlinearity, mechanical contact, piezoelectric materials, thermal strain, fluid-structure interaction (FSI), and elastic waves.

Four add-on modules are available for the Structural Mechanics Module: the Nonlinear Structural Materials Module, Geomechanics Module, Fatigue Module, and Multibody Dynamics Module. The Structural Mechanics Module also works in tandem with COMSOL Multiphysics and the other discipline-specific modules to couple structural analysis into any multiphysics phenomenon.

CV JOINT
Von mises stresses and deformation in the ball bearings, cage and rubber seal of a continuous velocity (CV) joint.
Model courtesy of Fabio Gatelli, Metelli S.p.A., Cologne, Italy.





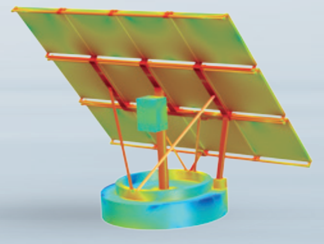
MECHANICAL

HIGHLIGHTS

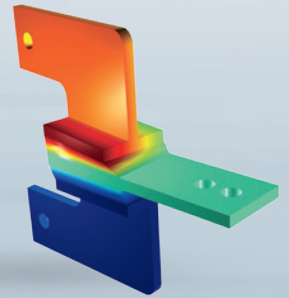
- Beams
- Buckling and postbuckling
- Elastic waves
- Fluid-structure interaction (FSI)
- Geometric nonlinearity
- Large deformation
- Lubrication and elastohydrodynamics*
- Membranes
- Modal analysis
- Piezoelectric devices
- Prestressed structures
- Rotordynamics
- Shells
- Stress-optical effects
- Structural contact and friction
- Structural vibrations
- Thermal stress
- Trusses and cables

* *Together with the CFD Module*

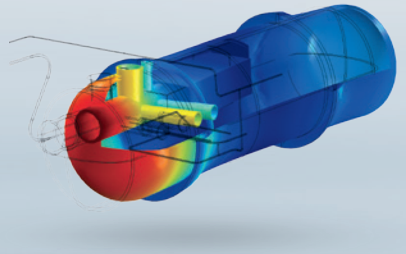
SOLAR PANEL
The von Mises stresses on the struts supporting a solar panel having being subjected to the forces from wind.



DAMPING ELEMENT
Structural analysis of a visco-elastic damping element used to stabilize tall buildings. Shown is the displacement as both the color and deformed shape plot.



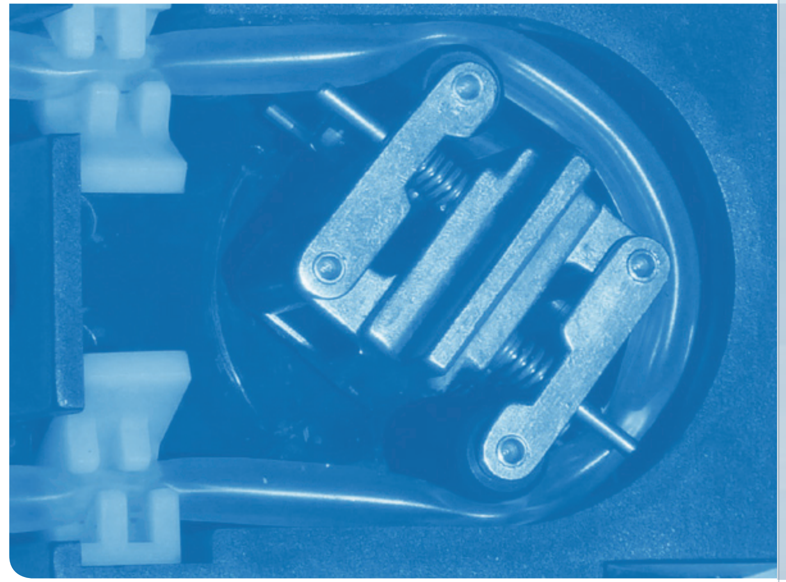
KNOCK-OUT DRUM
Deformations in a knock-out drum connected to a petroleum refinery.
Model courtesy of Stig Sandström, SSM Engineering, Sweden.



Nonlinear Structural Materials Module

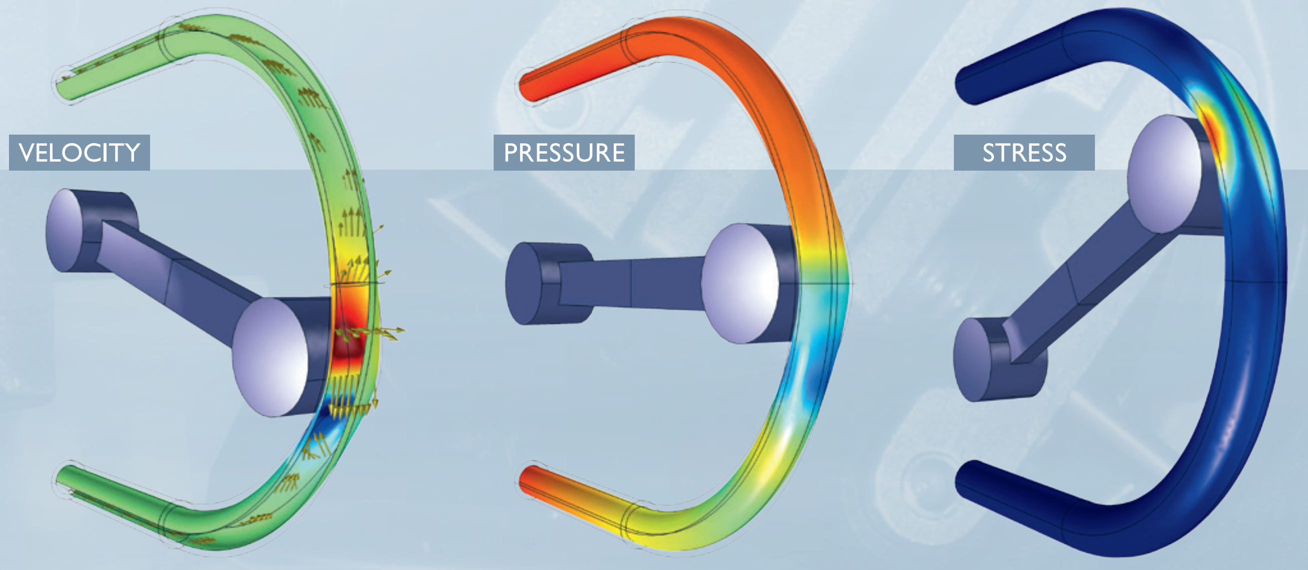
The Nonlinear Structural Materials Module augments the mechanical capabilities of the Structural Mechanics and MEMS Modules by adding nonlinear material models, including large strain plastic deformation. When the mechanical stress in a structure becomes large, certain nonlinearities in the material properties force the user to abandon linear material models. This situation also occurs in some operating conditions, such as high temperature.

The module adds elastoplastic, viscoplastic, creep, and hyperelastic material models. User-defined material models based on strain-invariants, flow rules, and creep laws can easily be created directly in the user interface with the built-in constitutive laws as a starting point. Material models can be combined as well as include multiphysics effects. The tutorial models illustrate this by showcasing combined creep and elastoplasticity, thermally induced creep and viscoplasticity.

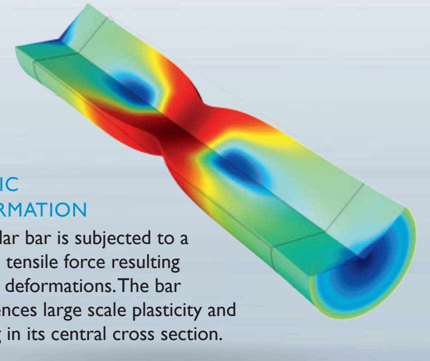


PUMPING

This model of a peristaltic pump accounts for the fluid structure interaction caused by the roller squeezing the tubing's wall and the pressure resulting from the fluid flow within the tubing. The model considers large deformations, contact, and the hyperelastic behavior of the tubing material, modeled using the Arruda-Boyce material model. Shown are the von Mises stresses, fluid pressure, and velocity direction and magnitude at three different time intervals.

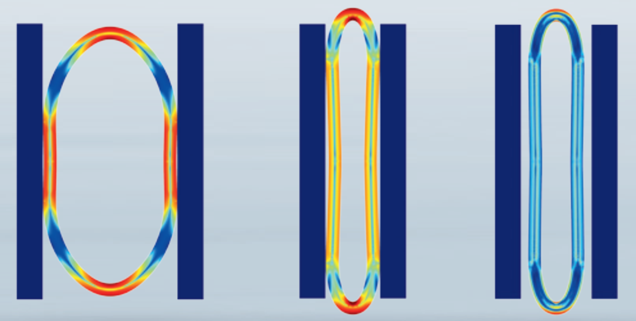


Model images are provided courtesy of Nagi Elabbasi of Veryst Engineering, Needham, MA. To read more, visit: comsol.com/papers/11574. Photograph of peristaltic pump first produced by Andy Dingley.



PLASTIC DEFORMATION

A circular bar is subjected to a uniaxial tensile force resulting in large deformations. The bar experiences large scale plasticity and necking in its central cross section.



CLAMPING

This model shows the von Mises stresses of a pipe during its flattening. The material model assumes large strain elastoplastic deformation.

HIGHLIGHTS

- Anand viscoplasticity
- Arruda-Boyce hyperelasticity
- Biomechanics
- Blatz-Ko hyperelasticity
- Coble creep
- Creep
- Deviatoric creep
- Elastomers
- Elastoplasticity
- Gao hyperelasticity
- Garofalo creep
- Gent hyperelasticity
- Hill plasticity
- Hyperelastic materials
- Large deformation
- Large strain plasticity
- Mooney-Rivlin hyperelasticity
- Murnaghan hyperelasticity
- Nabarro-Herring creep
- Neo-Hookean hyperelasticity
- Nonlinear materials
- Norton and Norton-Bailey creep
- Ogden hyperelasticity
- Orthotropic plasticity
- Polymers
- Rubber
- Saint Venant–Kirchhoff hyperelasticity
- Storakers hyperelasticity
- User-defined creep, hyperelasticity, and plasticity
- Varga hyperelasticity
- Viscoplasticity
- Yeoh hyperelasticity

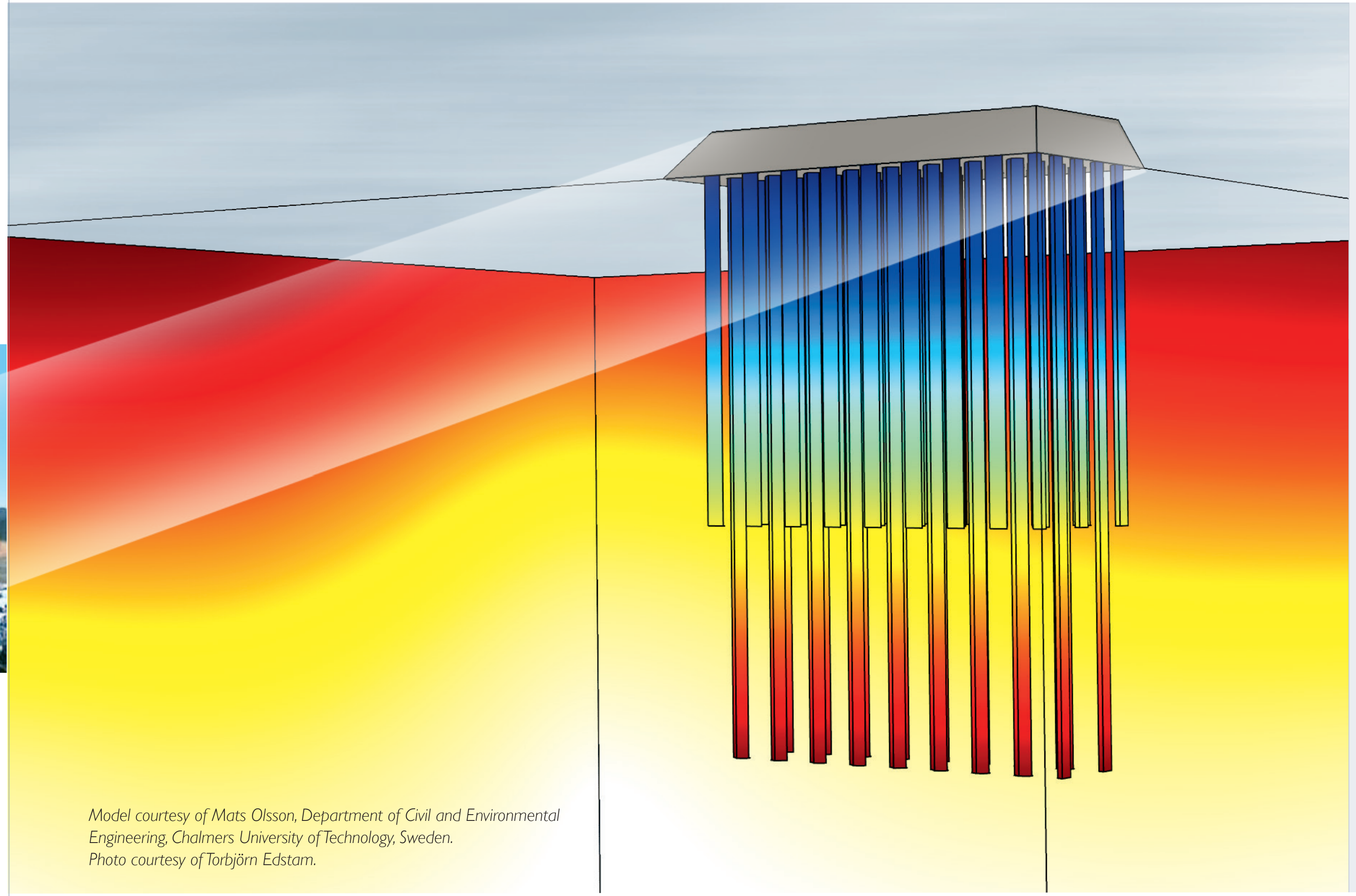
Geomechanics Module

The Geomechanics Module is a specialized add-on to the Structural Mechanics Module for simulation of geotechnical applications such as tunnels, excavations, slope stability, and retaining structures. The module features tailored user interfaces to study deformation, creep, plasticity, and failure of soils and rocks, as well as their interaction with concrete and human-made structures. A variety of material models for soils are provided: Cam-Clay, Drucker-Prager, Mohr-Coulomb, Matsuoka-Nakai, and Lade-Duncan. In addition to the built-in plasticity models, user-defined yield functions can be created by the versatile equation-based user interface provided by the COMSOL Multiphysics environment. Dependencies of a computed temperature field as well as other field quantities can be blended into these material definitions.

The Geomechanics Module also makes available very powerful tools for modeling concrete and rock materials: the Willam-Warnke, Bresler-Pister, Ottosen, and Hoek-Brown models are available as built-in options and can also be adapted and extended to a more general class of brittle materials. The Geomechanics Module can easily be combined with analysis from other modules such as the porous media flow, poroelasticity, and solute transport functionality of the Subsurface Flow Module.

SETTLEMENT IN EMBANKMENTS

Long-term settlement in clay constitutes an engineering challenge in, for example, road and railway design and construction where supporting Lime-Cement Columns are used. A test site was constructed to evaluate, among other things, the deformation properties of the supporting columns and surrounding clay. Shown in the model is the stresses in the vertical direction in the supporting columns, and the displacement of the surrounding environment (background boundary surface plot).



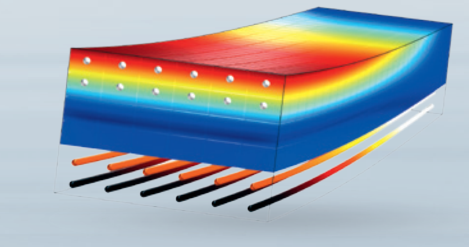
Model courtesy of Mats Olsson, Department of Civil and Environmental Engineering, Chalmers University of Technology, Sweden.
Photo courtesy of Torbjörn Edstam.

HIGHLIGHTS

- Bresler-Pister and Ottosen concrete models
- Concrete and brittle materials
- Drucker-Prager and Mohr-Coulomb soil models
- Ductile materials and saturated soils
- Creep
- Embankments
- Excavations
- Foundations
- Hoek-Brown rock model
- Matsuoka-Nakai and Lade-Duncan soil models
- Modified Cam-Clay soil model
- Nuclear waste installations
- Retaining structures and reinforcements
- Roads
- Slabs
- Slope stability
- Soil and rock modeling
- Tunnels
- User-defined soil, rock, and concrete materials
- Willam-Warnke concrete model

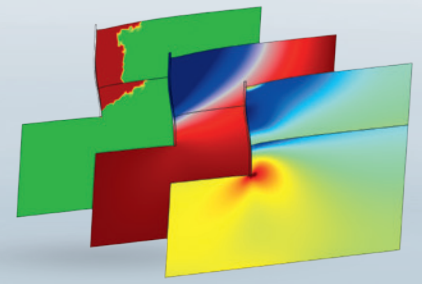
CIVIL ENGINEERING

The simulation shows how force is transferred from a concrete beam to its steel reinforcement bars during tension failure. Shown are the von Mises stresses in the concrete and the axial stresses in the bars.



EXCAVATION

The horizontal stresses, deformation and plastic regions are plotted from a model of the excavation of soil. The Drucker-Prager plastic model is used in the simulation.



Fatigue Module

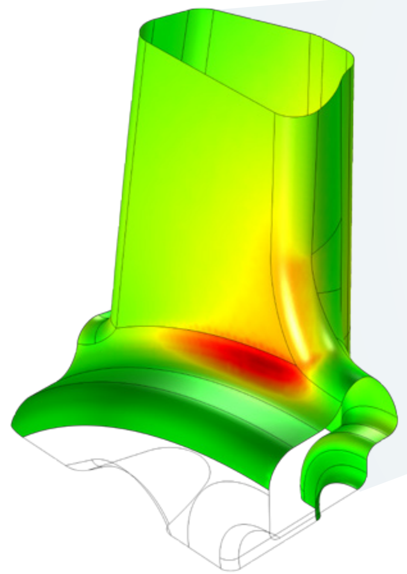
Performing structural fatigue life computations in the COMSOL Multiphysics environment is done with the Fatigue Module. Available as an add-on to the Structural Mechanics Module, three different fatigue methods are offered:

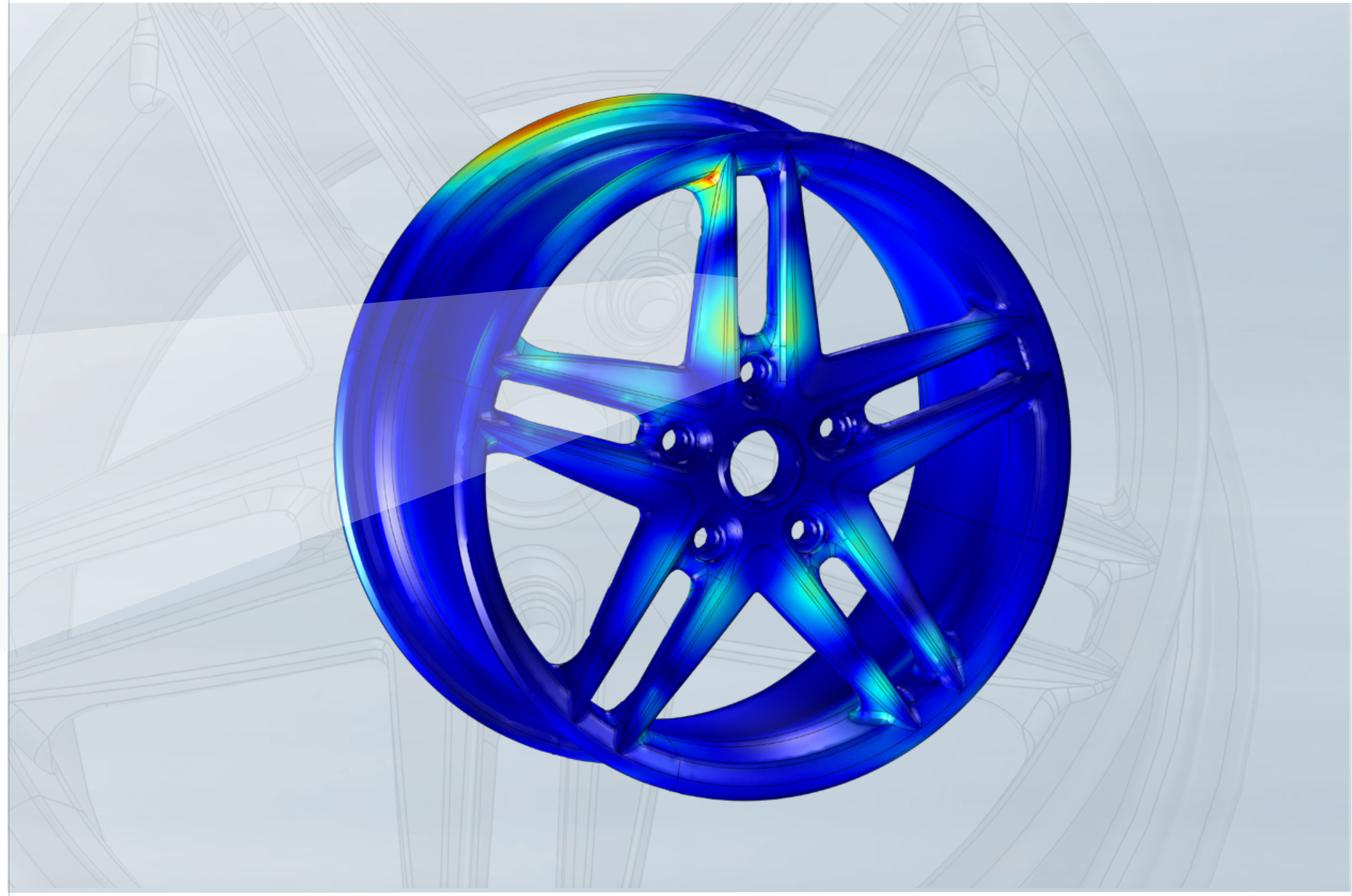
• Stress based analysis for high-cycle fatigue (HCF). The result is a usage factor, which tells you how close to the fatigue limit the load cycle is.

• Strain bases analysis for low-cycle fatigue (LCF). The result is a lifetime prediction in terms of the number of cycles to fatigue.

• Cumulative damage analysis for variable load fatigue. The load is first processed with the cycle, or Rainflow, counting method followed by a damage estimation according to the Palmgen-Miner damage model. The results are usage factor, which tells you how close to the fatigue limit the load cycle is, counted stress cycles, which shows the stress distribution of the applied load, and the relative usage factor, which defines the effect of certain stress loads on the overall fatigue usage.

Fatigue analysis is available in combination with the user interfaces for: Solid Mechanics, Shell, Plate, Multibody Dynamics, Thermal Stress, Joule Heating and Thermal Expansion, and Piezoelectric Devices.

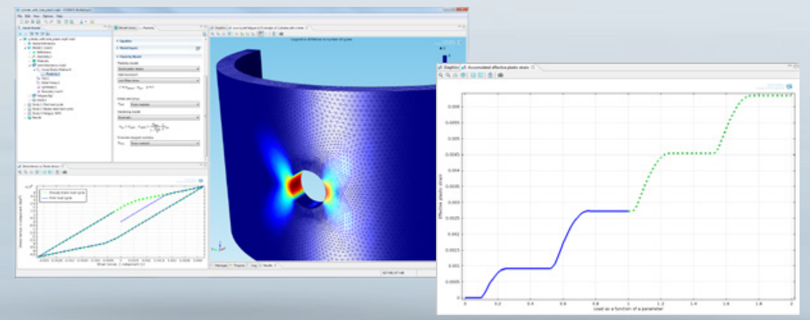




HIGH-CYCLE FATIGUE ANALYSIS OF A CAR WHEEL
High-cycle stress-based fatigue analysis of a ten-spoke car wheel. The highest stress occur in the fillet where the spoke connects to the hub. Results show the von Mises stress distribution for the whole wheel (above on the right) and the fatigue usage factor according to the Findley criterion for the fillet (above).

HIGHLIGHTS

- Cumulative damage analysis
- Strain-Based Fatigue
- Low-Cycle Fatigue
- Fatemi-Socie Criterion
- Smith-Watson-Topper (SWT) Criterion
- Wang-Brown Criterion with Morrow Mean Stress Correction
- Stress-Based Fatigue
- High-Cycle Fatigue
- Findley Criterion
- Matake Criterion
- Normal Stress Criterion
- Fatigue Life Computation
- Fatigue Usage Factor Computation
- Rainflow counting



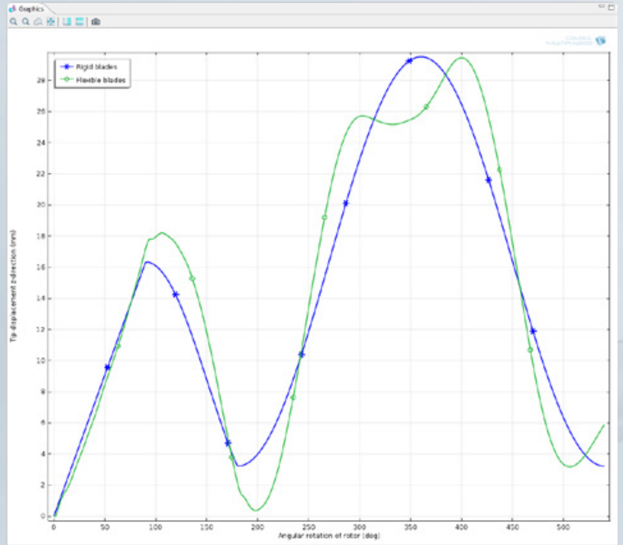
ELASTOPLASTIC LOW-CYCLE FATIGUE (LCF) ANALYSIS
Low-cycle strain-based fatigue resulting from plastic deformation near the hole in a cylinder is simulated. The visualizations (from left to right) show a stress-strain curve for the last three load cycles, a surface plot of lifetime logarithm, and the accumulated effective plastic strain curve.

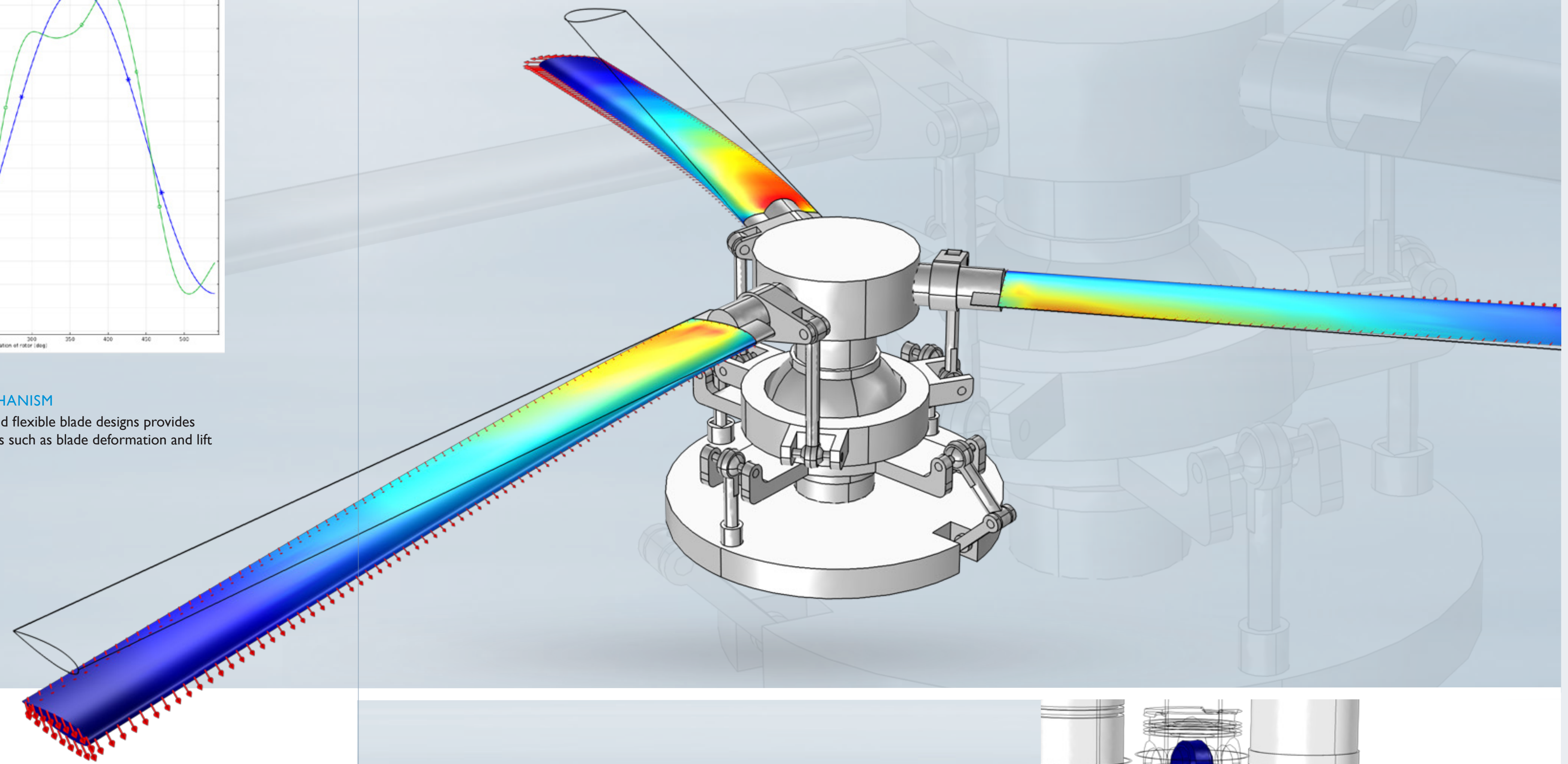
Multibody Dynamics Module

The Multibody Dynamics Module is an add-on to the Structural Mechanics Module that provides an advanced set of tools to design and optimize multibody structural mechanics models using finite element analysis. The module enables simulation of a mixed system of flexible and rigid bodies, each of which may be subjected to large rotational and translational displacements.

The relative motion of the bodies can be restricted by specifying rotational and translational constraints in addition to locking.

All bodies in a multibody structural mechanics model have elastic properties by default and can be made rigid through tagging them selectively with a Rigid Domain property. Boundaries or parts of boundaries of these flexible bodies can also be made rigid. You can assign nonlinear material properties to the flexible bodies in a multibody system by combining the Multibody Dynamics Module with the Nonlinear Structural Materials Module and the Geomechanics Module. Transient, frequency-domain, eigenfrequency, and stationary multibody dynamics analysis can be performed. Joints can be assigned linear/torsional springs with damping properties, applied forces and moments, and prescribed motion as a function of time.



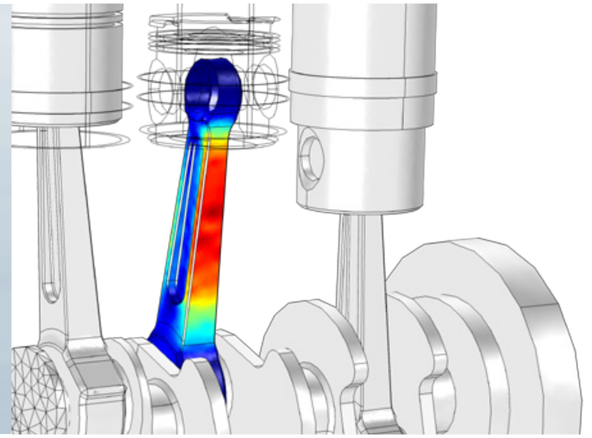


HELICOPTER SWASHPLATE MECHANISM

Transient simulation with both rigid and flexible blade designs provides insight into useful performance metrics such as blade deformation and lift force.

RECIPROCATING ENGINE

A dynamic analysis of a three-cylinder reciprocating engine is performed to investigate stresses generated during operation, thereby permitting identification of the critical components.



HIGHLIGHTS

- Automotive and Aerospace
- Biomechanics
- Biomedical instruments
- Engine dynamics
- General dynamic simulations of mechanical assemblies
- Mechatronics and Robotics
- Vehicle dynamics

JOINT TYPES

- Ball (3D)
- Cylindrical (3D)
- Hinge (2D, 3D)
- Planar (3D)
- Prismatic (2D, 3D)
- Reduced Slot (2D, 3D)
- Screw (3D)
- Slot (3D)

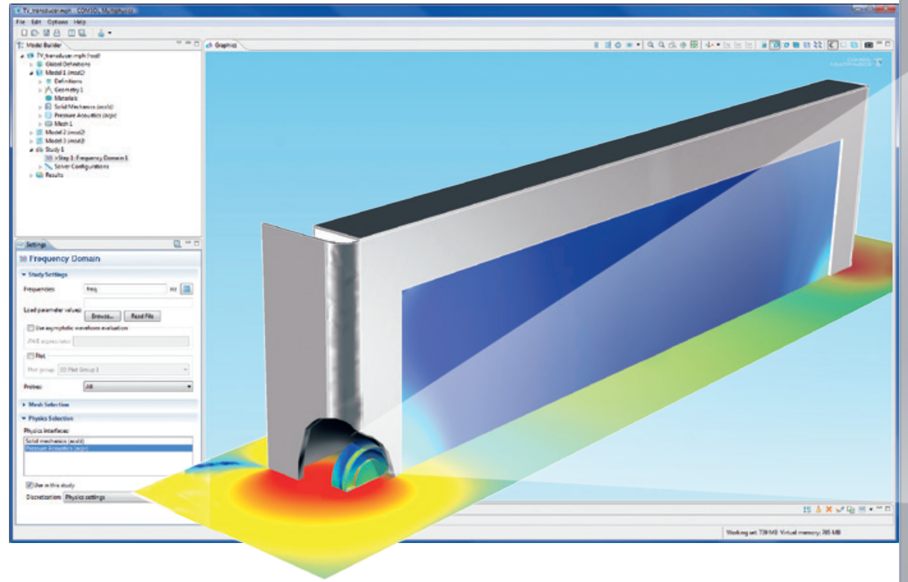
CAPABILITIES

- Eigenmodes of flexible multibody systems
- Fatigue analysis of critical flexible bodies by combining with the Fatigue Module
- Local and global coordinate-system frames of reference
- Reaction forces and moments at a joint
- Relative displacement/rotation between two components and their velocities
- Stresses and deformations in flexible bodies

Acoustics Module

The Acoustics Module is a world-class solution to your acoustics modeling needs. This module is designed specifically for those who work with devices that produce, measure, and utilize acoustic waves. Application areas include speakers, microphones, hearing aids, and sonar devices, as well as noise control that can address muffler design, soundbarriers, and building acoustics.

Easy-to-use physics interfaces provide the tools to model acoustic pressure wave propagation in air, water, and other fluids. Dedicated modeling tools for thermoviscous acoustics enable highly accurate simulation of miniaturized speakers and microphones in handheld devices. You can also model vibrations and elastic waves in solids, piezoelectric materials, and poroelastic structures. Multiphysics user interfaces for acoustic-solid, acoustic-shell, and piezo-acoustics bring your acoustic simulations to a new level of predictive power.

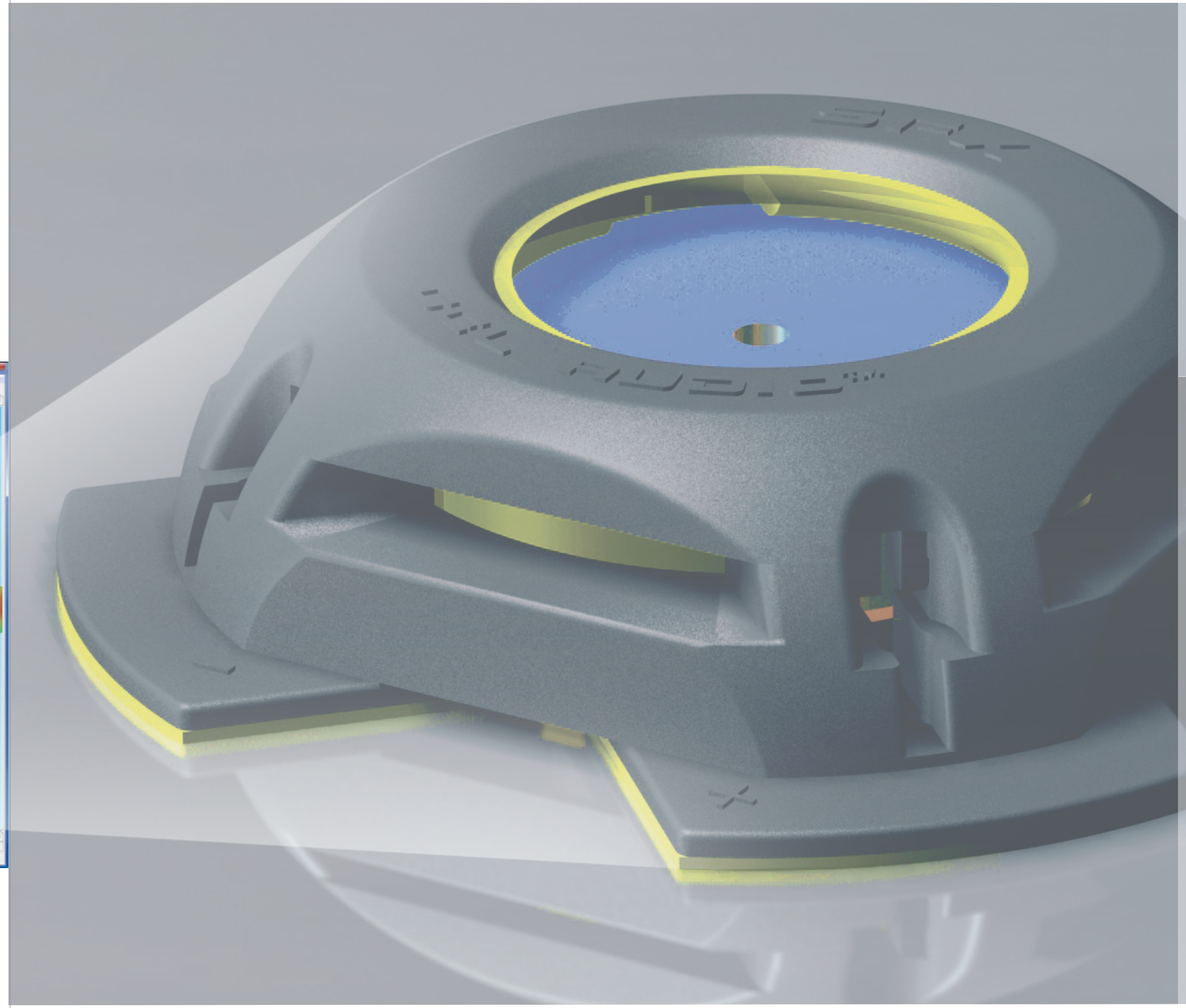


TV LOUDSPEAKER

Placed inside a television, the Gel Audio™ transducer can produce very good bass response using the TV itself as the speaker surface. The model shows a slice plot illustrating the sound pressure levels that emit from a typical TV surface and a surface plot of the deformation of the TV surface and transducer that produce the sound.

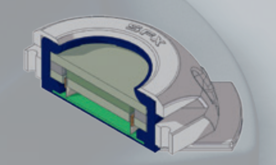
Model courtesy of Rod Habeshaw, SFX Technologies Ltd., Dunfermline, Scotland.

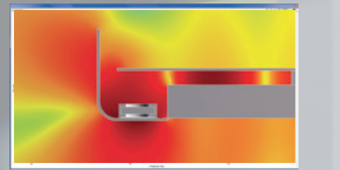
Gel Audio is a trademark of SFX Technologies Ltd.

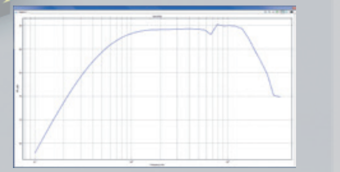


ACOUSTIC TRANSDUCER

A Gel Audio™ transducer, when placed on a panel such as a wall, mirror, or dashboard, turns that surface into a loudspeaker with good frequency response across the audio range. The CAD model is imported into COMSOL Multiphysics, and the acoustic pressure waves and sensitivity plot as a function of frequency can be plotted.





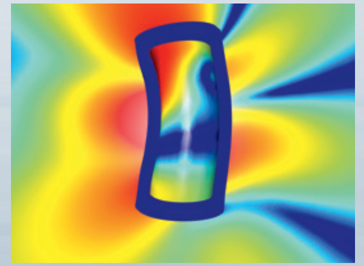


HIGHLIGHTS

- Acoustic-structure interaction
- Elastic waves
- Electroacoustic transducers and speakers
- Hearing aids
- Loudspeakers and microphones
- MEMS acoustics sensors
- MEMS microphones
- Noise and vibration of machinery
- Noise reducing materials and insulation
- Piezoacoustics
- Poroelastic waves
- Reactive and absorptive mufflers
- SONARs
- Structural vibrations
- Thermoacoustics

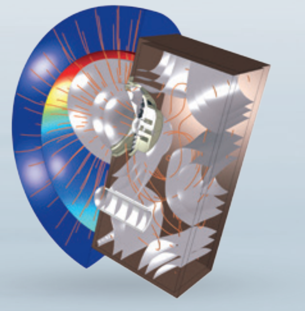
SONAR DEVICES

SONAR and ultrasound are two applications where structural deformation coupled to acoustics must be considered. Here, pressure waves are generated from a source inside a water-filled metal cylinder, where sound propagates through the cylinder and surrounding water.



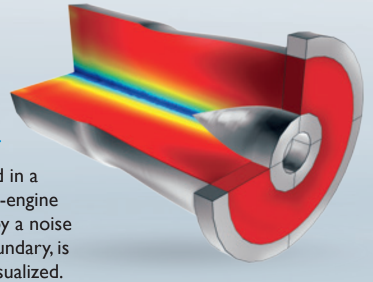
LOUDSPEAKER

A model of a loudspeaker and its driver includes both an electromagnetic analysis of the voice coil and an acoustic-structure interaction analysis of the sound-generating diaphragm. Shown here are isosurfaces of the acoustic pressure waves and a streamline plot of the intensity.



ENGINE DUCT

The acoustic field in a model of an aero-engine duct, generated by a noise source at the boundary, is computed and visualized.



CFD Module

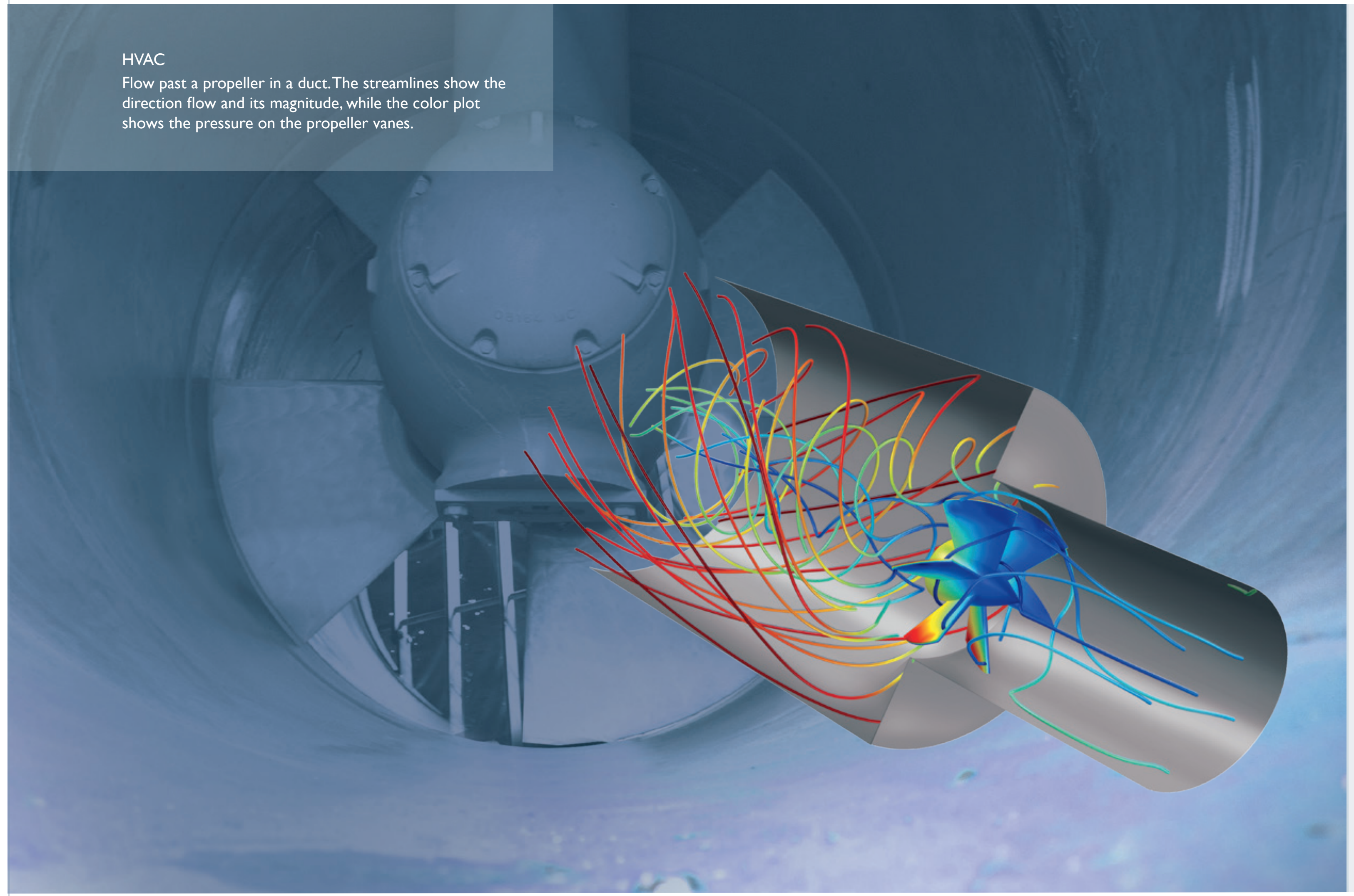
The CFD Module is the premier tool in the COMSOL product suite for sophisticated fluid flow simulations. Compressible as well as incompressible flows can be combined with advanced turbulence models and forced and natural convection. An important characteristic of the CFD Module is its capability of precise multiphysics-flow simulations such as conjugate heat transfer with non-isothermal flow, fluid-structure interactions, non-Newtonian flow with viscous heating, and fluids with concentration-dependent viscosity. Porous-media flow user interfaces allow for isotropic or anisotropic media, as well as automatically combined free flow and porous domains. Tools for modeling of stirred vessels with rotating parts are available for both 2D and 3D flows.

The module's interfaces for homogeneous two-phase flow include a mixture model for fine particle suspensions and a bubbly flow model for macroscopic gas bubble flow. For interface tracking two-phase flow, formulations are provided using the level-set and phase-field methods.

The tools available in the CFD Module for advanced transport and reacting flow simulations are automatically extended when combined with the Chemical Reaction Engineering Module. For fluid-structure interactions, the Structural Mechanics Module is compatible with the CFD Module's flow models and makes available elastic solid-fluid couplings as well as lubricating flow and elastohydrodynamics.

POLYMERIZATION
Simulation of the polymer as it fills the mold cavity after 10, 40, and 100 seconds. The red isosurface indicates where the boundary between the polymer mixture and air occurs, the green isosurface indicates where the volume fraction between the two polymers is at 50%, while the blue isosurface is where the second polymer has a volume fraction of 100%.

Model courtesy of Mark Yeoman, Continuum Blue Ltd., Hengoed, U.K.

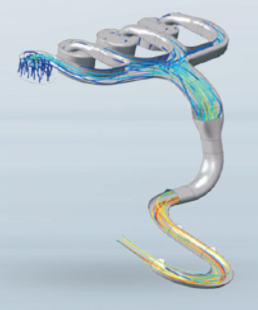


HVAC
Flow past a propeller in a duct. The streamlines show the direction flow and its magnitude, while the color plot shows the pressure on the propeller vanes.

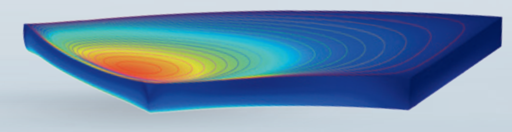
HIGHLIGHTS

- Conjugate heat transfer
- Cyclones, filters and separation units
- Electronic cooling
- Fans, grills, and pumps
- Flow around vehicles and structures
- Flows in pipes, valves, joints, nozzles
- Fluidized beds and sprays
- Fluid-structure interaction (FSI)*
- Gas bubble flow
- Heat exchangers and cooling flanges
- Lubrication and elastohydrodynamics
- Medical/biophysical applications such as flow in blood vessels
- Mixers and stirred vessels
- Non-isothermal flow
- Non-Newtonian flow
- Polymer flow and viscoelastic flow
- Porous media flow
- Sedimentation, emulsions, and suspensions
- Turbulent flow

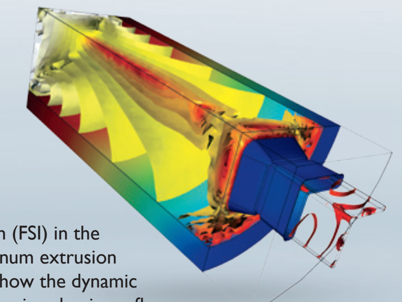
* *Together with the Structural Mechanics Module or MEMS Module*



EXHAUST MANIFOLD
Flow from a car engine through a manifold to the exhaust system.



LUBRICATING OIL FILM
Tilted pad thrust bearings are used in rotating machines with high thrust loading. The picture shows pressure distribution contours for the lubricating engine oil together with elastic deformation (exaggerated) and effective stress.



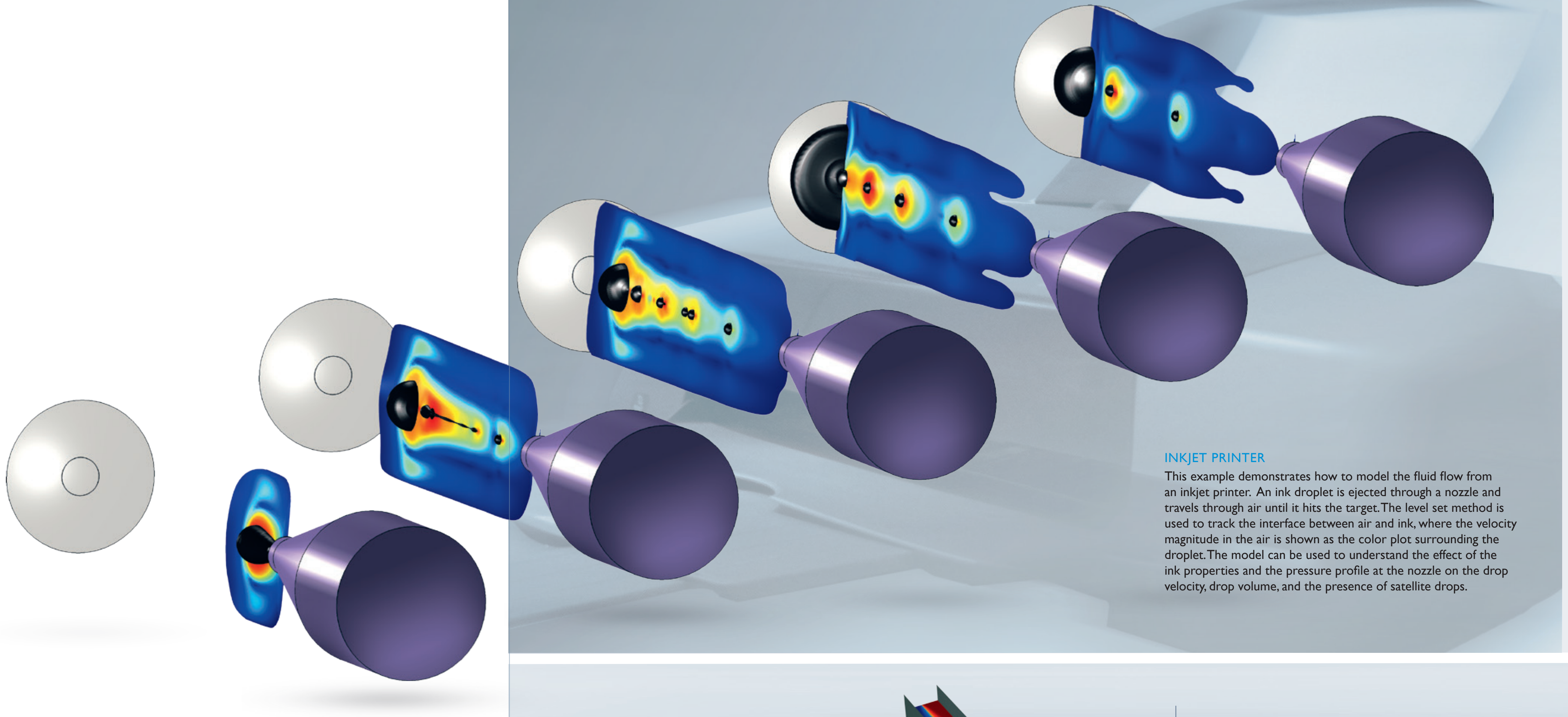
METAL FORMING
Fluid-structure Interaction (FSI) in the cast and mold of an aluminum extrusion process. The isosurfaces show the dynamic viscosity in the non-Newtonian aluminum flow.

Microfluidics Module

The Microfluidics Module brings easy-to-use tools for the study of microfluidic devices and rarefied gas flows. Important applications include simulations of lab-on-a-chip devices, digital microfluidics, electrokinetic and magnetokinetic devices, inkjets, and vacuum systems.

In addition to enhanced interfaces for single phase flow, Microfluidics Module users will have dedicated interfaces for two-phase flow using the level set, phase field, and moving mesh methods. These interfaces enable the modeling of surface tension forces, capillary forces, and Maragoni effects.

The general purpose multiphysics features of COMSOL make it easy to set up coupled electrokinetic and magnetodynamic simulations including electrophoresis, magnetophoresis, dielectrophoresis, electroosmosis, and electrowetting. The chemical diffusion and reactions for dilute species interfaces included in the module enable the simulation of processes occurring in lab-on-chip devices. Gas flows in microstructures can be modeled with the slip flow interface.



INKJET PRINTER

This example demonstrates how to model the fluid flow from an inkjet printer. An ink droplet is ejected through a nozzle and travels through air until it hits the target. The level set method is used to track the interface between air and ink, where the velocity magnitude in the air is shown as the color plot surrounding the droplet. The model can be used to understand the effect of the ink properties and the pressure profile at the nozzle on the drop velocity, drop volume, and the presence of satellite drops.

HIGHLIGHTS

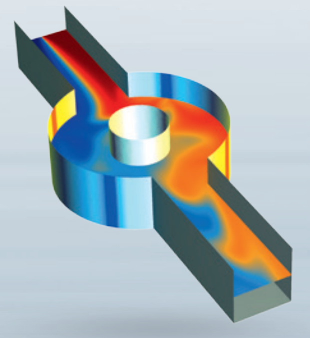
- Capillary forces
- Chemical and biochemical sensors
- Dielectrophoresis (DEP)
- DNA chips and lab-on-chips
- Electrocoalescence
- Electrokinetic flow
- Electroosmosis
- Electrophoresis
- Electrowetting
- Fluid-structure interaction (FSI)*
- Inkjets
- Magnetophoresis
- Marangoni effects
- Microreactors, micropumps, and micromixers
- Porous media flow
- Slip flow
- Static mixers
- Surface tension effects
- Two-phase flow
- Vacuum systems

* *Together with the Structural Mechanics Module or MEMS Module*

FLUID

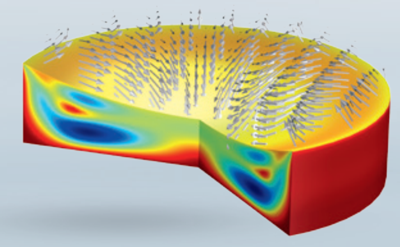
ELECTROOSMOSIS

Microlaboratories for biochemical applications often require rapid mixing of different fluid streams. This model takes advantage of electroosmosis to mix fluids. The system applies a time-dependent electric field (surface plot), and the resulting electroosmosis perturbs the parallel streamlines and concentration distribution (slice plot) in an otherwise highly-ordered laminar flow.



ELECTROWETTING

Simulation of a variable-focus liquid lens for a miniature camera during the transition between focal lenghts. The lens is made from the interface between two fluids - the lower phase velocity field is colored, while the upper phase is shown by an arrow plot.



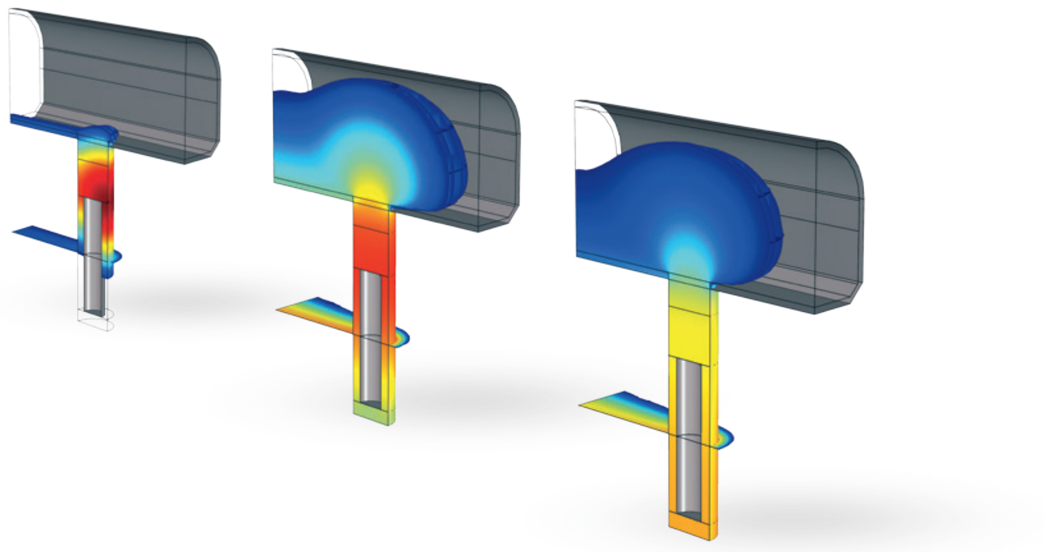
Subsurface Flow Module

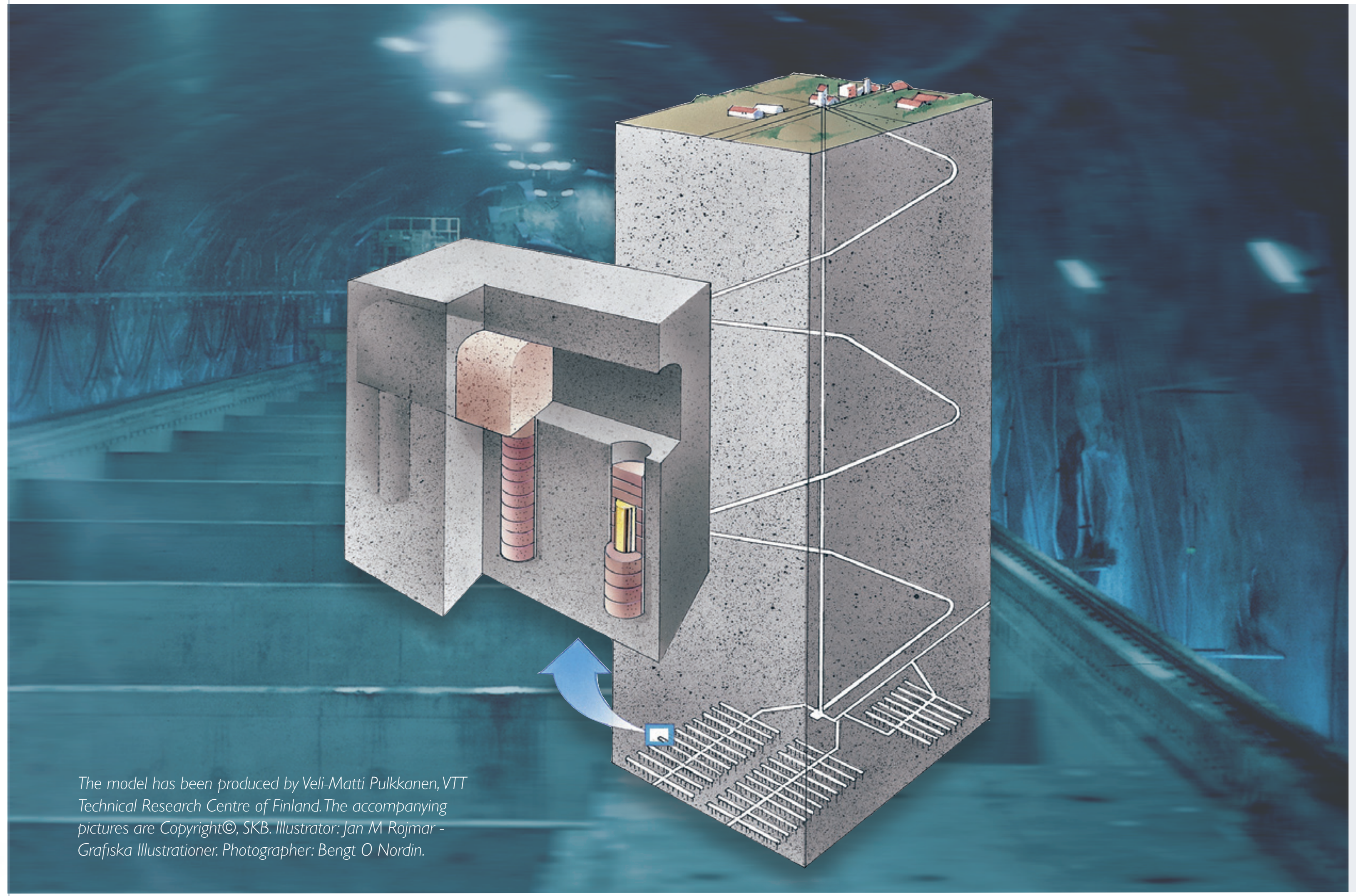
The Subsurface Flow Module is designed for geophysical and environmental phenomena studies such as the modeling of groundwater flow, the spread of pollution through soil, and oil and gas flow in porous media. The Richards' Equation interface describes nonlinear flow in variably saturated porous media, while the options for saturated porous media include the Darcy's Law interface for slow flow and the Brinkman Equations interface where shear is non-negligible. Free laminar Navier-Stokes flow can easily be combined with porous media flow and even include flow in thin fractures. The module also handles solute transport in solid, liquid, and gas phases for free, saturated, and variably saturated fluid flows, including solute transport in fractures.

For heat transfer simulations, background geotherms are available as well as automated calculation of effective thermal properties for multicomponent systems. Compaction and subsidence modeling is enabled by a very powerful user interface for poroelasticity. To apply multiphysics modeling to geophysical and environmental applications, the Subsurface Flow Module also allows arbitrary couplings to other physics interfaces in COMSOL Multiphysics, such as chemical reaction kinetics and electromagnetics.

NUCLEAR WASTE DISPOSAL

Nuclear waste repositories are now being built to store spent fuel rods for the next one hundred thousand years or so, and modeling has been used extensively to investigate them. This model shows a hypothetical case where a breach in the fuel bundle canister leads to leakage through a fracture in the surrounding rock and backfill in the tunnel above. The concentration distribution after 20, 200, and 2000 years is shown.





The model has been produced by Veli-Matti Pulkkanen, VTT Technical Research Centre of Finland. The accompanying pictures are Copyright©, SKB. Illustrator: Jan M Rojmar - Grafiska Illustrationer. Photographer: Bengt O Nordin.

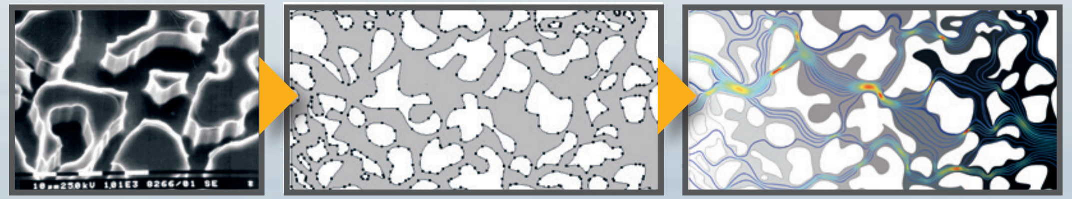
HIGHLIGHTS

- Estuary and riparian analyses—flow, advection, and diffusion
- Gas storage, remediation, and sequestration
- Groundwater and geothermal system modeling
- Mechanical and gravity dewatering of porous and fibrous materials
- Petroleum extraction analysis
- Pollutant plume analyses in subsurface, surface, and atmospheric flows
- Poroelastic compaction and subsidence
- Poroelastic stress, and failure analysis
- Radionuclide transport through bedrock
- Saturated and unsaturated porous media flow
- Shallow water flows and sediment transport
- Single phase and two-phase flow through porous media
- Water table analyses and saline intrusion into groundwater
- Well head analyses

SUBSURFACE FLOW

Produced by scanning electron microscope images, the geometry can be imported to COMSOL where the velocity and pressure distributions are calculated.

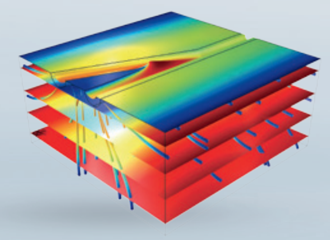
Model courtesy of Arturo Keller, University of California, Santa Barbara.



RESERVOIR MECHANICS

This model analyzes 3D compaction of an oil reservoir brought about by pumping, and the possible failure at the junction of an "open" multilateral well.

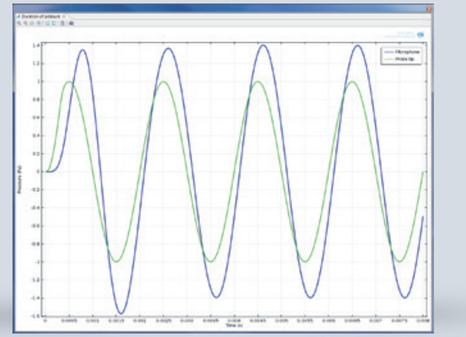
Model idea: A simulation performed by Roberto Suarez-Rivera, Schlumberger, Salt Lake City, Utah.

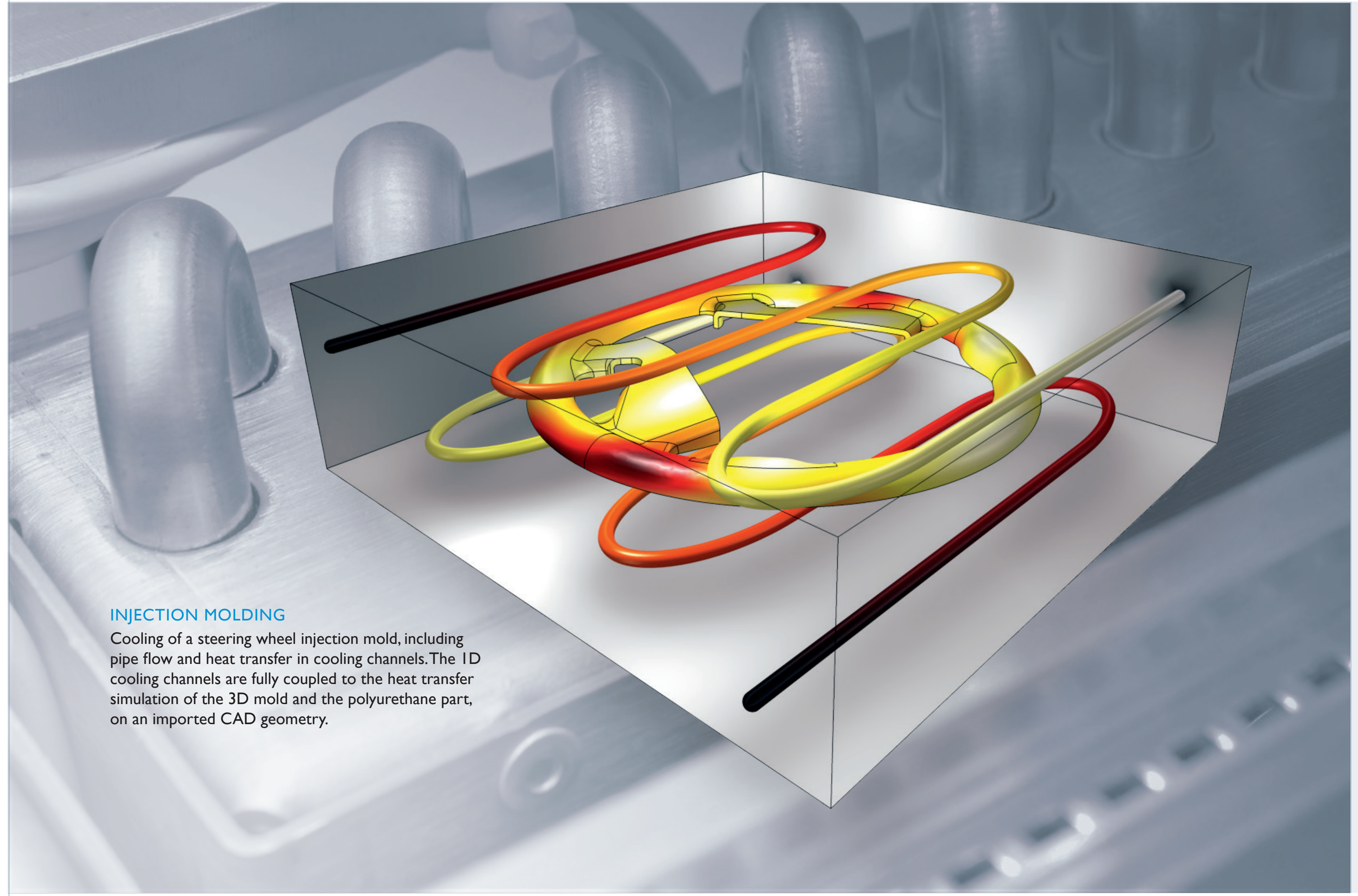


Pipe Flow Module

The Pipe Flow Module is used for simulations of fluid flow, heat and mass transfer, hydraulic transients, and acoustics in pipe and channel networks. Pipe flow simulations yield the velocity, pressure variation, and temperature along the pipes and channels. The module is suitable for pipes and channels which have lengths large enough so that flow in them can be considered to be fully developed and represented by a 1D approximation.

The module can be used to design and optimize complex cooling systems in turbines, ventilation systems in buildings, geothermal heating systems, heat exchangers, pipe systems in chemical processes, and pipelines in the oil, gas and mining industry. Preset piping components such as bends, valves, T-junctions, contractions/expansions and pumps are available. A dedicated user interface is included for transient simulations of the water hammer effect. Multispecies mass transport is available when the Pipe Flow Module is combined with the CFD Module or any of the other modules that feature multispecies transport. Acoustic wave propagation in pipes is available when the Pipe Flow Module is combined with the Acoustics Module.



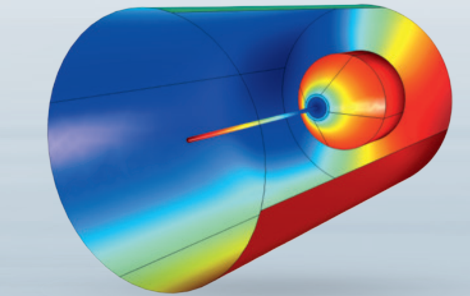


INJECTION MOLDING

Cooling of a steering wheel injection mold, including pipe flow and heat transfer in cooling channels. The 1D cooling channels are fully coupled to the heat transfer simulation of the 3D mold and the polyurethane part, on an imported CAD geometry.

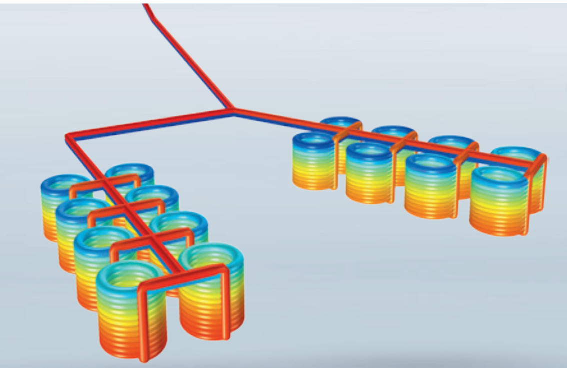
HIGHLIGHTS

- Chemical plant distribution systems
- Chemical reactions in pipes
- Cooling systems
- Geothermal systems
- Heat exchangers and cooling flanges
- Heat transfer in pipes
- Hydraulics
- Mass transfer in pipes
- Nonisothermal pipe flow
- Oil refinery pipe systems
- Pipe acoustics
- Pipe flow
- Water hammer
- Lubrication



MICROPHONES

A probe tube is attached to a microphone for a transient analysis that couples two pressure acoustics domains. Results indicate the pressure at the probe tip as well as at the microphone diaphragm.



GEOTHERMAL HEATING

Ponds and lakes can serve as thermal reservoirs in geothermal heating applications. In this example, fluid circulates underwater through polyethylene piping in a closed system.

Molecular Flow Module

The Molecular Flow Module is a tool that enables the design and simulation of low pressure gas flow in vacuum systems. Kinetic effects become important as the mean free path of the gas molecules becomes comparable to the length scale of the flow. Under these conditions, conventional fluid dynamics tools cannot produce an accurate model.

The Molecular Flow Module uses a fast angular coefficient method to simulate free molecular flows. Isothermal and non-isothermal flows can be modeled and the heat flux contribution from the gas molecules can also be computed. For transitional flows, an interface based on the discrete velocity method is also included.

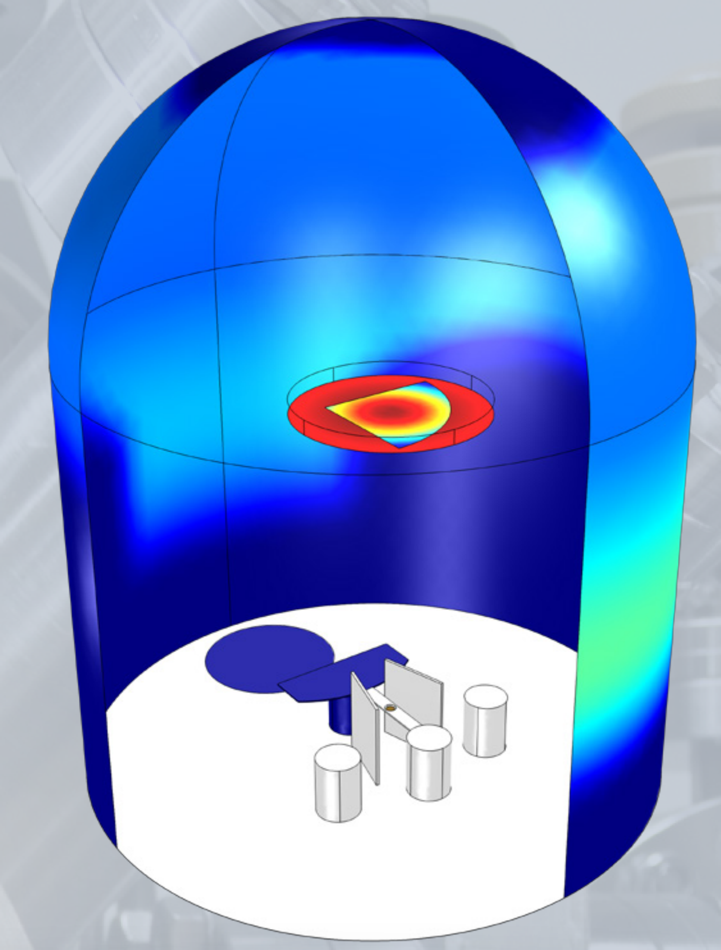
The Molecular Flow Module is ideal for the simulation of vacuum systems including those used in semiconductor processing, particle accelerators and mass spectrometers. Small channel applications (e.g. shale gas exploration and flow in nanoporous materials) can also be addressed.

Processes such as chamber pump-down and film growth can be designed and optimized through simulation by utilizing the features for defining adsorption/desorption and deposition. Mesh generation for complex CAD geometries is greatly simplified by the possibility to mesh surfaces only. The functionality to recover the number density anywhere within the flow geometry is also available.

FLOW TYPE	KNUDSEN NUMBER
Continuum flow	Kn<0.01
Slip flow	0.01<Kn<0.1
Transitional flow	0.1<Kn<10
Free molecular flow	Kn>10

Flow regimes categorized quantitatively via the Knudsen number (Kn) representing the ratio of the molecular mean free path to the flow geometry size.

While the Microfluidics Module is used to model slip and continuum flows, the Molecular Flow Module is designed for accurately simulating flows in the free molecular flow and transitional flow regimes.



FILM DEPOSITION

Thermally evaporated gold film thickness on both a sample and the interior surfaces of the evaporator chamber are shown. The thickness is computed as a function of time with a transient simulation.

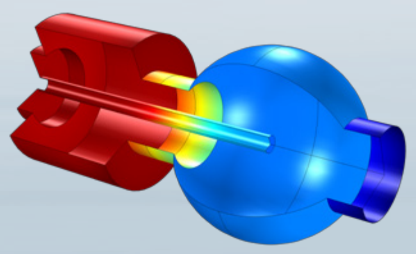
HIGHLIGHTS

- Mass spectrometers
- Materials processing equipment
- Nanopore flow
- Particle accelerators
- Semiconductor processing equipment
- Shale gas exploration
- Vacuum systems

FLUID

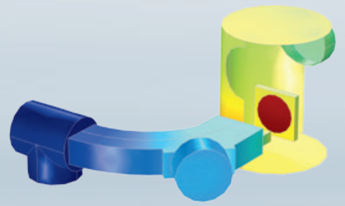
LOAD LOCK VACUUM SYSTEM

Time dependent simulation of adsorption and desorption of water in a vacuum system at low pressures. The water is introduced into the system when a gate valve to a load lock is opened and the subsequent migration and pumping of the water is modeled.



ION-IMPLANT VACUUM SYSTEM

In ion implantation, outgassing molecules interact with the ion beam to produce undesirable species. The average number density of outgassing molecules along the beam path is simulated and used as a figure of merit to evaluate the design.

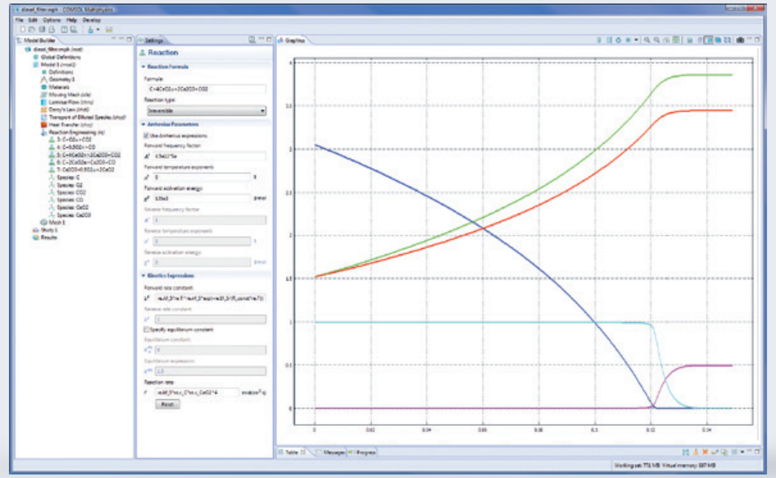


Chemical Reaction Engineering Module

The Chemical Reaction Engineering Module is optimized for the modeling of reactors, filtration and separation units, and other equipment common in the chemical and similar industries. It is specifically designed to easily couple fluid flow and mass and energy transport to chemical reaction kinetics. First the Chemical Reaction Engineering Module uses reaction formulas to create models of reacting systems. It can then solve the material and energy balances for such systems, including the reaction kinetics, where the composition and temperature vary with time, space, or both.

The Chemical Reaction Engineering Module melds seamlessly with the power of COMSOL Multiphysics for coupled as well as equation-based modeling. This allows for the inclusion of arbitrary expressions, functions, and source terms in the material property, transport, and reaction kinetic equations. You also have access to a variety of thermodynamic and physical property data through the CHEMKIN® file import feature and CAPE-OPEN interface.

DIESEL ENGINE FILTER
A filter system for a diesel engine includes a soot layer that builds up at the filter walls and is subsequently oxidized by both catalytic and non-catalytic reactions in the reactor volume and on a moving surface. All reactions are temperature and material transport dependent. The graph shows the concentrations of the carbon monoxide, carbon dioxide, and the cerium additive in a pre-study of the chemical kinetics. The model shows the carbon dioxide concentration in the filter.



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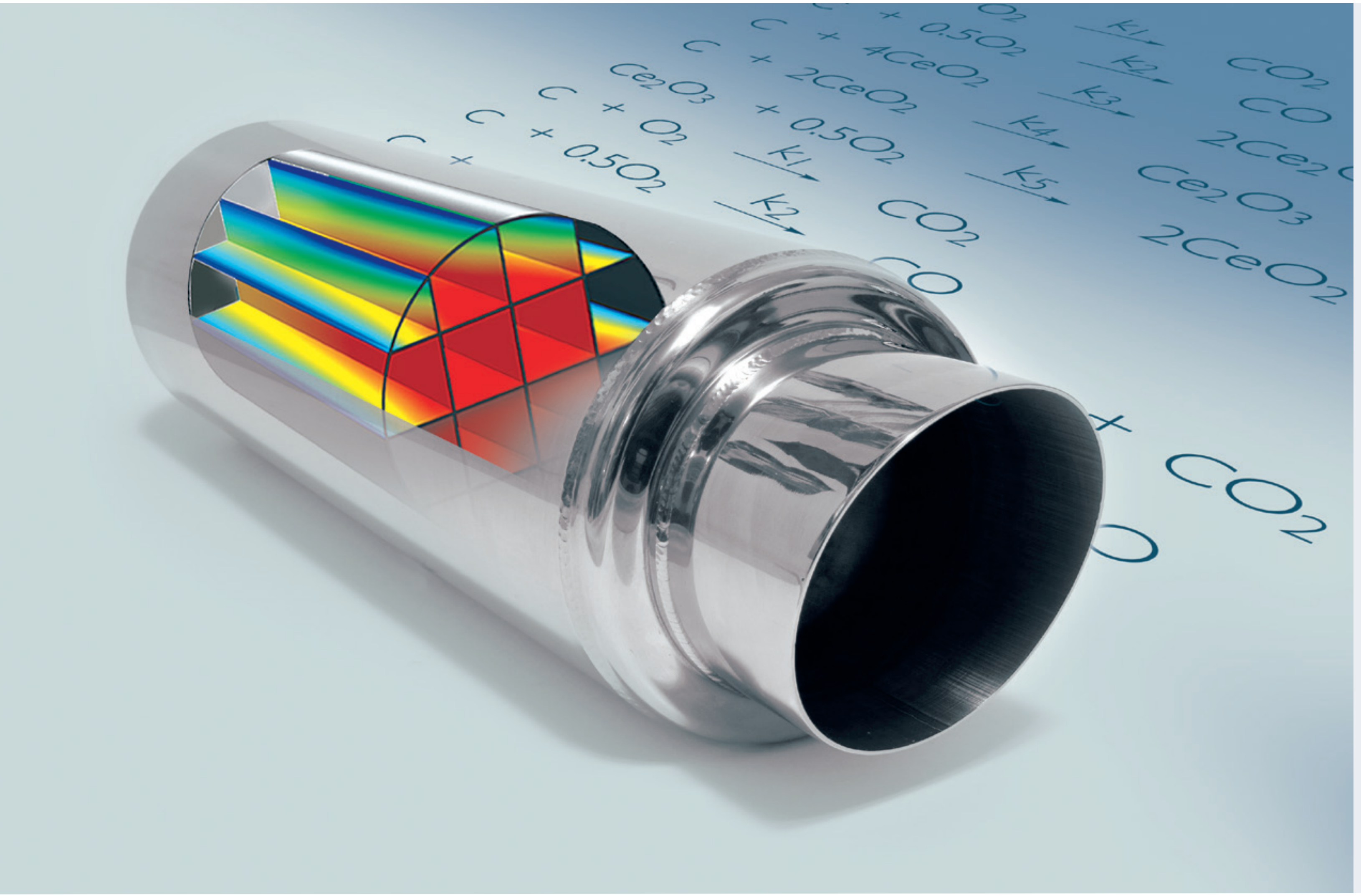


HIGHLIGHTS

- Batch reactors, fermenters, and crystallizers
- Biochemistry and food science
- Chemical reactor sizing and optimization
- Chromatography and electrophoresis
- Cyclones, separators, scrubbers, and leaching units
- Exhaust after-treatment and emission control
- Filtration and sedimentation
- Kinetics modeling in chemical reactors
- Microfluidics and lab-on-chip devices
- Multicomponent and membrane transport
- Packed bed reactors
- Pharmaceutical synthesis
- Plug-flow and tubular reactors
- Polymerization kinetics and manufacture
- Pre-burners and internal combustion engines
- Reformers and catalytic converters
- Semiconductor manufacture and CVD
- Surface chemistry kinetics and adsorption

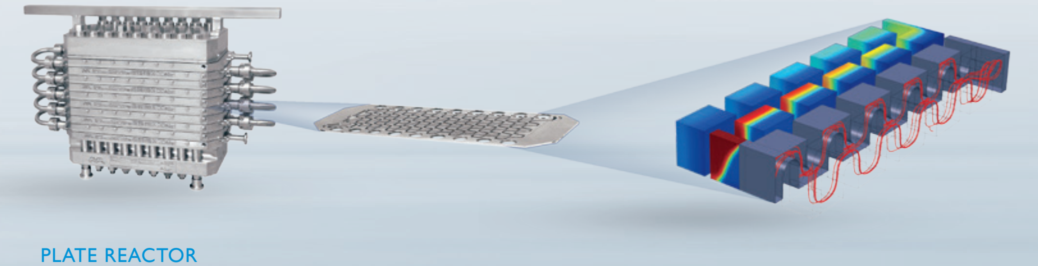
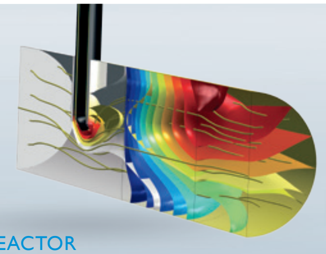
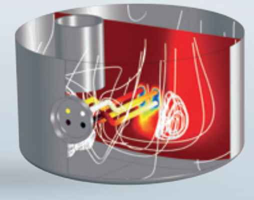


PLATE REACTOR
Flow streamlines and concentration in a plate reactor. One species is included at the beginning of the reactor while another is introduced half-way through it.

Picture courtesy: The photographs of the Plate Reactor are Copyright© Alfa Laval AB, Tumba, Sweden.



POROUS REACTOR
Two species enter a reactor from different inlets and then undergo a reaction in a porous part of the reactor. The flow streamlines and concentration isosurfaces for one of the reactants and the product species are shown.

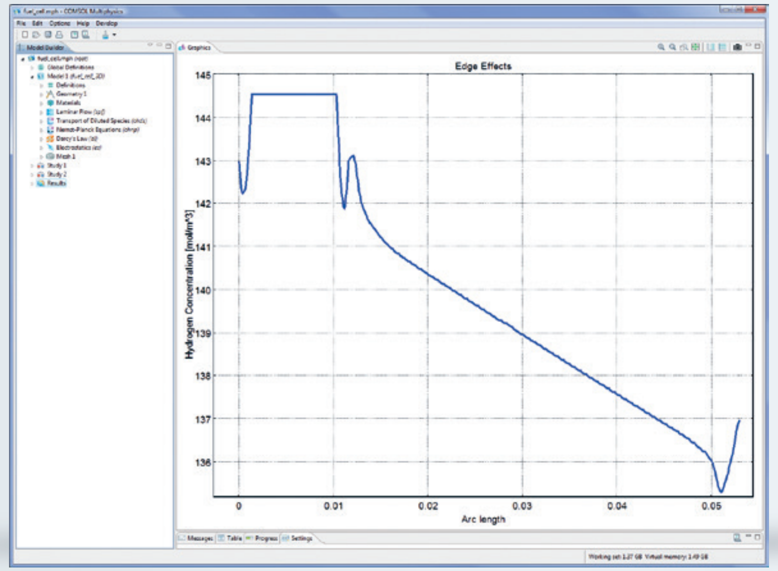


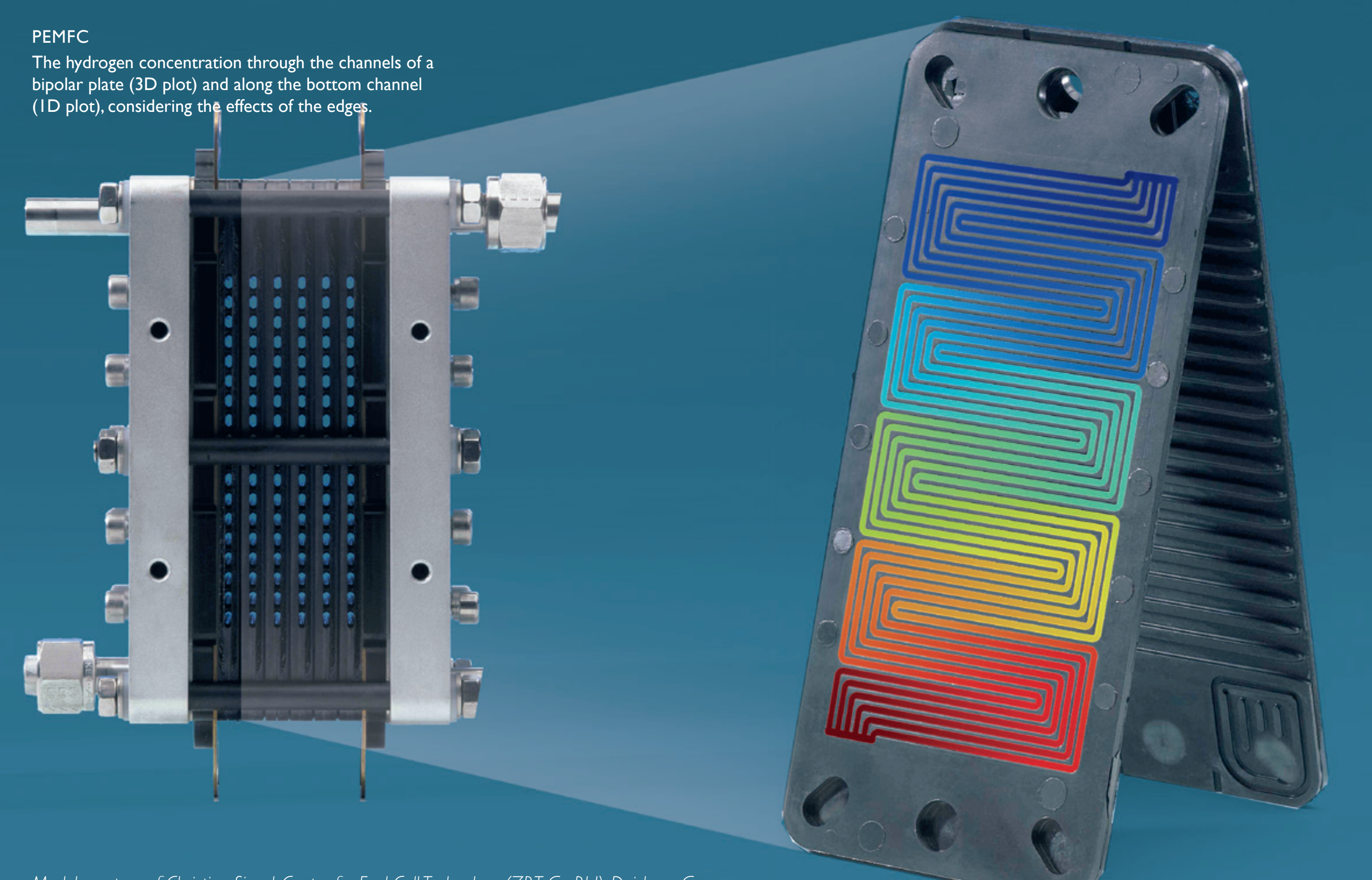
SCALE REMOVAL
The cleaning of scale from the heating element in the boiler is very much dependent on the flow of the species. This plot shows the concentration distribution of the scale (surface plot) and cleaning chemical (slice plot), and flow (streamlines).

Batteries & Fuel Cells Module

The Batteries & Fuel Cells Module provides a full set of easy-to-use tools for simulation of fundamental processes in the electrodes and electrolytes of lithium-ion batteries, nickel metal-hydride batteries, solid oxide fuel cells, and proton exchange membrane fuel cells. With it you can quickly and accurately investigate the performance impact of different materials, geometric configurations, and operating conditions.

The module features tailored interfaces to study primary, secondary, and tertiary current density distributions in electrochemical cells. Electrode reactions, which are fully coupled to the transport phenomena, provide full descriptions of the electrode kinetics including activation and concentration overpotential. The cell can contain solid or porous electrodes with dilute or concentrated electrolytes. Furthermore, couplings of the electrochemical reactions and mass transfer in batteries and fuel cells to other phenomena, such as heat transfer, electric potential, and fluid flow, can be performed through the powerful capabilities of COMSOL Multiphysics.





PEMFC
The hydrogen concentration through the channels of a bipolar plate (3D plot) and along the bottom channel (1D plot), considering the effects of the edges.

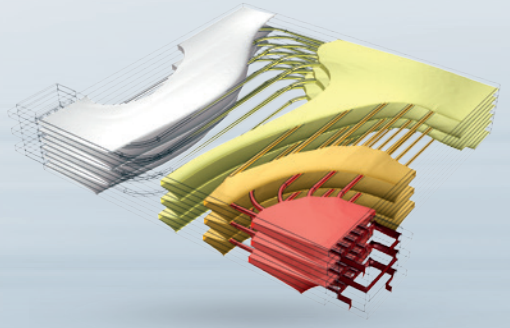
Model courtesy of Christian Siegel, Center for Fuel Cell Technology (ZBT GmbH), Duisburg, Germany.

HIGHLIGHTS

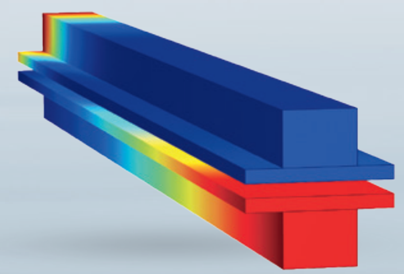
FUEL CELLS
- Alkaline
- Direct Methanol
- Molten Carbonate
- Proton Exchange Membrane
- Solid Oxide

BATTERIES
- Lead Acid
- Lithium Ion
- Nickel Hydride

CHEMICAL



BATTERY PACK
The picture shows the temperature field in the cooling channels and the batteries in a battery pack for automotive applications. The model includes a high-fidelity electrochemical model of the batteries coupled to a thermal analysis for the batteries and the components in the battery pack, and the fluid flow in the cooling channels.



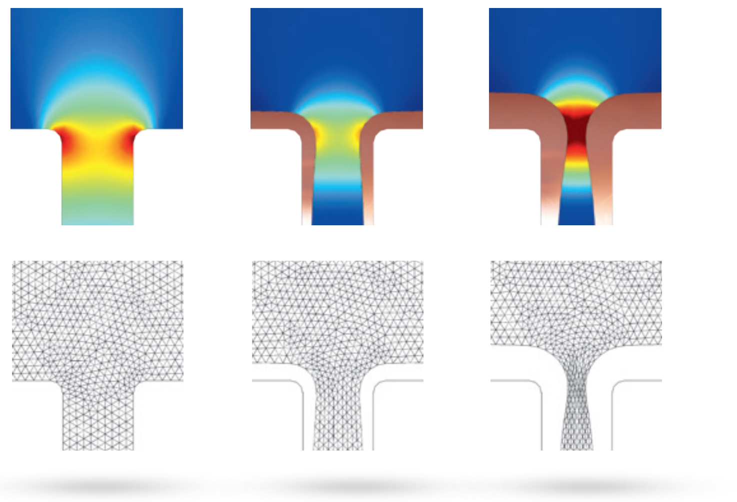
SOFC
Current density distribution in a solid oxide fuel cell, including full coupling between the mass balances at the anode and cathode, the momentum balances in the gas channels, the gas flow in the porous electrodes, the balance of the ionic current carried by the oxide ion, and a balance of electronic current.

Electrodeposition Module

Modeling and simulation are cost effective ways for understanding, optimizing, and controlling electrodeposition processes. A typical simulation yields the current distribution at the surface of the electrodes and the thickness and composition of the deposited layer. They are used to study important parameters such as cell geometry, electrolyte composition, electrode kinetics, operating voltages and currents, as well as temperature effects.

The Electrodeposition Module brings the power of COMSOL Multiphysics to simulate electrodeposition processes. Easy-to-use physics interfaces are provided for primary, secondary, and tertiary current distribution models, while very accurate geometric representations of deposited layer buildup are included as model parameters. The shape of the electrode can also be simulated with moving boundaries.

The Electrodeposition Module is applicable to a variety of diverse applications including metal deposition for electronics and electrical parts, corrosion and wear protection, decorative electroplating, electroforming of parts with thin and complex structure and metal electrowinning.

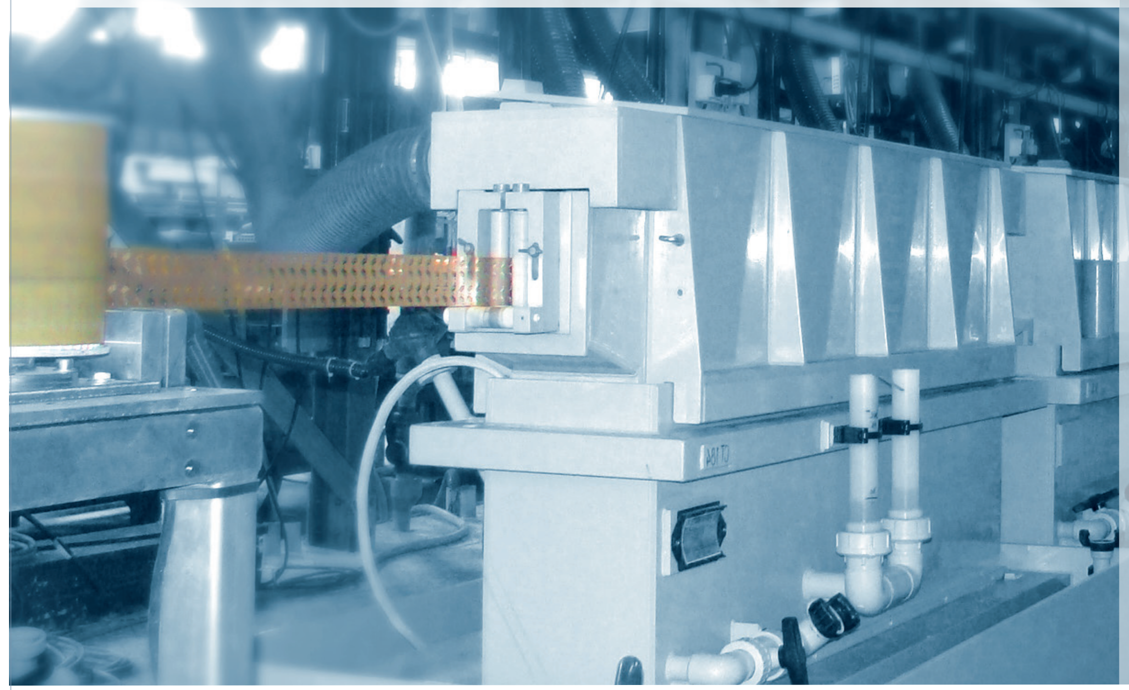


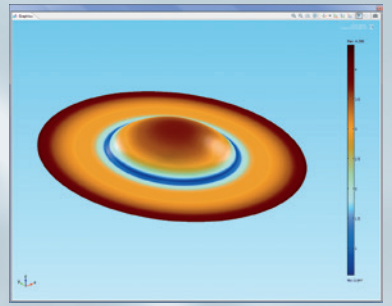
ELECTRODEPOSITION
This model demonstrates the effect of a moving boundary in the application of copper electrodeposition on circuit boards. The model is time-dependent and results clearly show that the mouth of the trench narrows, due to the non-uniform deposition of the copper.

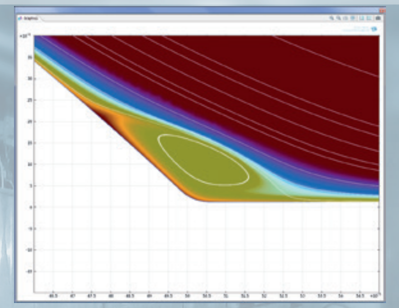
INDUSTRIAL ELECTROPLATING

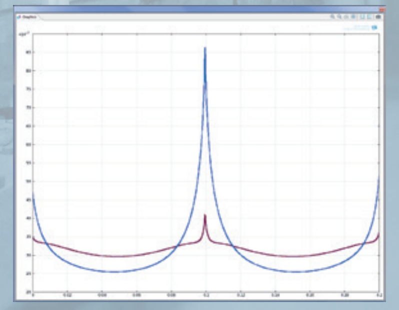
Model of a gold electroplated contact for the automotive industry, which would sit on the tape moving through the electroplating unit. The 3D figure shows the extent of gold deposition on the contact, which is a maximum at the top of the contact, and a minimum where the contact is bent. Zooming in on the region of the bend, the 2D figure indicates flow recirculation where deposition is least; an area where secondary reactions can take place. The graph shows a different application, the distribution of tin thickness across a copper strip, when the process uses screens (red line), and when it does does not (blue line).

Model and picture courtesy of Philippe Gendre, PEM, Siaugues, France.







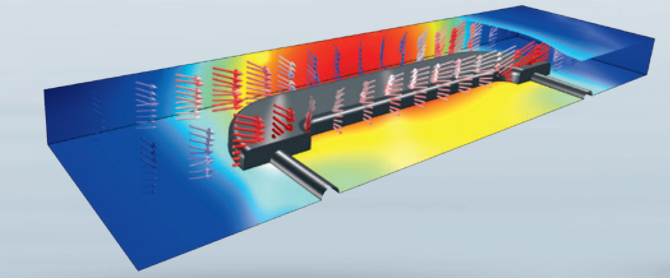


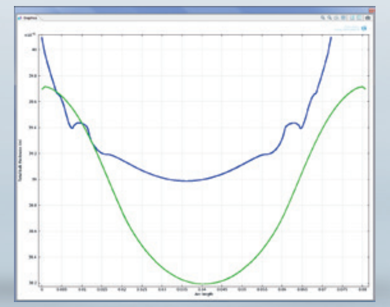
HIGHLIGHTS

- Anodizing
- Chrome plating
- Chroming
- Corrosion protection
- E-coating
- Electrocoating
- Electrocoloring
- Electrodeposition for mining applications
- Electrodeposition for PCB manufacturing
- Electroforming
- Electroplating
- Functional electroplating
- Wear resistance coatings

DECORATIVE ELECTROPLATING

In this example, the anode is planar and dissolves, while the cathode is a furniture fitting that is to be decorated by the dissolved metal. Shown is the thickness of the deposited layer at the cathode as well as the pattern caused by dissolution of the anode surface. The model assumes secondary current distribution with full Butler-Volmer kinetics for both the anode and the cathode.

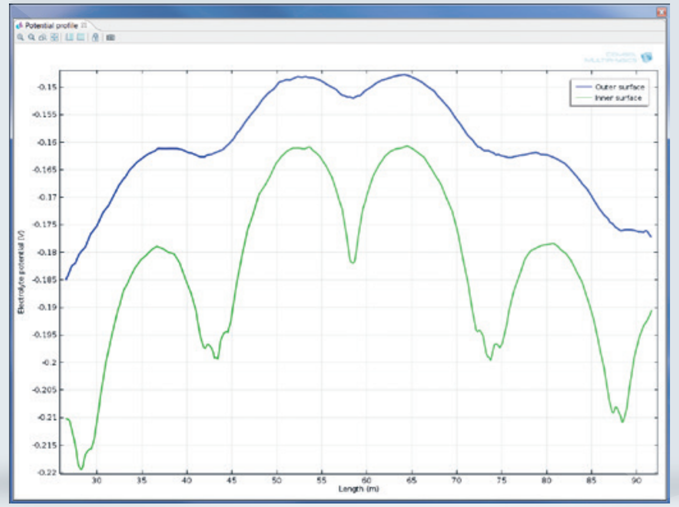


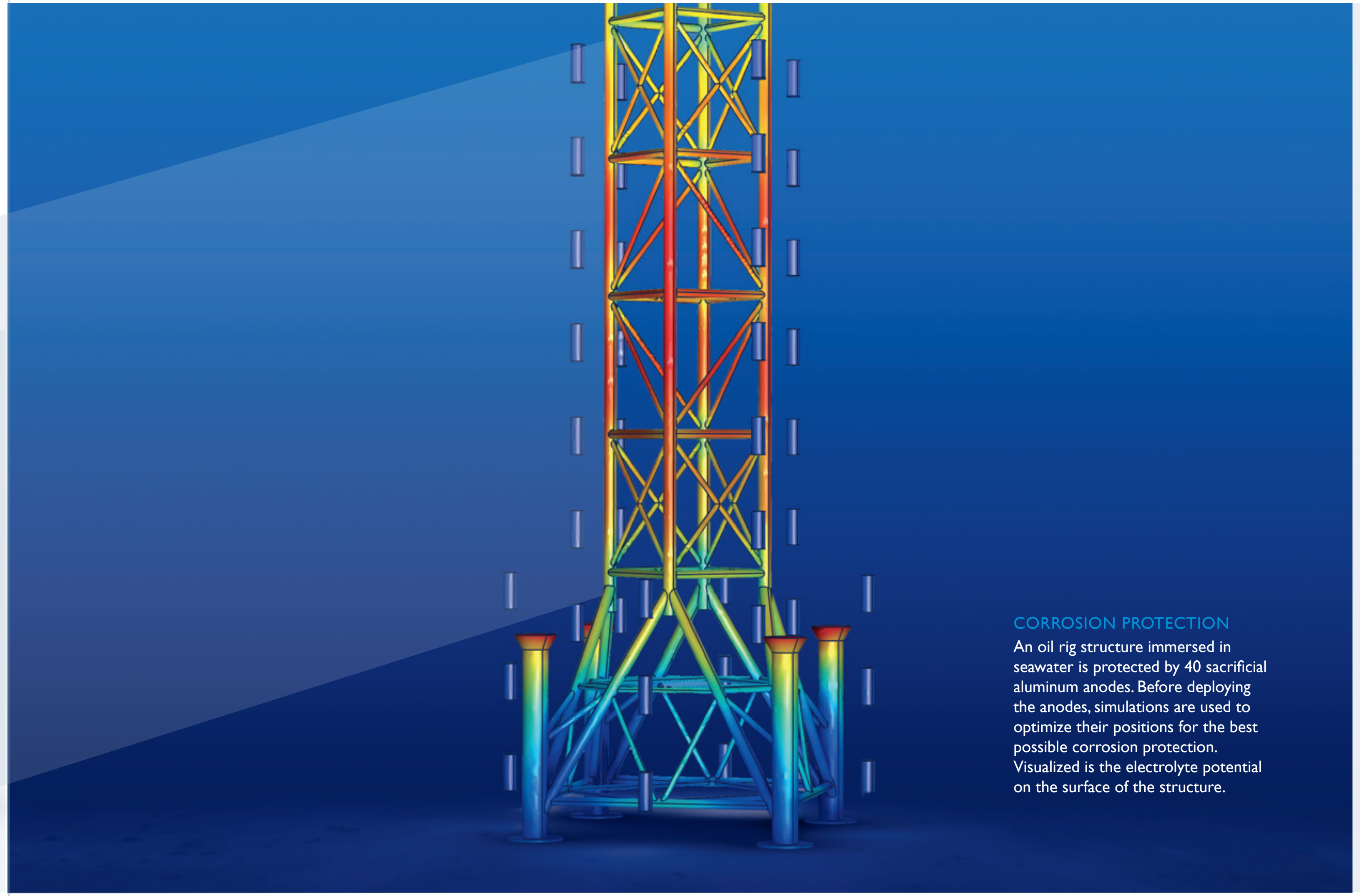


Corrosion Module

The Corrosion Module empowers engineers to simulate the electrochemistry of corrosion and corrosion protection of metal structures. Models in 1D, 2D, and 3D are set-up to include the relevant corrosion and other reactions within the electrolyte and at the metal surface interface using a series of pre-defined user interfaces. These are solved while considering the transport of ions and neutral species in the solution, the current conduction in the metal structure, and other phenomena such as fluid flow and heat transfer.

Simulations using the Corrosion Module can be used to understand and avoid corrosion situations, as well as to design and optimize corrosion protection. This can be done at the microscopic scales, such as in crevice and pitting corrosion where the localized concentrations can be significant parameters in the charge-transfer reactions, or at larger scales, where the placement of sacrificial anodes around a structure is the goal of the simulation. In some cases, linking the simulations at both these scales is necessary and also achievable with the Corrosion Module.





CORROSION PROTECTION

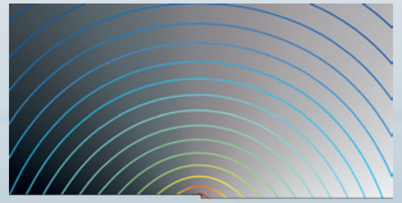
An oil rig structure immersed in seawater is protected by 40 sacrificial aluminum anodes. Before deploying the anodes, simulations are used to optimize their positions for the best possible corrosion protection. Visualized is the electrolyte potential on the surface of the structure.

HIGHLIGHTS

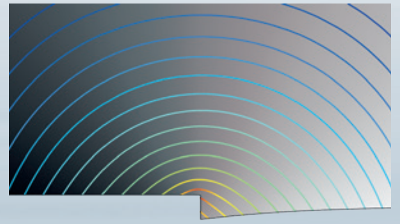
- Anodic protection
- Atmospheric corrosion
- Butler-Volmer equation
- Cathodic protection
- Corrosion
- Corrosion protection
- Crevice corrosion
- Galvanic corrosion
- Impressed Current Cathodic Protection (ICCP)
- Nernst-Planck equation
- Passivation
- Pitting corrosion
- Primary current distribution
- Secondary current distribution
- Tafel equation
- Tertiary current distribution

GALVANIC CORROSION

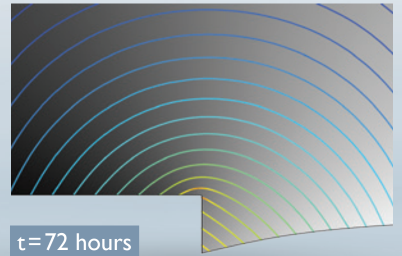
The corrosion of a magnesium alloy (AE44) connected to mild steel in a salt-water solution. The electrode material removal is also modeled, as it is an important variable to be considered when performing such simulations.



t=0 hours



t=28 hours



t=72 hours

Electrochemistry Module

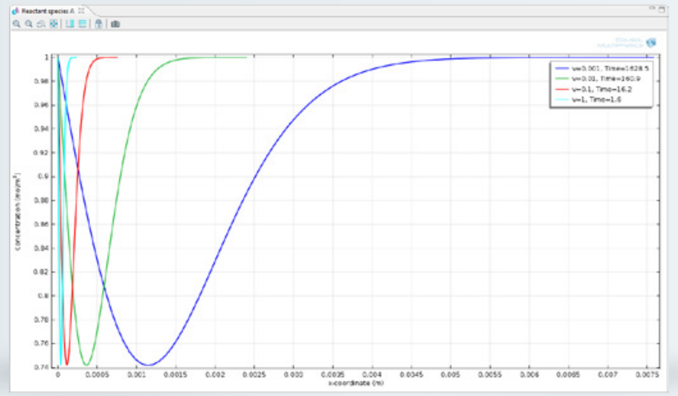
The Electrochemistry Module expands the possibilities in designing, understanding, and optimizing electrochemical systems through accurate simulation. This module offers significant benefits to researchers in the lab or to the industrial chemical engineer. Capabilities such as modeling current density distributions, electrochemical reactions, and mass transport enable efficient simulation for applications including electrolysis, electrochemical sensors, electrodialysis, electroanalysis, and electrobiochemistry.

Dedicated interfaces in the Electrochemistry Module enable the definition of voltammetry, amperometry, potentiometry, electrochemical impedance, and coulometry studies. Exchange current densities and activation overpotentials can then be determined from the combined experiment and simulation results.

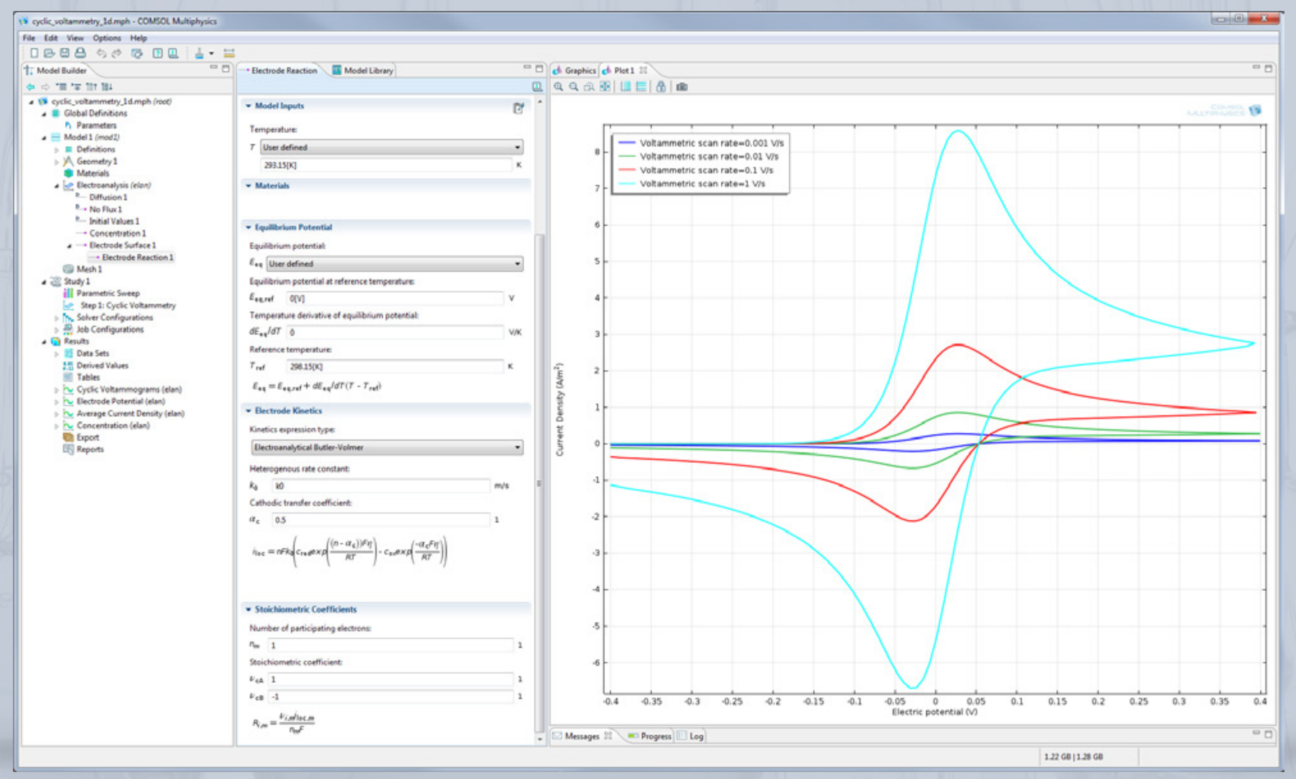
The Electrochemistry Module permit modeling systems assuming primary, secondary, or tertiary current distributions, as implemented via the Nernst-Planck and Butler-Volmer equations. The Electrochemistry Module covers a wide range of applications. This is accomplished through interfaces for electric currents, flow in free and porous media, heat transfer, surface and homogeneous chemical reactions, and material transport in dilute and porous media.

ELECTROCHEMICAL ANALYSIS

Cyclic voltammetry is a common technique for electrochemical analysis. During simulation, the potential at the working electrode is swept over a voltage range while the current is recorded. This waveform provides information about the reactivity and mass transport properties of an electrolyte.



Concentration of the reactant species along the diffusion layer.



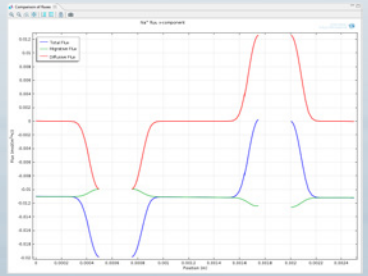
HIGHLIGHTS

- Bioelectrochemistry
- Chlor-alkali electrolysis
- Control of electrochemical reactions in biomedical implants
- Desalination of seawater
- Electroanalysis
- Electrochemical sensors
- Electrodialysis
- Electrolysis
- Electrolyte waste treatment
- Gas sensors
- Glucose sensors
- Hydrogen and oxygen production
- pH control of liquid foods
- Ultra-pure water production

CHEMICAL

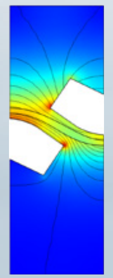
ELECTRODIALYSIS

Simulation of the removal of sodium chloride from a water solution (diluate) into another stream (concentrate). Such an application can be found in desalination of process streams, food and juice products, biomedical engineering.



CHLOR-ALKALI MEMBRANE CELL

Advances in membrane cell design by increased internal convection, decreased ohmic losses, and better membranes have allowed for large increases in current density with small increases in cell voltage. One of the important parameters in the design of modern membrane cells is the current-density distribution on the electrode surfaces. This model describes the current-density distribution in a realistic structure for the anodes and cathodes in a chlor-alkali membrane cell.



Optimization Module

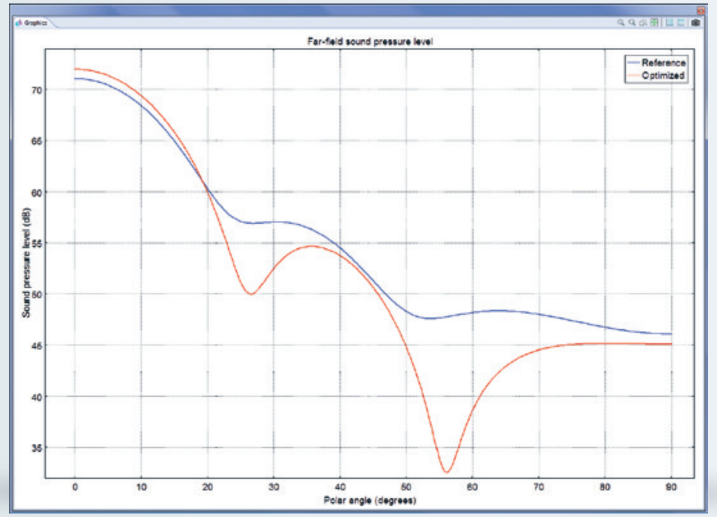
No matter the engineering discipline, once you have a model of a product or a process, you want to improve upon it. The Optimization Module can be used throughout the COMSOL Multiphysics product family; it is a general interface for computing optimal solutions to engineering problems. Any model input, be it geometric dimensions, part shapes, material properties, or material distribution, can be treated as a design variable, and any model output can be an objective function.

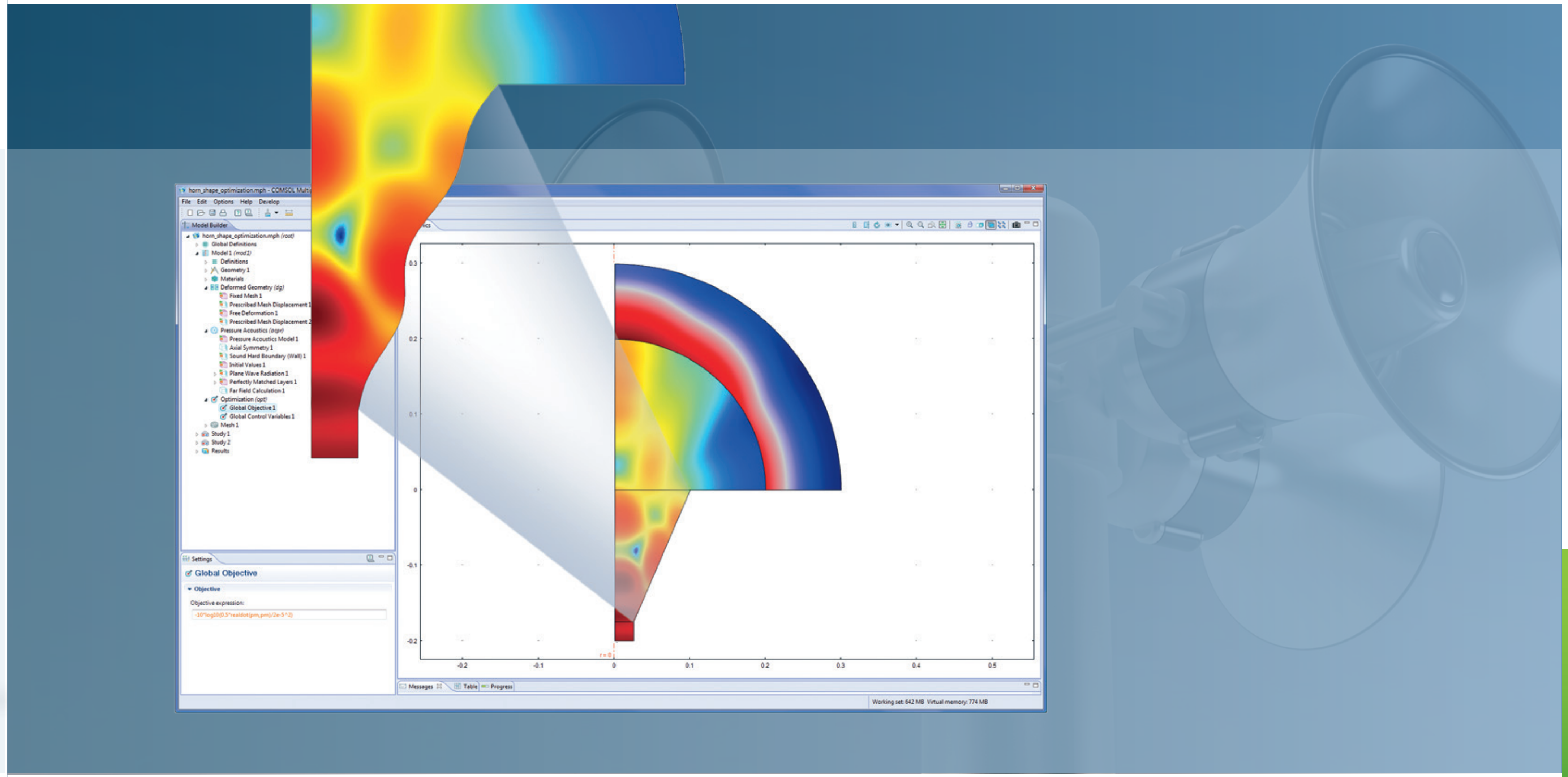
The Optimization Module computes the analytic sensitivities of the objective function to the design variables, considers any constraints imposed upon the problem. One of its methods uses a gradient-based optimization technique based on the SNOPT code developed by Philip E. Gill of the University of California San Diego, and Walter Murray and Michael A. Saunders of Stanford University.

The Optimization Module can be used to solve shape, size, and topology optimization problems, inverse problems such as parameter estimation, as well as time-dependent sensitivity and optimization. With a very general interface, the capabilities of the Optimization Module can be used in conjunction with any combination of other COMSOL products.

SHAPE OPTIMIZATION OF A HORN

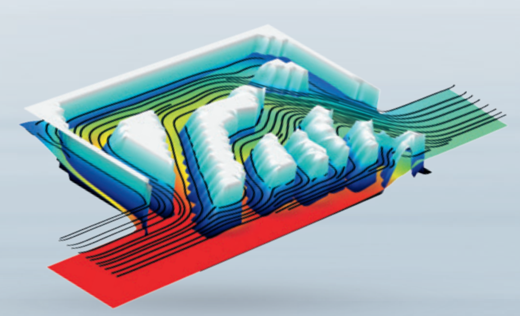
A horn has the initial shape of an axisymmetric cone with a straight boundary. This is optimized with respect to the far-field sound pressure level. Shown is the new shape on the internal boundary and the optimized far-field sound pressure level in comparison to the original one.





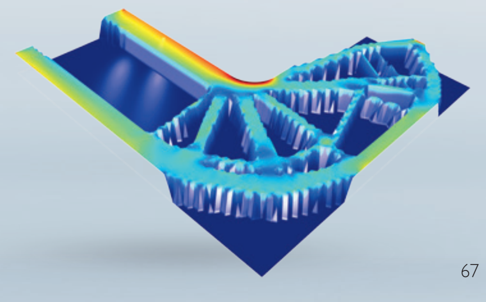
PLACING CATALYST IN A REACTOR

A chemical solution is pumped through a catalytic reactor where a solute species reacts in contact with the catalyst surface. The model aims to maximize the total reaction rate of the solute for a given total pressure difference across the bed by finding an optimal catalyst distribution. Shown is the catalyst distribution (as the height), direction of flow (streamlines) and concentration distribution (color plot).



TOPOLOGICAL OPTIMIZATION OF A SUPPORTING FRAME

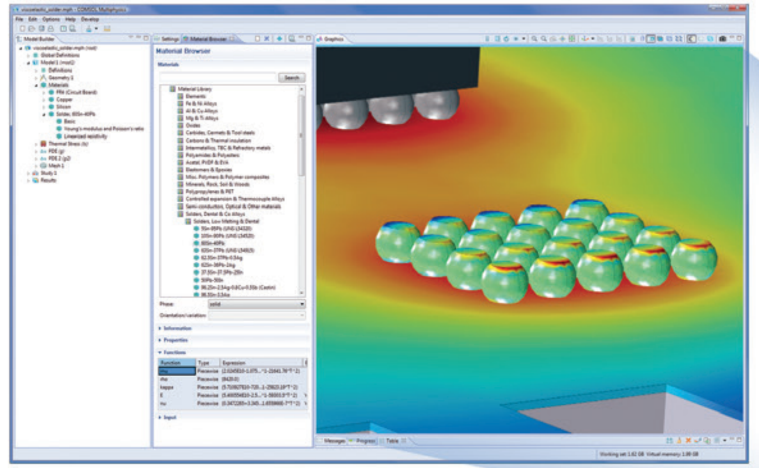
The optimal distribution of a given amount of material forming an L-shaped frame is topologically optimized. The optimality criterion is the minimum compliance for the load case where the frame's upper boundary is fixed and a downward load is applied along its right end. The material distribution is displayed as the height and von Mises stresses as the color.



Material Library

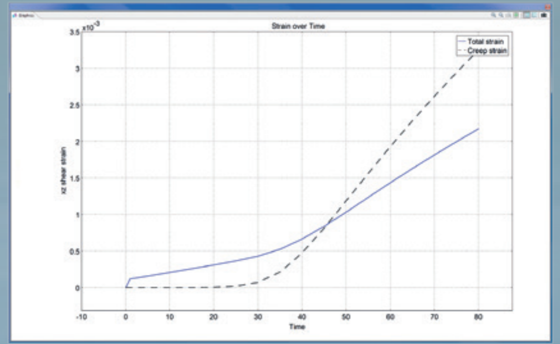
COMSOL Multiphysics gives you complete control over definitions and use of your material properties through the Model Builder and Material Browser. The Material Browser allows you to manage all your model's materials in one place and can be complemented by the Material Library.

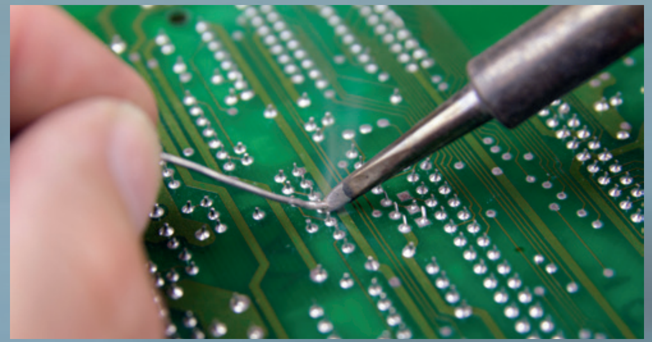
The Material Library contains data for 2,500 materials including the elements, minerals, metal alloys, thermal insulators, semiconductors, and piezoelectric materials. Each material is represented by referenced property functions for as many as 24 key properties, dependent on some variable, typically temperature. You can plot and inspect these function definitions, as well as change and add to them. They can then be used in any coupling to other physics simulations that also depend on the property function variable in your multiphysics modeling.

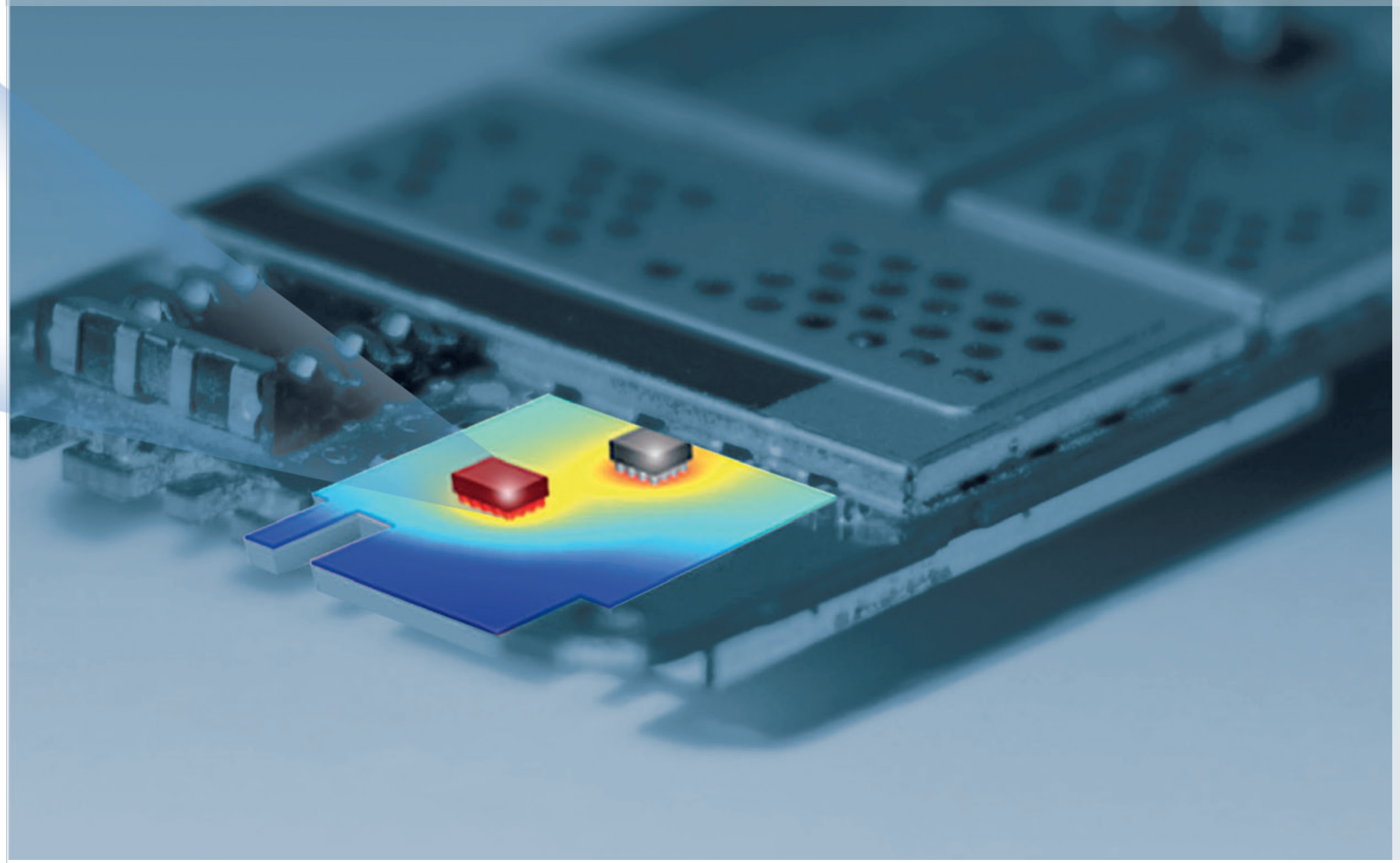


SOLDER JOINTS

This example studies viscoplastic creep in solder joints under thermal loading used to mount two chips to a cellular phone circuit board. The circuit board consists of two layers: a thin layer of copper and a thicker layer of FR4 material, while the chips are made of silicon. The Material Library is utilized to provide temperature-dependent material properties for the model. The plot shows plastic flow clearly appears after about 40 s of the loading. The model results show a closeup of the temperature distribution in the circuit board and the plastic strain in the solder joints.







AVAILABLE MATERIALS

- Elements
- Fe and Ni alloys
- Al and Cu alloys
- Mg and Ti alloys
- Oxides
- Carbides, cermets, and tool steels
- Carbons and thermal insulation
- Intermetallics, TBC, and refractory metals
- Polyamids and polyesters
- Acetal, PVDF, and EVA
- Elastomers and epoxies
- Miscellaneous polymers and polymer composites
- Minerals, rock, soil, and wood
- Polypropylenes and PET
- Controlled expansion and thermocouple alloys
- Semiconductors, optical, and related materials
- Solders, dental, and Co alloys
- Resistance and magnetic alloys
- Metal and ceramic matrix composites
- Salts, fuel cell, battery, and electro-ceramics
- Silicides and Borides
- Glasses, metallic glasses, nitrides and beryllides
- Cast irons and mold materials

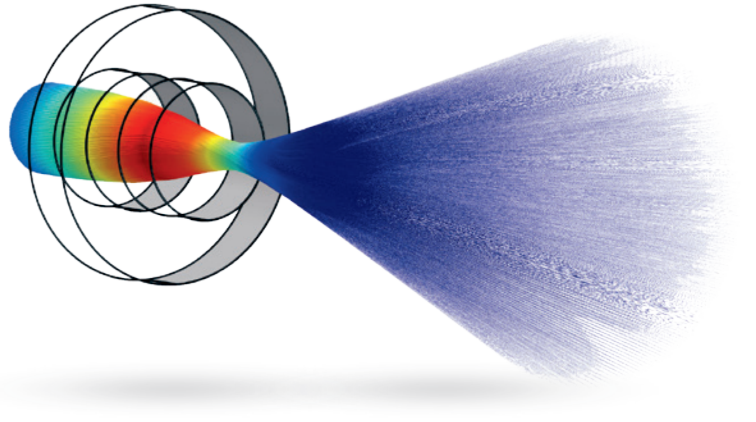
Particle Tracing Module

The Particle Tracing Module extends the functionality of the COMSOL Multiphysics environment for computing the trajectory of particles in a fluid or electromagnetic field, including particle-particle and particle-field interactions. Any application-specific module combines seamlessly with the Particle Tracing Module and gives you access to additional modeling tools and fields to drive the particle motion.

Loss or gain of mass, spin or similar quantities may be represented as auxiliary variables and equations for each particle along its trajectory. Secondary emission of particles is included as an option, where the emission may depend on incident velocity and energy. Particles can be massless or have mass, where the movement is governed by Newtonian, Lagrangian, or Hamiltonian formulations from classical mechanics. Low-level access to the mathematical formalism is available for highly customized simulations.

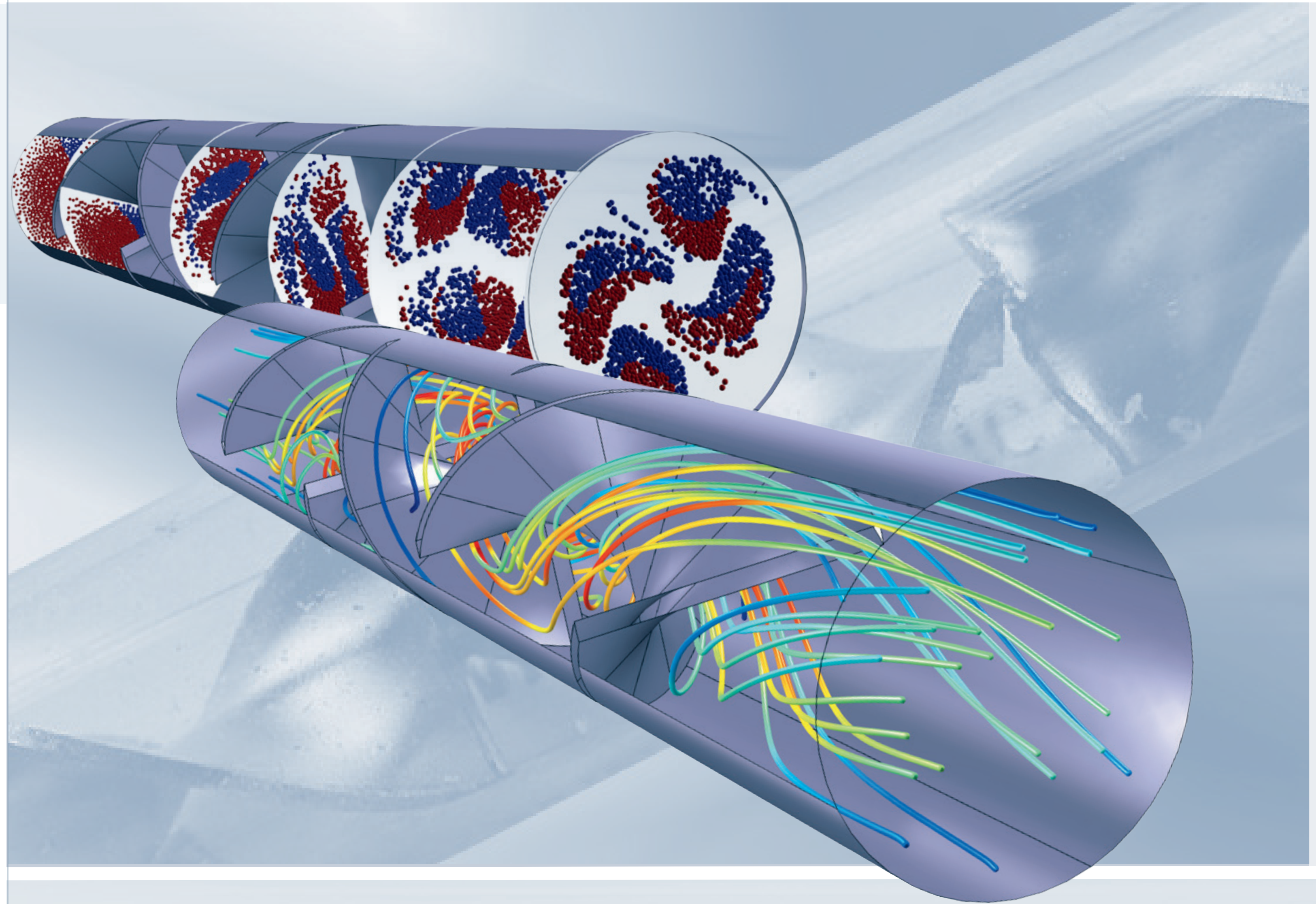
MIXING

In static mixers, a fluid is pumped through a pipe containing stationary blades designed in a way to promote mixing with small pressure loss. This example evaluates mixing performance by calculating the trajectory and distribution of suspended particles. The color scale on the particle traces (bottom model picture) indicates the particle velocity and path of the particles. The Poincaré Map (top model picture) indicates the particle distribution where the colors differentiate between the two species being mixed. In this case, mixing is due to convection only, which corresponds to a diffusionless system. Such a system is best modeled using a particle tracing approach.



ELECTRON MICROSCOPE

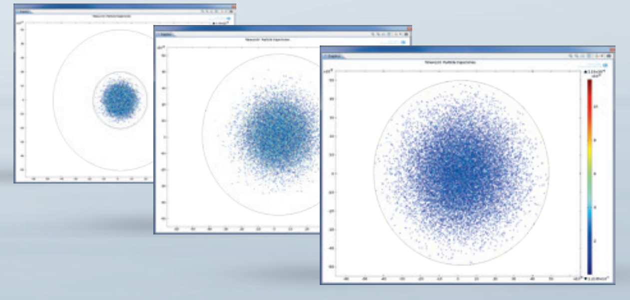
A scanning electron microscope samples images using a high-energy beam of electrons to scan the target. Electromagnetic lenses are employed to focus the beam down to a spot 10 nm wide on the sample surface. Use of modeling allows for proper placement of the coil configuration and to determine distance of the focal point from the lens.



HIGHLIGHTS

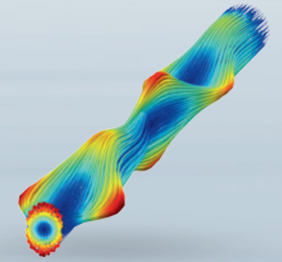
- Acoustophoresis
- Aerosol dynamics
- Beam physics
- Brownian motion
- Classical mechanics
- Fluid flow visualization
- Ion energy distribution function visualization
- Ion optics
- Mass spectrometry
- Mixers
- Secondary emission
- Sprays
- Separation and filtration

MULTIPURPOSE



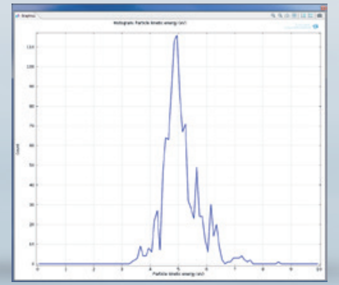
NATURAL DIFFUSION

Transport that is purely diffusive in nature can be modeled using a Brownian force. Here, particle diffusion in a stationary fluid is modeled over time where the color of the particles indicates its local velocity.



MASS SPECTROMETRY

Trajectories of argon ions are modeled in a quadrupole mass spectrometer. The electric fields, which exert forces on the ions have both AC and DC components, and the combination of the two is essential for the function of the spectrometer. The graph shows the ion energy distribution function at the spectrometer's collector.



CAD Import Module

Collaboration within design teams is made easy with the CAD interoperability tools for COMSOL. The CAD Import Module allows for all major CAD file formats to be brought directly into the COMSOL Desktop where you can simulate your design accurately using real-world multiphysics simulations. By including the Parasolid® geometry engine, the CAD Import Module enables more advanced geometry operations to be performed on complex CAD models within the COMSOL Desktop. The interactive repair feature assures that imported geometries are mathematically correct for simulation and includes defeaturing tools that remove fillets, small faces, sliver faces, as well as spikes and short edges.

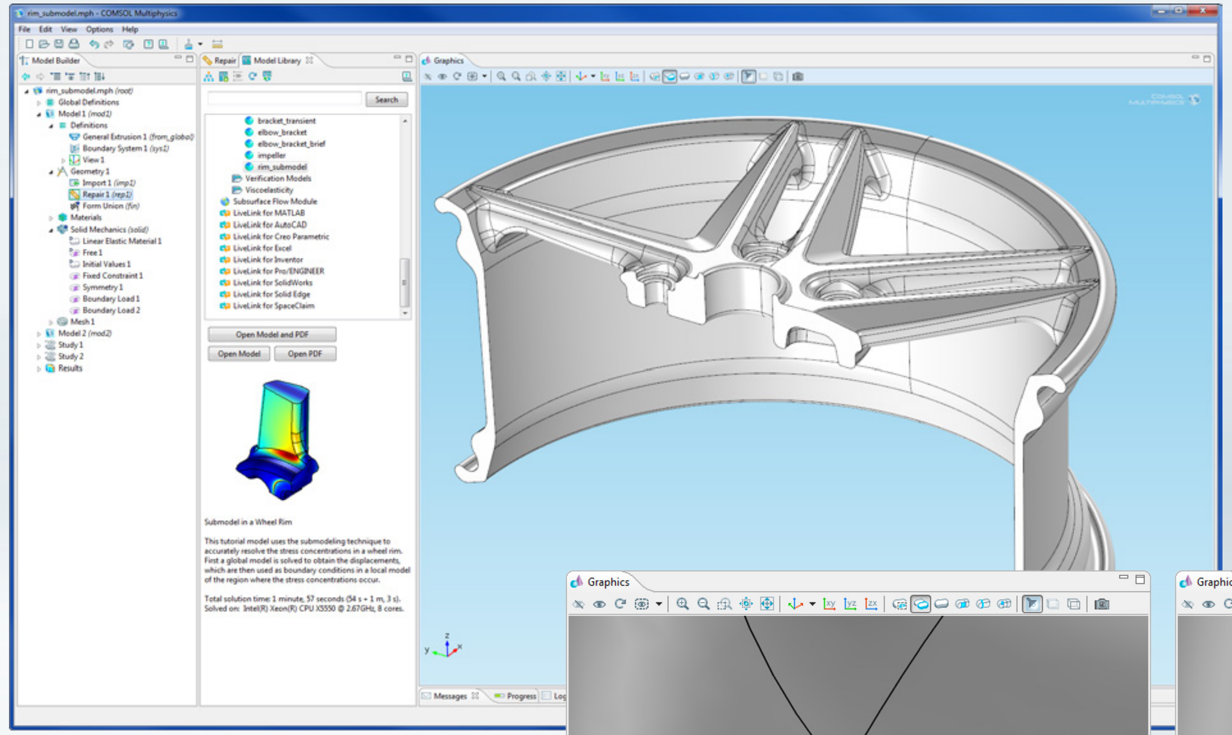
LiveLink™ Products for CAD

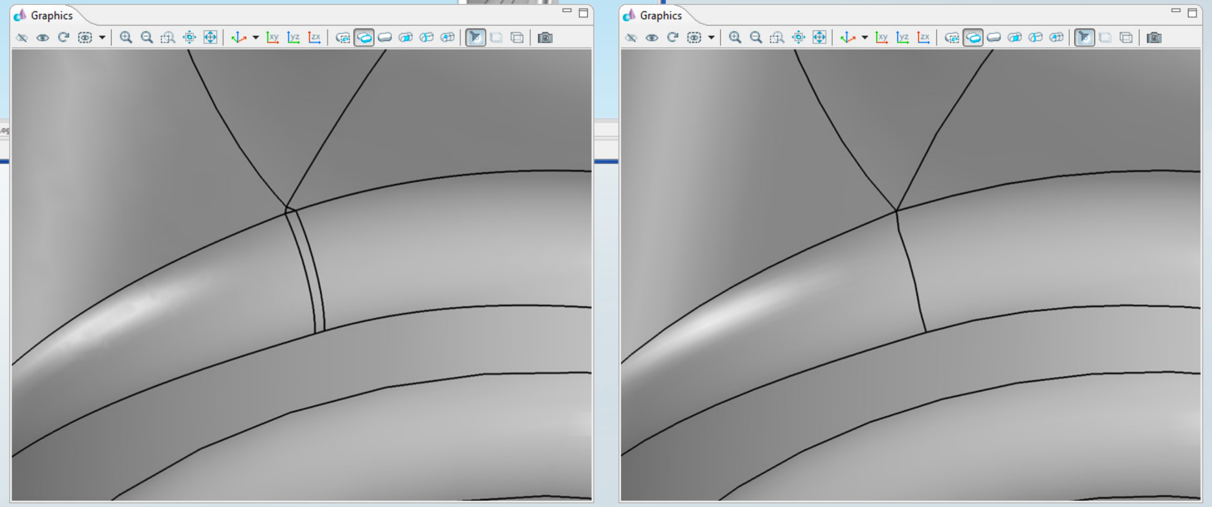
All the capabilities of the CAD Import Module are also available in the LiveLink products for SolidWorks®, SpaceClaim®, Inventor®, AutoCAD®, Creo™ Parametric, Pro/ENGINEER® and Solid Edge® CAD systems, all of which deliver further seamless integration between your CAD designs and multiphysics simulations. With these products, changing a feature in the CAD design automatically updates the geometry in COMSOL Multiphysics, while retaining the physics settings. This enables simulations that involve sweeps of the geometric parameters, and allows you to optimize your designs directly from within COMSOL Multiphysics.

SUPPORTED CAD FILE FORMATS

ACIS® (.sat, .sab, .asat, .asab)
Autodesk Inventor® (.ipt, .iam)
CATIA® V5 (.CATPart, .CATProduct) *
Creo™ Parametric (.prt, .asm)
IGES (.iges, .igs)
Parasolid® (.x_t, .xmt_txt, .x_b, .xmt_bin)
Pro/ENGINEER® (.prt, .asm)
SolidWorks® (.sldprt, .sldasm)
STEP (.step, .stp)

* Requires File Import *for* CATIA® V5.



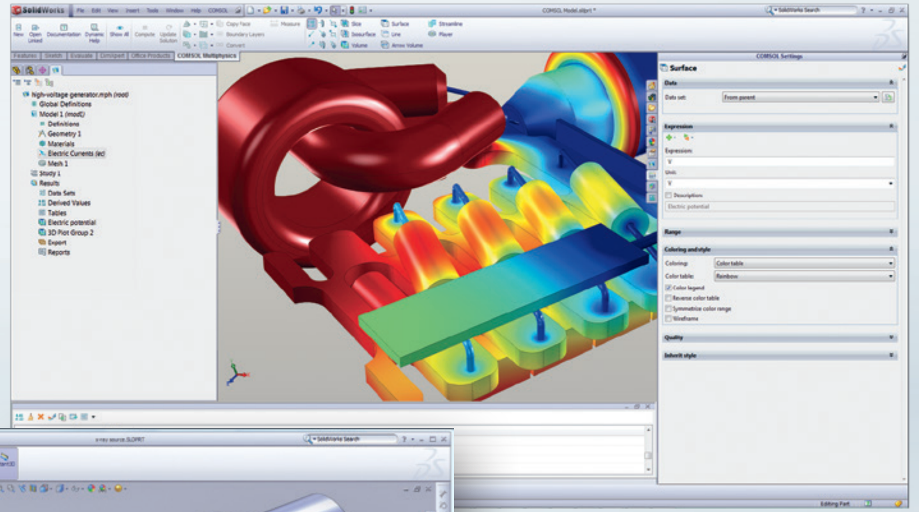


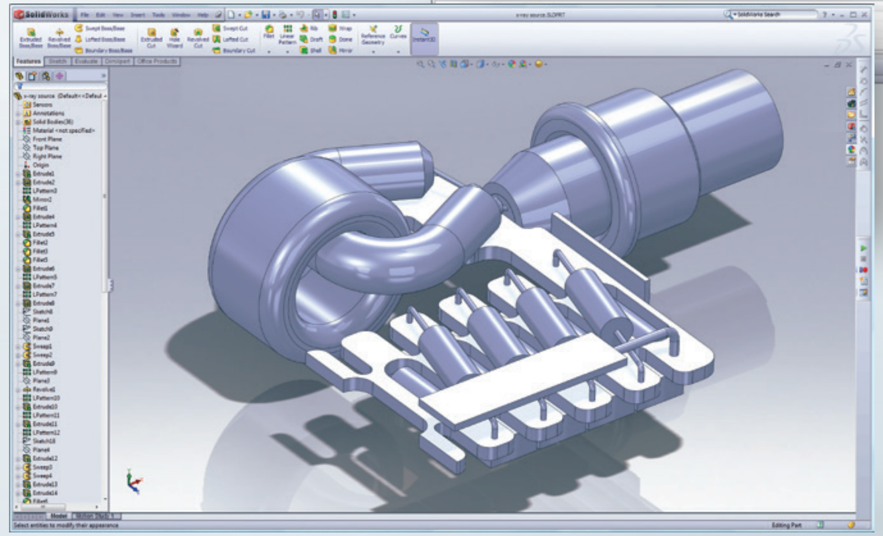
CAD REPAIR
Zooming in on the area around one of the bolt holes reveals a small triangular face adjacent to a sliver face. Two of these can be found around each bolt hole location. These faces can be removed by using the Repair feature. Repaired geometry to the right.

LiveLink™
for SolidWorks®

ONE-WINDOW INTERFACE

LiveLink™ *for* SolidWorks® has been extended with a One-Window Interface where a SolidWorks® CAD system user can stay inside its environment and work synchronously with COMSOL Multiphysics.





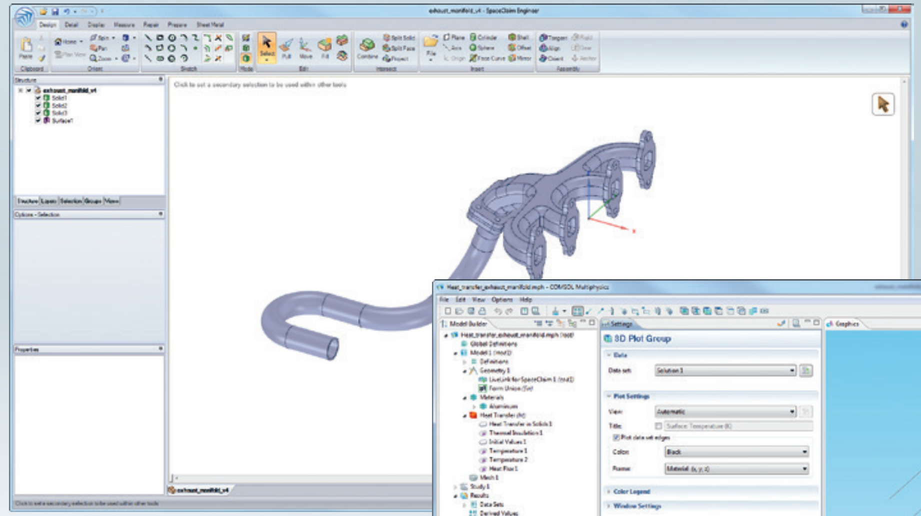
HIGH-VOLTAGE GENERATOR

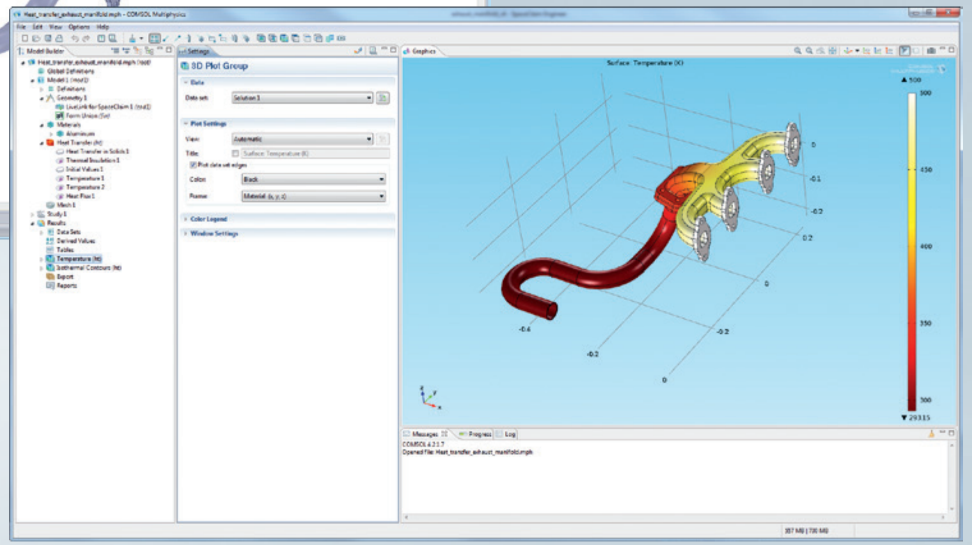
Simulation of the electromagnetic field in a high-voltage generator in an X-ray device. The design is created in SolidWorks® and brought into COMSOL using the LiveLink™ interface. From here, different parts can be selected, physical properties defined, and the model solved.

Model courtesy of Comet AG, Flamatt, Switzerland.

SolidWorks is a registered trademark of Dassault Systèmes SolidWorks Corp.

LiveLink™
for SpaceClaim®





EXHAUST MANIFOLD

Thermal simulation of an exhaust manifold illustrates the fusion of direct modeling and multiphysics simulation in a tightly integrated environment, enabling optimal designs and collaboration across CAD and CAE teams.

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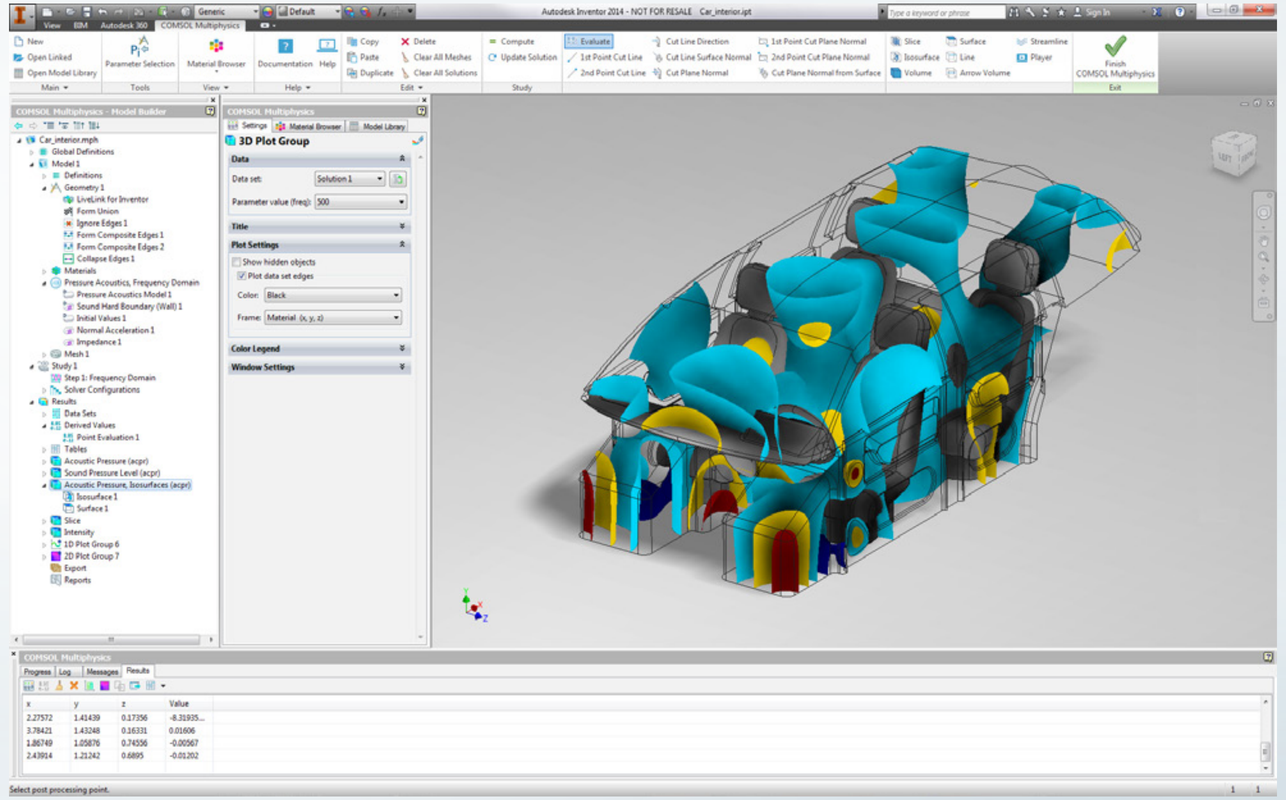
LiveLink™
for Inventor®



ONE-WINDOW INTERFACE

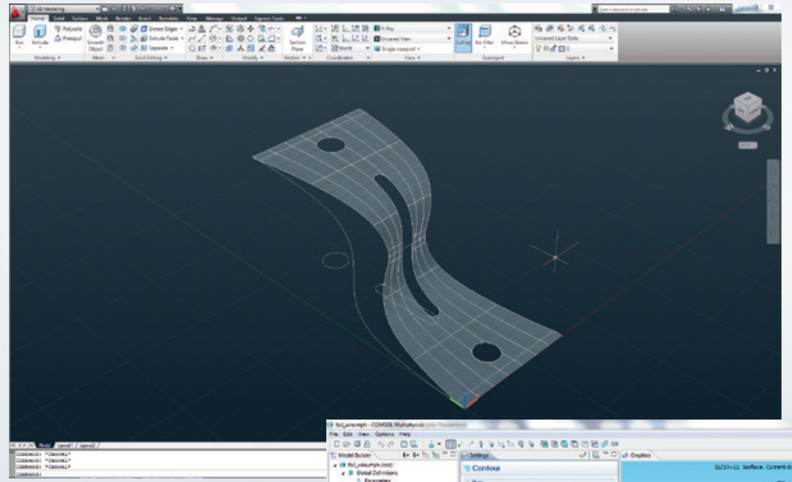
LiveLink™ *for* Inventor® has been extended with a One-Window Interface where Inventor® CAD system users can stay inside its environment and perform their multiphysics analysis directly form it. All of the COMSOL Multiphysics modeling tools are available through the One-Window interface, while changes in geometry are synchronously updated between the two packages.

ACOUSTICS ANALYSIS

Simulation results show the isosurfaces of the acoustic pressure in a car interior. The geometry is created in Inventor® while the simulation is set up and performed using COMSOL Multiphysics.

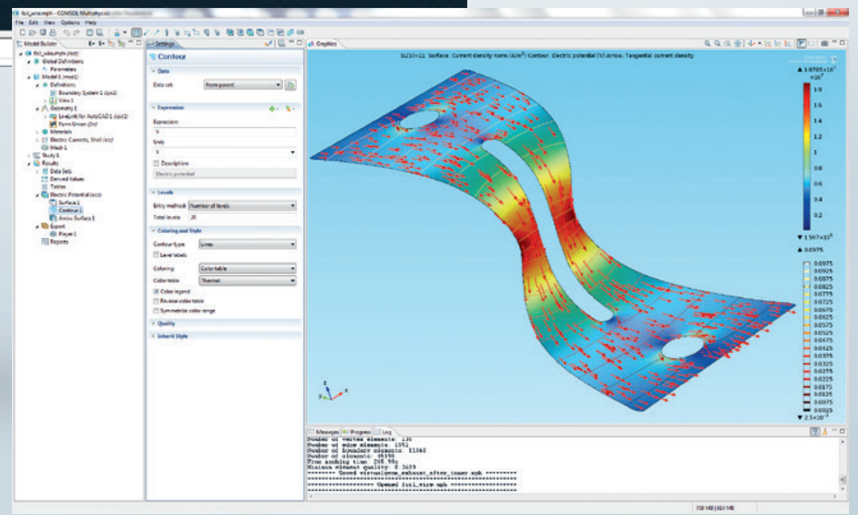
Autodesk Inventor 2012 Certified

LiveLink™
for AutoCAD®



FOIL WIRE CONDUCTOR

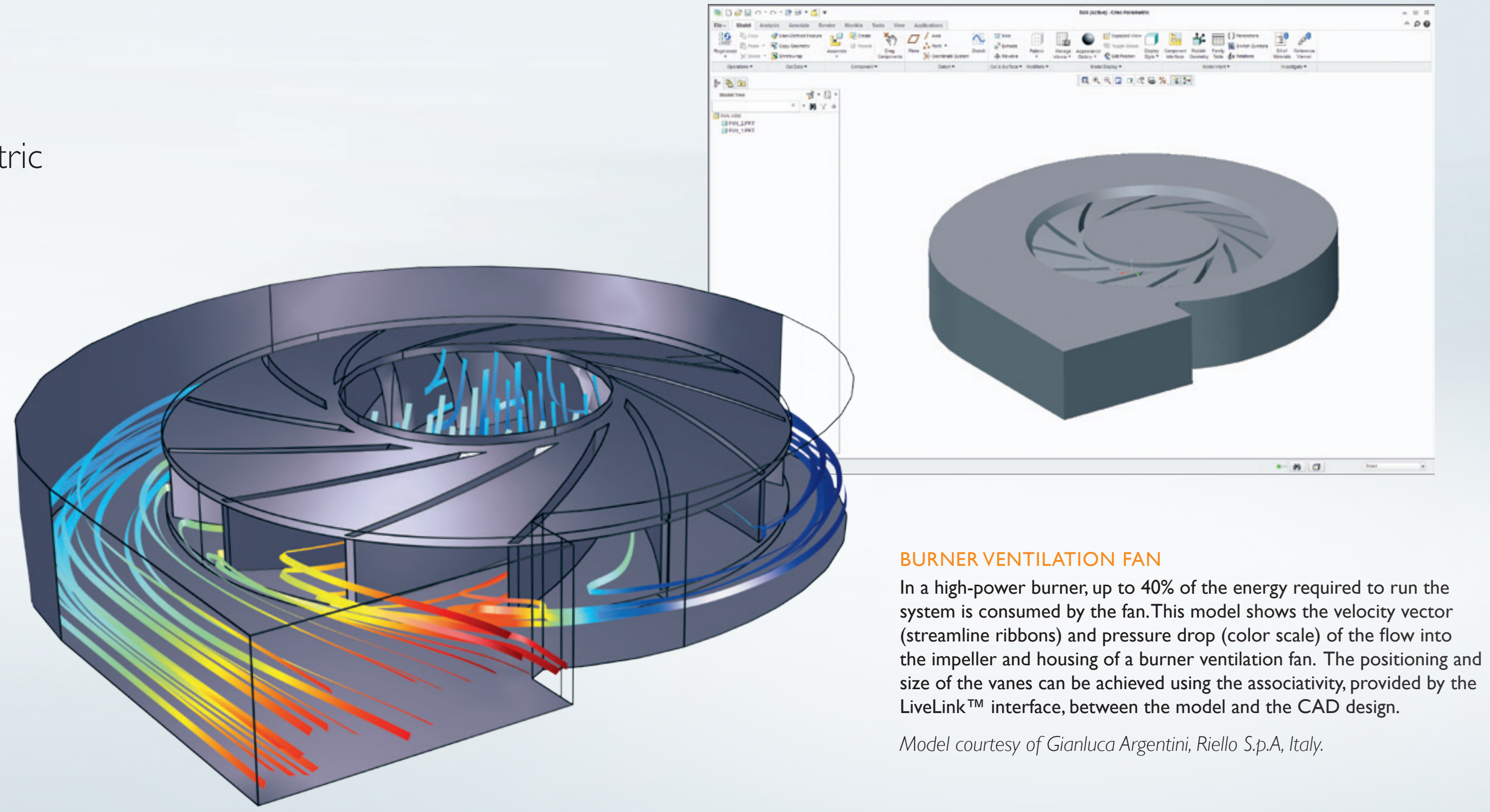
Electric current simulation of a foil wire from a solar collector based on a surface geometry in the AutoCAD® system. An Electric Currents Shell physics interface from the AC/DC Module is applied to the synchronized geometry.



Autodesk
Authorized Developer

LiveLink™

for Creo™ Parametric



BURNER VENTILATION FAN

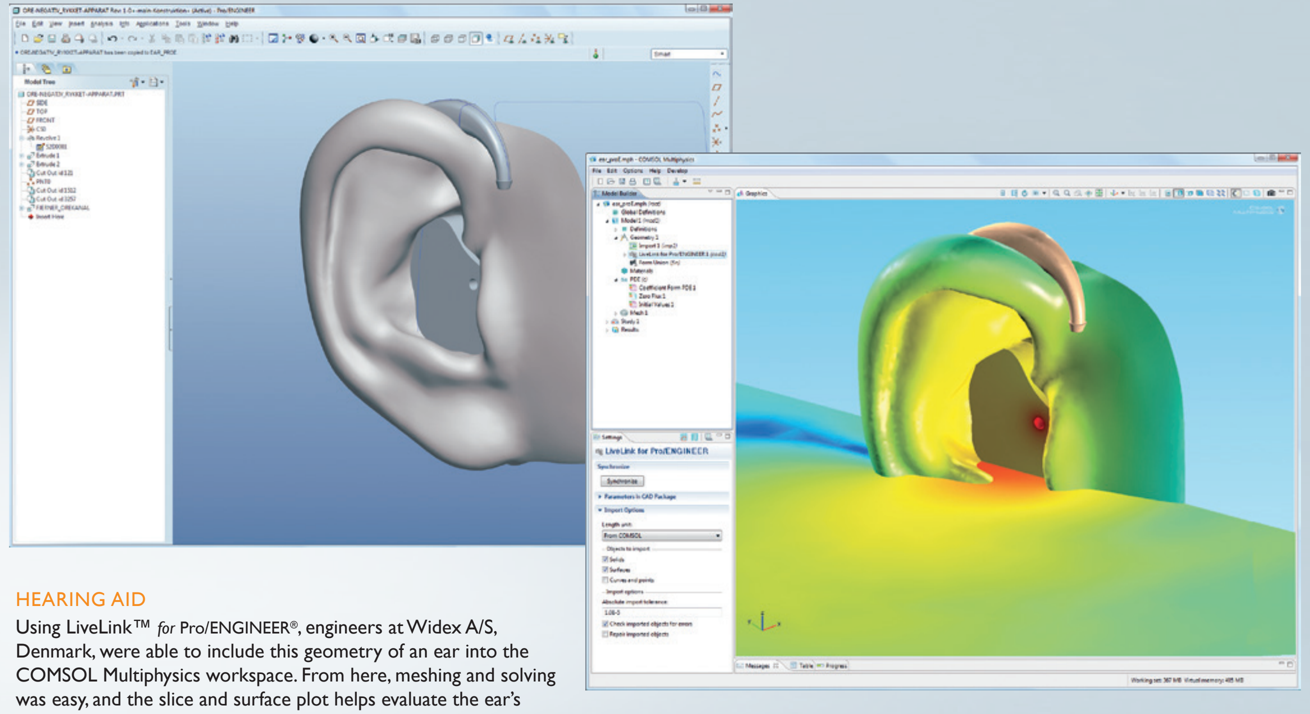
In a high-power burner, up to 40% of the energy required to run the system is consumed by the fan. This model shows the velocity vector (streamline ribbons) and pressure drop (color scale) of the flow into the impeller and housing of a burner ventilation fan. The positioning and size of the vanes can be achieved using the associativity, provided by the LiveLink™ interface, between the model and the CAD design.

Model courtesy of Gianluca Argentini, Riello S.p.A, Italy.

PTC PartnerAdvantage SOFTWARE/Gold

LiveLink™

for Pro/ENGINEER®

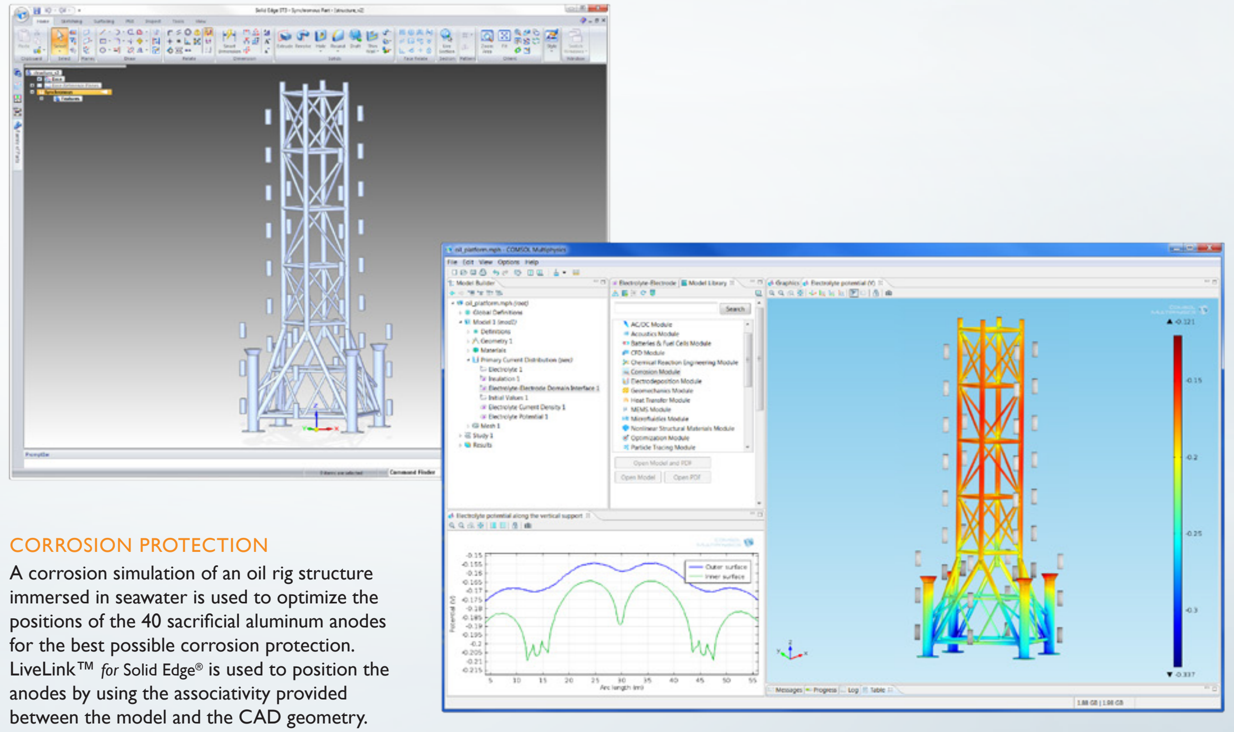


HEARING AID

Using LiveLink™ *for* Pro/ENGINEER®, engineers at Widex A/S, Denmark, were able to include this geometry of an ear into the COMSOL Multiphysics workspace. From here, meshing and solving was easy, and the slice and surface plot helps evaluate the ear's shadow effect at 1 kHz.

PTC PartnerAdvantage SOFTWARE/Gold

LiveLink™
for Solid Edge®



CORROSION PROTECTION
A corrosion simulation of an oil rig structure immersed in seawater is used to optimize the positions of the 40 sacrificial aluminum anodes for the best possible corrosion protection. LiveLink™ *for* Solid Edge® is used to position the anodes by using the associativity provided between the model and the CAD geometry.

ECAD Import Module

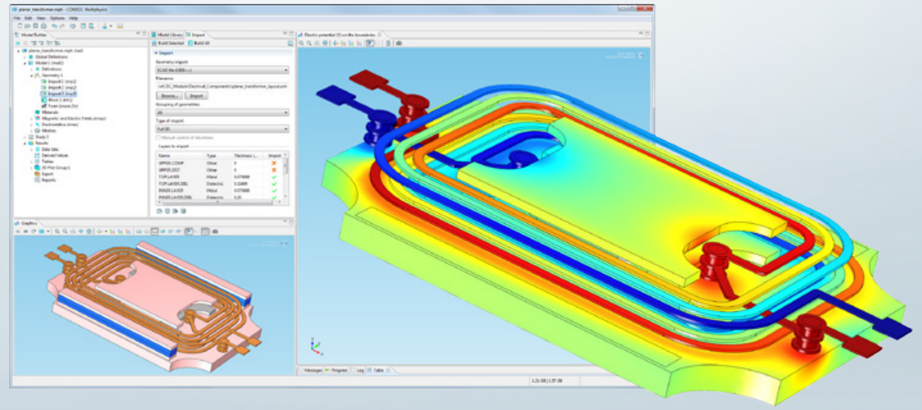
Using the ECAD Import Module, you can bring your ECAD files into COMSOL Multiphysics where the 2D layouts are automatically converted to 3D CAD models. This opens up the world of modeling for simulating, among other applications, the components in integrated circuits, systems of connected MEMS devices, and electronics cooling.

The ECAD Import Module supports the popular GDS-II, ODB++(X), and NETEX-G file formats. As part of the import process, you can select which subset of cells, nets and layers to import. You can also edit layer thicknesses, control the geometric representation of bond wires, and include selected dielectric regions prior to or after importing.

The layout is automatically extruded and converted to a 3D CAD model for use in any kind of COMSOL Multiphysics simulations with any combination of add-on products. The 3D geometry model can further take part in general solid modeling operations in COMSOL Multiphysics. When combined with the CAD Import Module or one of the LiveLink products, the 3D model can be exported to the Parasolid® (.x_b, .x_t) or ACIS® (.sat) file formats, for use in other software.

SUPPORTED ECAD FILE FORMATS

GDS-II (.gds)
ODB++ (X) (.xml)
NETEX-G (.asc)

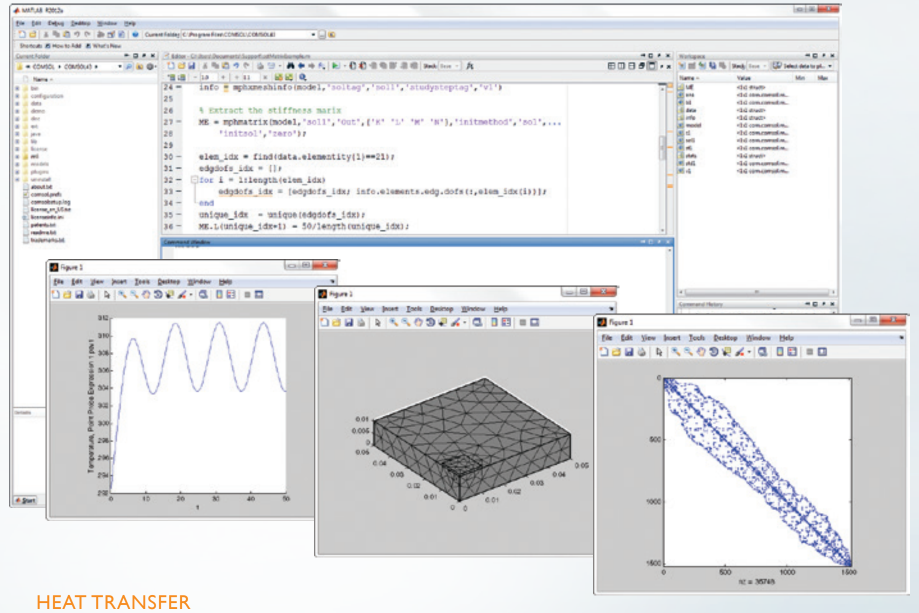


POWER ELECTRONICS
The simulation results show the electric potential on the surface of a planar transformer. The layout is imported from an ODB++(X) file using the ECAD Import Module and is converted to a 3D geometry model.

LiveLink™
for MATLAB®

Seamlessly integrate COMSOL Multiphysics with MATLAB® to extend your modeling with scripting and automatic control system design. LiveLink™ *for* MATLAB® lets you utilize the full power of MATLAB® and its toolboxes in preprocessing, model manipulation, and postprocessing:

- Enhance your in-house MATLAB® code with powerful multiphysics simulations
- Base your geometry modeling on probabilistic or image data
- Perform arbitrary statistical analysis on simulation results
- Use multiphysics models together with genetic or simulated annealing algorithms
- Export COMSOL models on state-space matrix format for incorporating in control systems
- Call MATLAB® functions from the COMSOL Desktop



HEAT TRANSFER

A transient heat transfer model is modified using the LiveLink™ *for* MATLAB®. State-space matrices, mesh and solution data from COMSOL Multiphysics are made available in the MATLAB® workspace, where the state-space model has been run in the MATLAB® environment. The figures show: temperature vs. time, the finite element mesh, and the sparsity pattern of the stiffness matrix.

MathWorks Partner

MathWorks and MATLAB are registered trademarks of The MathWorks, Inc.

LiveLink™
for Excel®

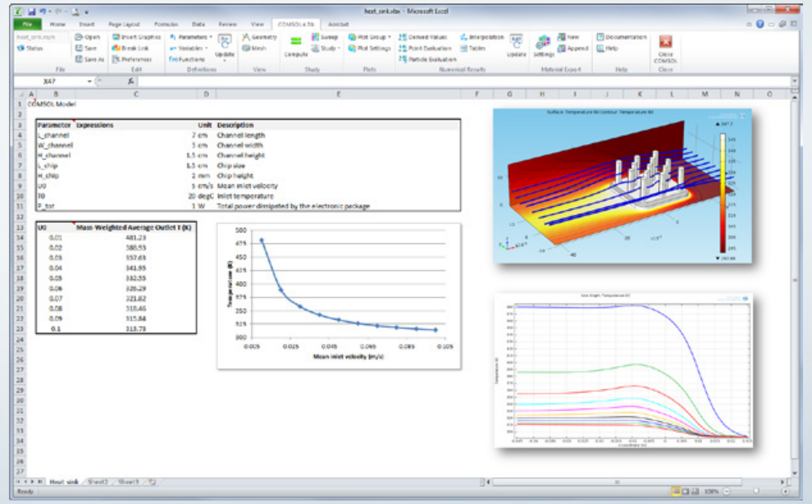
Extend your modeling capacity by running COMSOL Multiphysics simulations from a spreadsheet with LiveLink™ *for* Excel®. Parameters and variables defined and modeled in COMSOL Multiphysics are instantly available in Microsoft® Excel® and automatically synchronized to your physics model.

LiveLink™ *for* Excel® adds a COMSOL Multiphysics tab and specialized toolbar to the Excel® ribbon for controlling the parameters, variables and mesh or for running a simulation. This allows for a simplified workflow where you only display and edit the most important simulation parameters, which can be changed on the fly or as part of an extensive parameter study controlled from Excel®.

Interactive 3D visualizations are presented in a separate dedicated window and COMSOL Multiphysics images and graphs can be embedded into the spreadsheet environment. In addition, LiveLink™ *for* Excel® adds the capability of import/export of Excel® files for parameter and variable lists in the COMSOL Desktop GUI. LiveLink™ *for* Excel® requires Excel® 2007, 2010 or 2013 for Windows®.

SUPPORTED FILE FORMATS

Microsoft Excel® 2013 workbook (.xlsx)
Microsoft Excel® 2010 workbook (.xlsx)
Microsoft Excel® 2007 workbook (.xls)



PARAMETERIZED STUDY

LiveLink™ *for* Excel® is here used for a parameterized simulation of an aluminum heat sink used for the cooling of electric components. The parameters controlling the geometric dimensions as well as the mean inlet air velocity are edited in an Excel® spreadsheet and synchronized to the underlying COMSOL Multiphysics model. A dedicated ribbon tab is added to Excel® for easy access to parameters, variables, functions, geometry, mesh, solvers, and results.

Microsoft, Excel and Windows are either registered trademarks or trademarks of Microsoft Corporation in the USA and/or other countries.

AC/DC

	COMSOL Multiphysics	AC/DC Module	Acoustics Module	Batteries & Fuel Cells Module	CFD Module	Chemical Reaction Engineering Module	Corrosion Module	Electrochemistry Module	Electrodeposition Module	Fatigue Module	Geomechanics Module	Heat Transfer Module	MEMS Module	Microfluidics Module	Molecular Flow Module	Multibody Dynamics Module	Nonlinear Structural Materials Module	Optimization Module	Particle Tracing Module	Pipe Flow Module	Plasma Module	RF Module	Semiconductor Module	Structural Mechanics Module	Subsurface Flow Module	Wave Optics Module
Physics and Study Types																										
Charged Particle Tracing																			●							
Electric Currents, Shell		●																								
Electrical Circuit		●											●								●	●				
Magnetic and Electric Fields		●																								
Magnetic Field Formulation		●																								
Magnetic Fields, No Currents		●																								
Rotating Machinery in 2D and 3D, Magnetic		●																								
Electric Currents with Current Conservation	●																									
Frequency Domain and Time Dependent		●																								
Stationary	●																									
Electrostatics with Charge Conservation	●																									
Frequency Domain		●																					●			
Stationary and Time Dependent	●																									
Magnetic Fields	●																									
Stationary and Frequency Domain in 2D	●																									
Stationary, Frequency Domain and Time Dependent in 2D, Axisymmetry, and 3D		●																								
Boundary Conditions																										
Circuit Terminal, Distributed Capacitance and Impedance, Dielectric Shielding, Floating Potential		●											●								●		●			
Contact Resistance, Periodic Boundary Condition	●																									
Fundamental Voltage, Current, and Magnetic Boundary Conditions	●																									
Lumped Port, Magnetic Shielding, Surface Impedance, Thin Low Permeability Gap, Electrical Contact, Surface Magnetic Current		●																								
Charged Particle Tracing																										
Boundary Conditions: Bounce, Diffuse Reflection, Disappear, Freeze, Inlet, Outlet, Particle Continuity, Secondary Emission, Stick																			●							
Formulation: Massless and Newtonian																			●							
Particle Properties and Forces: Auxiliary Dependent Variables, Elastic Collisional Force, Electric Force, General Force, Magnetic Force, Particle-Field Interaction, Particle-Particle Interaction																			●							
Particle Release: Density and Mesh Based, Release from Grid, Uniform Distribution																			●							

AC/DC *(continued)*

	COMSOL Multiphysics	AC/DC Module	Acoustics Module	Batteries & Fuel Cells Module	CFD Module	Chemical Reaction Engineering Module	Corrosion Module	Electrochemistry Module	Electrodeposition Module	Fatigue Module	Geomechanics Module	Heat Transfer Module	MEMS Module	Microfluidics Module	Molecular Flow Module	Multibody Dynamics Module	Nonlinear Structural Materials Module	Optimization Module	Particle Tracing Module	Pipe Flow Module	Plasma Module	RF Module	Semiconductor Module	Structural Mechanics Module	Subsurface Flow Module	Wave Optics Module
Edge and Point Conditions																										
Edge/Line and Point Currents and Charges	●																									
Electric Point Dipole		●											●													
Magnetic Point Dipole		●																								
Electrical Circuit																										
Import of SPICE Netlist and Circuit Element Modeling		●											●								●	●	●			
Lumped Parameters																										
Capacitance, Impedance, Admittance, and S-Parameter Matrix Calculation		●											●								●					
Inductance Matrix Calculation		●																								
Touchstone File Export		●											●													
Volumetric Domain Properties																										
1D, 2D, Axisymmetric, and 3D Formulations	●																									
Coil Excitation in 2D, Axisymmetry, and 3D		●																								
Electric Force and Torque; Electric Infinite Domain Modeling with Infinite Elements		●											●								●					
Electromagnetic Force and Torque		●																								
Magnetic Infinite Domain Modeling with Infinite Elements; Reduced Potential		●																								
Porous Media and Mixture Materials		●																								
Constitutive Relations																										
Anisotropic Materials; BH Curve	●																									
Constitutive Relationships for Magnetic Fields, 3D		●																								

Acoustics

	COMSOL Multiphysics	AC/DC Module	Acoustics Module	Batteries & Fuel Cells Module	CFD Module	Chemical Reaction Engineering Module	Corrosion Module	Electrochemistry Module	Electrodeposition Module	Fatigue Module	Geomechanics Module	Heat Transfer Module	MEMS Module	Microfluidics Module	Molecular Flow Module	Multibody Dynamics Module	Nonlinear Structural Materials Module	Optimization Module	Particle Tracing Module	Pipe Flow Module	Plasma Module	RF Module	Semiconductor Module	Structural Mechanics Module	Subsurface Flow Module	Wave Optics Module
Physics and Study Types																										
Acoustic-Structure Interaction																										
Acoustic-Piezoelectric Interaction (Eigenfrequency, Frequency Domain, and Time Dependent)			●																							
Acoustic-Shell Interaction* (Eigenfrequency, Frequency Domain, and Time Dependent)			●																					●		
Acoustic-Solid Interaction (Eigenfrequency, Frequency Domain, and Time Dependent)			●																							
Elastic waves (Eigenfrequency and Frequency Domain)			●																							
Pipe Acoustics (Eigenfrequency, Frequency Domain, and Time Dependent)			●																	●						

* Requires all indicated products.

	COMSOL Multiphysics	AC/DC Module	Acoustics Module	Batteries & Fuel Cells Module	CFD Module	Chemical Reaction Engineering Module	Corrosion Module	Electrochemistry Module	Electrodeposition Module	Fatigue Module	Geomechanics Module	Heat Transfer Module	MEMS Module	Microfluidics Module	Molecular Flow Module	Multibody Dynamics Module	Nonlinear Structural Materials Module	Optimization Module	Particle Tracing Module	Pipe Flow Module	Plasma Module	RF Module	Semiconductor Module	Structural Mechanics Module	Subsurface Flow Module	Wave Optics Module
Acoustics *(continued)*																										
Poroelastic Waves (Eigenfrequency and Frequency Domain)			•																							
Aeroacoustics																										
Aeroacoustics (Frequency Domain and Time Dependent)			•																							
Aeroacoustics with Flow (Frequency Domain and Time Dependent)			•																							
Boundary Mode Aeroacoustics			•																							
Compressible Potential Flow (Stationary and Time Dependent)			•																							
Pressure Acoustics																										
Boundary Mode Acoustics			•																							
Pressure Acoustics	•																									
Eigenfrequency and Frequency Domain	•																									
Time Dependent			•																							
Thermoacoustics																										
Thermoacoustic-Shell Interaction (Eigenfrequency and Frequency Domain)*			•																					•		
Thermoacoustic-Solid Interaction (Eigenfrequency and Frequency Domain)			•																							
Thermoacoustics (Eigenfrequency and Frequency Domain)			•																							
Boundary Conditions																										
Edge and Point Conditions: Flow, Power, Gaussian, Intensity, Edge, and Point Source			•																							
Far Field Calculation			•																							
Impedance, Periodic, Sound Hard, and Soft Boundary Conditions	•																									
Pipe Acoustics: Edge and Point Properties*			•																	•						
Pressure Acoustics: Matched Boundary, Perforated Plate			•																							
Pressure Acoustics: Normal Acceleration, Radiation Boundary Conditions	•																									
Symmetry, Periodic Condition with Cyclic Symmetry and Floquet Periodicity			•																							
Thermoacoustics: Mechanical, Thermal, and Pressure Boundary Conditions			•																							
Volumetric Domain Properties																										
1D, 2D, Axisymmetric, and 3D Formulations	•																									
Background Pressure Field for Scattered Field Analysis in Pressure Acoustics			•																							

* Requires all indicated products.

	COMSOL Multiphysics	AC/DC Module	Acoustics Module	Batteries & Fuel Cells Module	CFD Module	Chemical Reaction Engineering Module	Corrosion Module	Electrochemistry Module	Electrodeposition Module	Fatigue Module	Geomechanics Module	Heat Transfer Module	MEMS Module	Microfluidics Module	Molecular Flow Module	Multibody Dynamics Module	Nonlinear Structural Materials Module	Optimization Module	Particle Tracing Module	Pipe Flow Module	Plasma Module	RF Module	Semiconductor Module	Structural Mechanics Module	Subsurface Flow Module	Wave Optics Module
Acoustics *(continued)*																										
Fluid Models for Pressure Acoustics: Ideal Gas, Linear Elastic with Attenuation, Viscous, Thermally Conducting, Biot Equivalent (J.C.A.), Delany-Bazley, and Miki			•																							
Infinite Acoustic Domain Modeling with Perfectly Matched Layers			•																							
Infinite Solid Domain Modeling with Perfectly Matched Layers			•										•											•		
Monopole and Dipole Source for Pressure Acoustics	•																									
Poroelastic Material: Isotropic, Orthotropic, or Anisotropic			•																							
Chemical Species Transport																										
Physics and Study Types																										
Nernst-Planck Equations						•																				
Reacting Flow in Porous Media, Diluted and Concentrated Species				•	•	•																				
Reacting Flow, Laminar Flow						•																				
Reacting Flow, Turbulent Flow: k-epsilon, k-omega, Low-Re k-epsilon					•																					
Reaction Engineering with Chemical Reaction Equations						•																				
Solute Transport																									•	
Species Transport in Porous Media				•		•	•	•	•					•												
Surface Reactions				•		•	•	•	•																	
Transport of Concentrated Species				•	•	•																				
Transport of Diluted Species	•																									
Reacting Pipe Flow																				•						
Add-on for Multiple-Species User Interface				•	•	•	•		•					•											•	
Transport of Diluted Species in Pipes																				•						
Add-on for Multiple-Species User Interface				•	•	•	•		•					•											•	
Boundary Conditions																										
Current Density, Electric Potential and Insulation						•																				
Electrochemical Reactions				•			•	•	•																	
Flow Boundary Volatilization				•		•	•	•	•					•											•	
Fundamental Concentration and Flux Boundary Conditions	•																									
Inflow and Outflow	•																									
Inflow with Mixture Specification				•	•	•																				
Mass Fraction				•	•	•																				
Open Boundary				•	•	•	•	•	•																•	
Reacting Boundary				•	•	•																				
Surface Properties				•		•	•	•	•																	

More specifications on www.comsol.com/products/specifications

Chemical Species Transport *(continued)*

	COMSOL Multiphysics	AC/DC Module	Acoustics Module	Batteries & Fuel Cells Module	CFD Module	Chemical Reaction Engineering Module	Corrosion Module	Electrochemistry Module	Electrodeposition Module	Fatigue Module	Geomechanics Module	Heat Transfer Module	MEMS Module	Microfluidics Module	Molecular Flow Module	Multibody Dynamics Module	Nonlinear Structural Materials Module	Optimization Module	Particle Tracing Module	Pipe Flow Module	Plasma Module	RF Module	Semiconductor Module	Structural Mechanics Module	Subsurface Flow Module	Wave Optics Module
Surface Reaction for Reaction Engineering						•																				
Thin Diffusion Barrier	•																									
Thin Impermeable Barrier	•																									
Volumetric Domain Properties																										
1D, 2D, Axisymmetric, and 3D Formulations	•																									
Effective Mass Transport Parameters: Bruggeman and User Defined				•	•	•																				
Electrochemical Reactions				•			•	•	•																	
Infinite Domain Modeling with Infinite Elements						•																				
Isotropic and Anisotropic Diffusion	•																									
Migration in Electric Field				•		•	•	•	•					•												
Mobile Liquid, Immobile Solid and Gas				•		•	•	•	•					•											•	
Multiple-Species User Interface				•	•	•	•	•	•					•											•	
Reactions	•																									
Reactions and Species for Reaction Engineering						•																				
Turbulent Mixing					•																					
Wall Mass Transfer, Pipe-Domain Coupling																				•						
Diffusion-Models for Transport of Concentrated Species																										
Fick's Law				•	•	•																				
Maxwell-Stefan				•		•																				
Mixture-Averaged				•	•	•																				

Electrochemistry

Physics and Study Types

	COMSOL Multiphysics	AC/DC Module	Acoustics Module	Batteries & Fuel Cells Module	CFD Module	Chemical Reaction Engineering Module	Corrosion Module	Electrochemistry Module	Electrodeposition Module	Fatigue Module	Geomechanics Module	Heat Transfer Module	MEMS Module	Microfluidics Module	Molecular Flow Module	Multibody Dynamics Module	Nonlinear Structural Materials Module	Optimization Module	Particle Tracing Module	Pipe Flow Module	Plasma Module	RF Module	Semiconductor Module	Structural Mechanics Module	Subsurface Flow Module	Wave Optics Module
Battery with Binary Electrolyte				•																						
Corrosion, Secondary							•																			
Corrosion, Tertiary, Nernst-Planck							•																			
Electroanalysis				•			•	•	•																	
Electrode, Shell				•			•	•	•																	
Electrodeposition, Secondary									•																	
Electrodeposition, Tertiary, Nernst-Planck									•																	
Lead-Acid Battery				•																						
Lithium-Ion Battery				•																						
Primary Current Distribution				•			•	•	•																	
Secondary Current Distribution				•			•	•	•																	
Tertiary Current Distribution, Nernst-Planck				•			•	•	•																	

Electrochemistry *(continued)*

	COMSOL Multiphysics	AC/DC Module	Acoustics Module	Batteries & Fuel Cells Module	CFD Module	Chemical Reaction Engineering Module	Corrosion Module	Electrochemistry Module	Electrodeposition Module	Fatigue Module	Geomechanics Module	Heat Transfer Module	MEMS Module	Microfluidics Module	Molecular Flow Module	Multibody Dynamics Module	Nonlinear Structural Materials Module	Optimization Module	Particle Tracing Module	Pipe Flow Module	Plasma Module	RF Module	Semiconductor Module	Structural Mechanics Module	Subsurface Flow Module	Wave Optics Module
Boundary Conditions																										
Corroding Electrode Surface with Thickness and Composition; Infinite Electrolyte							•																			
Depositing Electrode Surface with Thickness and Composition									•																	
Electric Reference Potential and Reference Electrode at Edges and Points				•			•	•	•																	
Insulation, Periodic, and Symmetry Conditions				•			•	•	•																	
Electrode Current and Potential Boundary Conditions				•			•	•	•																	
Power Boundary Condition				•																						
Electrode																										
Current, Current Density, Electrode Power, Ground, Potential				•			•	•	•																	
Electrolyte																										
Concentration, Flux, Current, and Potential Boundary Conditions				•			•	•	•																	
Inflow and Outflow				•			•	•	•																	
Electrolyte-Electrode Domain and Boundary Interface				•			•	•	•																	
Double Layer Capacitance and Electrode Reaction				•			•	•	•																	
Film Resistance				•			•	•	•																	
Volumetric Domain Properties																										
1D, 2D, Axisymmetric, and 3D Formulations				•			•	•	•																	
Current and Species Transport in Concentrated Binary Electrolytes				•																						
Effective Transport Parameter Correction: Bruggeman or User Defined				•																						
Electronic and Ionic Current Source				•			•	•	•																	
Infinite Domain Modeling with Infinite Elements				•			•	•	•																	
Intercalating Species (Li, Hydrogen, or other)				•																						
Porous Electrode Reaction and Double Layer Capacitance				•			•	•	•																	
Lead-Acid Battery																										
Electrolyte Reservoir and Separator				•																						
Negative and Positive Porous Electrode				•																						
Li-Ion Battery																										
Concentrated Binary Electrolyte				•																						
Li Intercalation and Additional Intercalating Material				•																						
Negative and Positive Porous Electrodes				•																						
Solid Electrolyte Interface (SEI)				•																						

Fluid Flow

	COMSOL Multiphysics	AC/DC Module	Acoustics Module	Batteries & Fuel Cells Module	CFD Module	Chemical Reaction Engineering Module	Corrosion Module	Electrochemistry Module	Electrodeposition Module	Fatigue Module	Geomechanics Module	Heat Transfer Module	MEMS Module	Microfluidics Module	Molecular Flow Module	Multibody Dynamics Module	Nonlinear Structural Materials Module	Optimization Module	Particle Tracing Module	Pipe Flow Module	Plasma Module	RF Module	Semiconductor Module	Structural Mechanics Module	Subsurface Flow Module	Wave Optics Module
Physics and Study Types																										
Fluid-Structure Interaction, One-Way and Two-Way Coupled (Stationary and Time Dependent)													●											●		
Molecular Flow															●											
Particle Tracing for Fluid Flow (Time Dependent)																			●							
Slip Flow														●												
Transitional Flow															●											
High Mach Number Flow (Stationary and Time Dependent)																										
Laminar Flow					●																					
Turbulent Flow, k-epsilon and Spalart-Allmaras					●																					
Non-Isothermal Flow (Stationary and Time Dependent)																										
Laminar					●							●														
Non-Isothermal Pipe Flow																				●						
Turbulent Flow, k-epsilon and Low-Reynolds k-epsilon					●							●														
Turbulent Flow, k-omega					●																					
Turbulent Flow, Spalart-Allmaras					●																					
Porous Media and Subsurface Flow (Stationary and Time Dependent)																										
Fracture Flow																									●	
Free and Porous Media Flow, Darcy's Law, Brinkman Equations				●	●	●	●	●	●					●											●	
Richards Equation																									●	
Two-Phase Darcy's Law					●																					
Single-Phase Flow																										
Creeping Flow (Stationary and Time Dependent)					●									●											●	
Laminar Flow (Stationary and Time Dependent)	●																									
Pipe Flow (Stationary and Time Dependent)																				●						
Rotating Machinery, Laminar and Turbulent Flow k-epsilon, Low-Reynolds k-epsilon, k-omega (Time Dependent)					●																					
Turbulent Flow, k-epsilon and Low-Reynolds k-epsilon (Stationary and Time Dependent)					●							●														
Turbulent Flow, k-omega (Stationary and Time Dependent)					●																					
Turbulent Flow, Spalart-Allmaras (Stationary and Time Dependent)					●																					
Turbulent Flow, SST (Stationary and Time Dependent)					●																					
Water Hammer (Time Dependent)																				●						

Fluid Flow *(continued)*

	COMSOL Multiphysics	AC/DC Module	Acoustics Module	Batteries & Fuel Cells Module	CFD Module	Chemical Reaction Engineering Module	Corrosion Module	Electrochemistry Module	Electrodeposition Module	Fatigue Module	Geomechanics Module	Heat Transfer Module	MEMS Module	Microfluidics Module	Molecular Flow Module	Multibody Dynamics Module	Nonlinear Structural Materials Module	Optimization Module	Particle Tracing Module	Pipe Flow Module	Plasma Module	RF Module	Semiconductor Module	Structural Mechanics Module	Subsurface Flow Module	Wave Optics Module
Thin-Film Flow (Stationary, Time Dependent, Eigenfrequency, Frequency Domain)																										
Modified Reynolds Equation (Gas & Rarefied Gas Flow)													●													
Reynolds Equation (Liquid or Gas Flow)					●								●													
Two-Phase Flow																										
Bubbly Flow, Laminar and Turbulent (Stationary and Time Dependent)					●																					
Euler-Euler Model, Laminar					●																					
Level Set or Phase Field, Laminar (Transient)					●									●												
Level Set or Phase Field, Turbulent (Transient)					●																					
Mixture Model, Laminar and Turbulent (Stationary and Time Dependent)					●																					
Moving Mesh, Laminar (Transient)														●												
Boundary Conditions																										
Atmosphere/Gauge																									●	
Boundary Stress, Open Boundary, Normal Stress or No Viscous Stress, Periodic Flow Condition; Symmetry Boundary Condition	●																									
Electrode-Electrolyte Interface Coupling, Porous Media				●			●		●																	
Grille and Fan												●														
Initial Interface, Two-Phase Flow					●									●												
Molecular Flow: Diffuse Flux, Evaporation, Number Density Reconstruction, Reservoir, Surface Temperature, Total Vacuum, Vacuum Pump															●											
Porous Media: Flux Discontinuity, Inflow Boundary, Mass Flux, No Flow, Pressure				●	●	●	●		●					●											●	
Porous Media: Hydraulic or Pressure Head; Pervious Layer																									●	
Two-Phase Flow Moving Mesh: External Fluid, Fluid-Fluid, and Wall-Fluid Interface; Navier Slip														●												
Inlet																										
Laminar Flow with Average Velocity, Volumetric Flow Rate or Pressure				●	●	●			●			●		●							●				●	
Mass Flow Rate and Mass Flux					●									●							●					
Standard Mass Flow Rate (SCCM)					●									●						●	●					
Turbulent Flow					●							●														
Velocity, Pressure, Normal Stress	●																									
Outlet																										
Laminar Flow with Average Velocity, Flow Rate or Pressure				●	●				●			●		●							●				●	

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Fluid Flow *(continued)*																										
Pressure, Stress, Velocity	●																									
Vacuum Pump					●																●					
Vacuum Pump, Outgassing Wall, and Diffuse Flux (Free Molecular Flow and Transitional Flow)														●												
Wall																										
Electroosmotic Velocity														●												
Interior Wall for Single Phase Flow: Moving, Slip, No Slip					●							●														
Molecular Flow: Adsorption/Desorption, Deposition, Outgassing Wall, Wall															●											
Rotating Wall					●																					
Slip or No Slip, Sliding, Moving or Leaking Wall	●																									
Slip Velocity using Viscous Slip and Thermal Creep					●									●							●					
Turbulent Flow Wall Functions					●							●														
Wetted Wall and Moving Wetted Wall					●									●												
Edge and Point Conditions																										
Molecular Flow: Number Density Reconstruction															●											
Non-Isothermal Pipe Flow with Viscous Heating																				●						
Pipe Flow Boundary Conditions at Points: Bend, No Flow, Contraction/Expansion, Local Friction Loss, Pump, T-Junction, Valve, Inlet, Outlet, Pressure																				●						
Pipe Flow Fluid Models: Newtonian, Bingham, Power Law, Gas-Liquid																				●						
Pressure Point Constraint	●																									
Thin-Film Flow Inlet, Outlet, Symmetry, Wall, Border					●								●													
Particle Tracing																										
Boundary Conditions: Bounce, Diffuse Reflection, Disappear, Freeze, General Reflection, Inlet, Outlet, Secondary Emission, Stick																			●							
Formulation: Massless, Newtonian																			●							
Particle Forces: Acoustophoretic, Brownian, Dielectrophoretic, Drag, Electric, General, Gravity, Magnetic, Magnetophoretic, Thermophoretic																			●							
Particle Properties: Auxiliary Dependent Variables, Fluid-Particle Interaction, Particle-Particle Interaction																			●							
Particle Release: Density and Mesh Based, Release from Grid, Uniform Distribution																			●							
Volumetric Domain Properties																										
1D Formulations for Porous Media Flow				●	●	●	●	●	●					●											●	
1D, 2D, Axisymmetric, and 3D Formulations	●																									

	COMSOL Multiphysics	AC/DC Module	Acoustics Module	Batteries & Fuel Cells Module	CFD Module	Chemical Reaction Engineering Module	Corrosion Module	Electrochemistry Module	Electrodeposition Module	Fatigue Module	Geomechanics Module	Heat Transfer Module	MEMS Module	Microfluidics Module	Molecular Flow Module	Multibody Dynamics Module	Nonlinear Structural Materials Module	Optimization Module	Particle Tracing Module	Pipe Flow Module	Plasma Module	RF Module	Semiconductor Module	Structural Mechanics Module	Subsurface Flow Module	Wave Optics Module
Fluid Flow *(continued)*																										
Forchheimer Drag				●	●	●	●	●	●					●											●	
Gravity Effects																									●	
Mass Transfer, Bubbly Flow and Mixture Model					●																					
Pressure Work, Non-Isothermal Flow					●							●														
Shallow Channel Approximation, 2D					●									●												
Surface Tension Effects					●									●												
Swirl Flow, Axisymmetric, Laminar and Turbulent					●																					
Viscous Heating, Non-Isothermal Flow					●							●														
Volume Force and Gravity	●																									
Fluid-Structure Interaction (FSI)													●											●		
Laminar Fluid Model	●																									
Microfluidics Fluid Model, Creeping Flow					●									●												
Turbulent Flow					●							●														
Fluid Properties																										
Non-Newtonian																										
Carreau Model and Power Law					●									●												
User-Defined Model	●																									
Porous Media																										
Fluid and Matrix Properties, Brinkman Equations				●	●	●	●	●	●					●											●	
Mass Source				●	●	●	●	●	●					●											●	
Porous Electrode Coupling				●			●	●	●																	
Richards' Equation and Storage Model, Isotropic and Anisotropic																									●	
Darcy's Law, Isotropic and Anisotropic				●	●	●	●	●	●					●											●	
Hydraulic Head and Pressure Head																									●	
Heat Transfer																										
Physics and Study Types																										
Electromagnetic Heating																										
Induction Heating (Frequency-Stationary, Frequency-Transient, Stationary, Time Dependent)		●																								
Fundamental Heat Transfer in Solids and Fluids	●																									
Heat Transfer in Solids and Fluids from Heat Transfer Module												●														
Joule Heating	●																									
Frequency-Stationary or Frequency-Transient		●																								
Stationary	●																									
Time Dependent	●																									

	COMSOL Multiphysics	AC/DC Module	Acoustics Module	Batteries & Fuel Cells Module	CFD Module	Chemical Reaction Engineering Module	Corrosion Module	Electrochemistry Module	Electrodeposition Module	Fatigue Module	Geomechanics Module	Heat Transfer Module	MEMS Module	Microfluidics Module	Molecular Flow Module	Multibody Dynamics Module	Nonlinear Structural Materials Module	Optimization Module	Particle Tracing Module	Pipe Flow Module	Plasma Module	RF Module	Semiconductor Module	Structural Mechanics Module	Subsurface Flow Module	Wave Optics Module
Heat Transfer *(continued)*																										
Electric Current Conservation from AC/DC Module		●																								
Fundamental Electric Current Conservation and Heat Transfer	●																									
Heat Transfer in Solids and Fluids from Heat Transfer Module												●														
Microwave Heating (Frequency-Stationary, Frequency-Transient, Stationary, Time Dependent)																						●				
Fundamental Heat Transfer in Solids and Fluids	●																									
Heat Transfer in Solids and Fluids from Heat Transfer Module												●														
Heat Transfer (Stationary and Time Dependent)																										
Bioheat Transfer												●														
Heat Transfer in Fluids	●																									
Heat Transfer in Pipes																				●						
Heat Transfer in Porous Media				●	●	●	●	●	●			●													●	
Heat Transfer in Solids	●																									
Heat Transfer in Thin Shell												●														
Heat Transfer with Radiation in Participating Media												●														
Heat Transfer with Surface-to-Surface Radiation												●														
Conjugate Heat Transfer, Laminar and Turbulent					●							●														
k-epsilon and Low-Reynolds k-epsilon tubulence model					●							●														
k-omega, Spalart-Allmaras, and SST turbulence model					●																					
Boundary Conditions																										
Convective Heat Flux: Forced and Natural Convection, External and Internal					●							●														
Electrochemical Reaction Heat Flux				●			●		●																	
Heat Flux and Temperature	●																									
Highly Conductive Layer												●														
Inflow Heat Flux, Open Boundary					●							●														
Outflow, Periodic Condition, and Symmetry	●																									
Radiation in Participating Media: Continuity, Incident Intensity, Opaque Surface with Emissivity												●														
Reaction Heat Flux																					●					
Surface-to-Ambient Radiation with Surface Emissivity	●																									
Surface-to-Surface Radiation: Surface Emissivity, Reradiating Surface, Prescribed Radiosity, Diffuse Mirror												●														
Thermal Contact												●														

* Requires all indicated products.

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Heat Transfer *(continued)*																										
Thin Conductive Shell												●														
Thin Thermally Resistive Layer	●											●														
Multiple layers structure												●														
Single layer structure	●																									
Edge and Point Conditions																										
Line and Point Heat Source	●																									
Wall Heat Transfer for Heat Transfer in Pipes																				●						
External Radiation Source																										
Solar Position, Point Source, and Directional Source												●														
Volumetric Domain Properties																										
1D, 2D, Axisymmetric, and 3D Formulations	●																									
Bioheat Source												●														
Geothermal Heating in Porous Media																									●	
Heat Source	●																									
Heat Source, Electrochemical Reactions				●			●	●	●																	
Heat Transfer with Phase Change												●													●	
Infinite Domain Modeling with Infinite Elements												●														
Opaque Material												●														
Out-of-plane Heat Transfer												●														
Pressure Work and Viscous Heating for Conjugate Heat Transfer					●							●														
Thermal Dispersion for Heat Transfer in Porous Media				●	●	●	●	●	●			●													●	
Translational Motion	●																									
Volume Averaging of Material Properties in Porous Media																									●	
Radiation in Participating Media												●														
Isotropic, Linear Anisotropic, and Nonlinear Anisotropic Scattering												●														
Thermodynamics for Heat Transfer in Fluids	●																									
Gas/Liquid	●																									
Ideal Gas					●	●						●									●					
Moist Air												●														
Mathematics																										
Physics and Study Types																										
Classical PDEs	●																									
Curvilinear Coordinates	●																									
Deformed Mesh: Deformed Geometry and Moving Mesh	●																									

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Mathematics *(continued)*																										
Global, Domain, Boundary, Edge, and Point ODEs and DAEs	●																									
Mathematical Particle Tracing																			●							
Moving Interface: Level Set or Phase Field					●									●												
Wall Distance Function	●																									
Optimization and Sensitivity																										
Optimization																		●								
Sensitivity	●																									
Parameter Estimation																		●								
Perfectly Mixed Reactor Models*						●												●								
Stationary and Time Dependent																		●								
PDE Interfaces																										
Coefficient Form Domain, Boundary, Edge, and Point PDE	●																									
General Form Domain, Boundary, Edge, and Point PDE	●																									
Wave Form PDE (Time Explicit)	●																									
Weak Form Domain, Boundary, Edge, and Point PDE	●																									
Boundary Conditions																										
Axial Symmetry	●																									
Continuity	●																									
Curvilinear Coordinates Boundary Conditions	●																									
Dirichlet, Flux, and Mixed Boundary Conditions	●																									
Edge and Point Sources and Constraints	●																									
Moving Interface Boundary Conditions					●									●												
Particle Tracing Boundary Conditions																			●							
Periodic Condition	●																									
Global Properties																										
ODEs and DAEs	●																									
Optimization and Sensitivity																										
Global, Integral, and Pointwise Inequality Constraint																		●								
Global, Integral, and Probe Objective Function	●																									
Particle Tracing																										
Boundary Conditions: Bounce, Diffuse Reflection, Disappear, Freeze, General Reflection, Inlet, Outlet, Particle Continuity, Secondary Emission, Stick																			●							
Formulation: Hamiltonian, Lagrangian, Massless, Newtonian																			●							
Particle Properties and Forces: Auxiliary Dependent Variables, General Force, Velocity Reinitialization																			●							

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Mathematics *(continued)*																										
Particle Release: Density and Mesh Based, Release from Grid, Uniform Distribution																			●							
Volumetric Domain Properties																										
0D, 1D, 2D, Axisymmetric, and 3D Formulations	●																									
Curvilinear Coordinates, Methods: Diffusion, Elasticity, Flow, User Defined	●																									
Particle Properties and Forces																			●							
Plasma																										
Physics and Study Types																										
Boltzmann Equation, Two-term Approximation																					●					
Capacitively Coupled Plasma																					●					
DC Discharge																					●					
Drift Diffusion																					●					
Heavy Species Transport																					●					
Inductively Coupled Plasma*		●																			●					
Microwave Plasma*																					●	●				
Boundary Conditions																										
Electrons																					●					
Flux or Insulation																					●					
Prescribed Electron Density or Mean Electron Energy																					●					
Wall																					●					
Electron Losses to Walls and Electron Reflection																					●					
Secondary or Thermionic Electron Emission																					●					
Heavy Species																					●					
Bulk Species																					●					
Flux, Inlet, or Outlet																					●					
Surface Reactions and Species																					●					
Volumetric Domain Properties																										
1D, 2D, Axisymmetric, and 3D Formulations																					●					
Collisionless Heating																					●					
Electron Energy Distribution Function: Druyvesteyn, Maxwellian, Generalized, User Defined																					●					
Electron Impact Reaction: Arrhenius, Cross-section, Look-up, Rate Constant, Townsend																					●					
Electron Production Rate																					●					
Inductive, Microwave, or General Power Deposition																					●					
Reaction																					●					

* Requires all indicated products.

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Plasma *(continued)*																										
Species, Non-Electron																					•					
Diffusion-Models for Heavy Species Transport																										
Fick's Law																					•					
Mixture-Averaged																					•					
RF and Optics																										
Physics and Study Types																										
Electromagnetic Waves																						•				•
Eigenfrequency, Frequency Domain, Time Dependent, Time Explicit																						•				•
Electromagnetic Waves, Beam Envelopes																										•
Eigenfrequency, Frequency Domain																										•
Transmission Line, 1D																						•				
Eigenfrequency, Frequency Domain																						•				
Boundary Conditions																										
Electromagnetic Waves, Beam Envelopes																										
Electric Field, Magnetic Field, Perfect Electric Conductor, Perfect Magnetic Conductor																										•
Periodic Condition, Scattering Boundary Condition, Surface Current																										•
Port																										•
Electromagnetic Waves, Frequency Domain																										
Electric Field, Magnetic Field, Perfect Electric Conductor, Perfect Magnetic Conductor																						•				•
Impedance Boundary Condition, Transition Boundary Condition																						•				•
Lumped Element (L,C,Z)																						•				
Lumped Port, Including Connection to Electrical Circuit																						•				
Periodic Condition, Scattering Boundary Condition, Surface Current																						•				•
Port																						•				•
Electromagnetic Waves, Time Explicit																										
Electric Field, Magnetic Field, Perfect Electric Conductor, Perfect Magnetic Conductor																						•				•
Low-Reflecting Boundary, Surface Current Density, Flux/Source																						•				•
Electromagnetic Waves, Transient																										
Lumped Element (Z)																						•				

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RF and Optics *(continued)*																										
Lumped Port, Including Connection to Electrical Circuit																						•				
Magnetic Field, Perfect Electric Conductor, Perfect Magnetic Conductor																						•				•
Periodic Condition, Scattering Boundary Condition, Surface Current																						•				•
Edge and Point Conditions																										
Edge Current and Magnetic Current																						•				•
Electric and Magnetic Point Dipole																						•				•
Lumped Parameters																										
S-Parameter Matrix Computation and Touchstone File Export																						•				•
Volumetric Domain Properties																										
Far-Field and Directivity Calculation (Electromagnetic Waves, Frequency Domain)																						•				•
Infinite Domain Modeling with Perfectly Matched Layers																						•				•
Scattered Field Formulation																						•				•
2D and Axisymmetric Electric Formulations																										
In-Plane Vector																						•				•
Out-of-Plane Vector																						•				•
Three-Vector																						•				•
Constitutive Relations																										
Anisotropic Materials																						•				•
Dielectric and Magnetic Losses, Loss Tangent																						•				•
Porous Media and Mixture Materials																						•				
Refractive Index																						•				•
Relative Permittivity and Permeability																						•				•
Dispersion Material Models																						•				•
Debye, Drude-Lorentz																						•				•
Sellmeier																										•
Semiconductor																										
Physics and Study Types																										
Semiconductor																							•			
Stationary																							•			
Time Dependent																							•			

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Semiconductor *(continued)*																										
Boundary Conditions																										
Insulation																							●			
Ohmic Contact																							●			
Schottky Contact																							●			
Thin Insulator Gate																							●			
Electrostatics Boundary Conditions																							●			
Distributed Capacitance																							●			
Electric Displacement Field																							●			
External Surface Charge Accumulation																							●			
Periodic Condition, Surface Charge Density, Zero Charge																							●			
Terminal, Electric Potential, Ground, Floating Potential																							●			
Discretization																										
Finite Element																							●			
Finite Volume																							●			
Volumetric Domain Properties																										
Semiconductor Material Model																							●			
Electrostatics Domain Properties																							●			
Charge Conservation																							●			
Space Charge Density																							●			
Generation-Recombination																										
Auger Recombination																							●			
Direct Recombination																							●			
Shockley-Read-Hall Recombination																							●			
Mobility Models																										
Arora Mobility Model																							●			
Fletcher Mobility Model																							●			
Power Law Mobility Model																							●			
User Defined Mobility Model																							●			
Structural Mechanics																										
Physics and Study Types																										
Beam (Eigenfrequency, Frequency Domain, Stationary, Time Dependent)																								●		
Beam Cross Section (Stationary)																								●		
Electromechanics (Eigenfrequency, Frequency Domain, Pre-Stressed, Stationary, Time Dependent)													●													
Fatigue (Stationary)										●																

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Structural Mechanics *(continued)*																										
Joule Heating and Thermal Expansion (Eigenfrequency, Stationary, Time Dependent)													●											●		
Membrane (Eigenfrequency, Frequency Domain, Pre-Stressed, Stationary, Time Dependent)																								●		
Multibody Dynamics (Eigenfrequency, Frequency Domain, Pre-Stressed, Stationary, Time Dependent)																●										
Piezoelectric Devices (Eigenfrequency, Frequency Domain, Stationary, Time Dependent)			●										●											●		
Piezoresistivity, Boundary Currents and Domain Currents (Eigenfrequency, Frequency Domain, Stationary, Time Dependent)													●													
Piezoresistivity, Shell (Eigenfrequency, Frequency Domain, Stationary, Time Dependent)*													●											●		
Plate (Eigenfrequency, Frequency Domain, Linear Buckling, Pre-Stressed, Stationary, Time Dependent)																								●		
Poroelasticity (Stationary, Time Dependent)																									●	
Shell (Eigenfrequency, Frequency Domain, Linear Buckling, Pre-Stressed, Stationary, Time Dependent)																								●		
Thermal Stress (Eigenfrequency, Frequency Domain, Stationary, Time Dependent)													●											●		
Thermoelasticity (Eigenfrequency, Frequency Domain, Time Dependent)													●													
Truss (Eigenfrequency, Frequency Domain, Linear Buckling, Pre-Stressed, Stationary, Time Dependent)																								●		
Solid Mechanics	●																									
Frequency Domain and Pre-Stressed Analysis			●										●											●		
Linear Buckling													●											●		
Stationary, Time Dependent, Eigenfrequency	●																									
Conditions on Surfaces																										
Multibody Dynamics																										
Added Mass; Spring Foundation with Pre-Deformation, Loss Factor and Viscous Damping; Prescribed Acceleration or Velocity																●										
Prescribed Displacement; Face Load with Total Force, Force per Area, and Follower Pressure Load																●										
Piezoresistivity																										
Piezoresistivity, Boundary Currents: Thin Conductive and Thin Piezoresistive Layer													●													

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Structural Mechanics *(continued)*

Feature	COMSOL Multiphysics	AC/DC Module	Acoustics Module	Batteries & Fuel Cells Module	CFD Module	Chemical Reaction Engineering Module	Corrosion Module	Electrochemistry Module	Electrodeposition Module	Fatigue Module	Geomechanics Module	Heat Transfer Module	MEMS Module	Microfluidics Module	Molecular Flow Module	Multibody Dynamics Module	Nonlinear Structural Materials Module	Optimization Module	Particle Tracing Module	Pipe Flow Module	Plasma Module	RF Module	Semiconductor Module	Structural Mechanics Module	Subsurface Flow Module	Wave Optics Module
Piezoresistivity, Shell: Damping, Thermal Expansion, Thin Conductive and Thin Piezoresistive Layer; Linear Elastic Material for Shell and Plate*													●											●		
Shell, Membrane, and Plate																										
Added Mass; Spring Foundation with Pre-Deformation, Loss Factor and Viscous Damping																								●		
Geometric Nonlinearity																								●		
Thermal Expansion; Body and Face Load; Initial Stress and Strain Tensors																								●		
Linear Elastic Material																								●		
Bulk, Shear, Young's Modulus; Poisson's Ratio, Lamé Parameters, Pressure/Shear Wave Speed																								●		
Isotropic																								●		
Orthotropic, Anisotropic (Shell and Plate Only)																								●		
Solid Mechanics																										
Added Mass; Spring Foundation with Pre-Deformation, Loss factor and Viscous Damping; Prescribed Acceleration or Velocity			●										●											●		
Contact with Friction; Follower Pressure Load													●											●		
Low-Reflecting Boundary			●										●											●		
Periodic Condition: Antiperiodicity, Continuity	●																									
Prescribed Displacement; Face Load with Total Force, Force per Area, and Pressure Load	●																									
Rigid Connector: Applied Force and Moment, Mass and Moment of Inertia													●											●		
Symmetry/Antisymmetry, Periodic Condition: Cyclic Symmetry, Floquet Periodicity			●										●											●		
Edge and Point Conditions																										
Beam and Truss																										
Cross section data																								●		
Elastic Material Model: Bulk, Shear, Young's Modulus; Poisson's Ratio, Lamé Parameters, Pressure/Shear Wave Speed																								●		
Point Mass; Spring Foundation with Pre-Deformation, Loss factor and Viscous Damping																								●		
Beam, Plate, and Shell																										
Prescribed Displacement/Rotation; Symmetry/Antisymmetry																								●		

Structural Mechanics *(continued)*

Feature	COMSOL Multiphysics	AC/DC Module	Acoustics Module	Batteries & Fuel Cells Module	CFD Module	Chemical Reaction Engineering Module	Corrosion Module	Electrochemistry Module	Electrodeposition Module	Fatigue Module	Geomechanics Module	Heat Transfer Module	MEMS Module	Microfluidics Module	Molecular Flow Module	Multibody Dynamics Module	Nonlinear Structural Materials Module	Optimization Module	Particle Tracing Module	Pipe Flow Module	Plasma Module	RF Module	Semiconductor Module	Structural Mechanics Module	Subsurface Flow Module	Wave Optics Module
Multibody Dynamics																										
Added Mass; Spring Foundation with Pre-Deformation, Loss Factor and Viscous Damping																●										
Point Load; Prescribed Displacement; Edge Load																●										
Shell, Membrane, and Plate																										
Added Mass; Spring Foundation with Pre-Deformation, Loss Factor and Viscous Damping																								●		
Edge Load; Pinned; Point Load																								●		
Edge Moment; Pinned; Point Moment (Shell and Plate Only)																								●		
Rigid Connector: Applied Force and Moment, Mass and Moment of Inertia (Shell only)																								●		
Solid																										
Added Mass; Spring Foundation with Pre-Deformation, Loss factor and Viscous Damping			●										●											●		
Point Load; Prescribed Displacement; Edge Load	●																									
Truss																										
Added Mass; Geometric Nonlinearity; Pinned; Prescribed Displacement; Straight Edge Constraint																								●		
Fatigue Evaluation																										
Cumulative Damage: Palmgren-Miner, Rainflow Counting										●																
Strain Based: Fatemi-Socie, Smith-Watson-Topper (SWT), Wang-Brown										●																
Stress Based: Findley, Matake, Normal Stress										●																
Special Conditions																										
Multibody Dynamics																										
Attachment																●										
Joint Conditions: Applied Force and Moment, Constraints, Locking, Prescribed Motion, Spring and Damper																●										
Joints: Ball, Cylindrical, Hinge, Planar, Prismatic, Reduced Slot, Screw, Slot																●										
Rigid Connector: Applied Force and Moment, Mass and Moment of Inertia																●										
Shell																										
Rigid Connector: Applied Force and Moment, Mass and Moment of Inertia																								●		

Structural Mechanics (continued)	COMSOL Multiphysics	AC/DC Module	Acoustics Module	Batteries & Fuel Cells Module	CFD Module	Chemical Reaction Engineering Module	Corrosion Module	Electrochemistry Module	Electrodeposition Module	Fatigue Module	Geomechanics Module	Heat Transfer Module	MEMS Module	Microfluidics Module	Molecular Flow Module	Multibody Dynamics Module	Nonlinear Structural Materials Module	Optimization Module	Particle Tracing Module	Pipe Flow Module	Plasma Module	RF Module	Semiconductor Module	Structural Mechanics Module	Subsurface Flow Module	Wave Optics Module
Solid Mechanics																										
Attachment																●										
Bolt Pre-Tension																								●		
Rigid Connector: Applied Force and Moment, Mass and Moment of Inertia																								●		
Volumetric Domain Properties																										
2D, Axisymmetric, and 3D Formulations	●																									
Geometric Nonlinearity			●										●											●		
Infinite Domain Modeling with Infinite Elements													●											●		
Infinite Domain Modeling with Perfectly Matched Layers			●										●											●		
Initial Stress and Strain Tensors			●										●											●		
Joule Heating Model for Thermal Expansion													●											●		
Electromechanics																										
Damping and Loss; Thermal Expansion													●													
Mixed Electric, Linear Elastic Dielectric, and Linear Elastic Materials													●													
Multibody Dynamics																										
Added Mass and Body Load																●										
Constitutive Relations																										
Linear Elastic Material																●										
Rigid Domain																●										
Piezoelectric Devices																										
Damping and Loss: Compliance, Elasticity, Coupling, Dielectric; Isotropic and Anisotropic			●										●											●		
Mixed Piezo, Dielectric, and Linear Elastic Materials			●										●											●		
Piezoresistivity, Domain Currents																										
Damping and Loss, Isotropic and Anisotropic													●													
Mixed Conductive, Piezoresistive, and Linear Elastic Materials													●													
Poroelasticity																										
Darcy's Law and Biot Poroelasticity																									●	
Isotropic Poroelastic Material																									●	
Add-on for Orthotropic and Anisotropic Poroelastic Material			●										●											●		

Structural Mechanics (continued)	COMSOL Multiphysics	AC/DC Module	Acoustics Module	Batteries & Fuel Cells Module	CFD Module	Chemical Reaction Engineering Module	Corrosion Module	Electrochemistry Module	Electrodeposition Module	Fatigue Module	Geomechanics Module	Heat Transfer Module	MEMS Module	Microfluidics Module	Molecular Flow Module	Multibody Dynamics Module	Nonlinear Structural Materials Module	Optimization Module	Particle Tracing Module	Pipe Flow Module	Plasma Module	RF Module	Semiconductor Module	Structural Mechanics Module	Subsurface Flow Module	Wave Optics Module
Solid Mechanics																										
Constitutive Relations																										
Concrete: Bresler-Pister, Ottosen, Willam-Warnke; Tension Cut-off											●															
Nonlinear Soil: Modified Cam-Clay Material Model											●															
Rocks: Hoek-Brown, Generalized Hoek-Brown											●															
Soil Plasticity: Lade-Duncan, Matsuoka-Nakai, Drucker-Prager with Cap, Mohr-Coulomb with Cap; Tension Cut-off											●															
Viscoelastic Material with Thermal Effects													●											●		
Viscoplasticity: Anand																	●									
Creep											●						●									
Coble, Garofalo (Hyperbolic Sine), Nabarro-Herring, Norton, Norton-Bailey, Weertman																	●									
Deviatoric, Potential, User-Defined, Volumetric											●						●									
Hyperelastic Material																	●									
Arruda-Boyce, Blatz-Ko, Gao, Gent, Mooney-Rivlin, two, five, nine parameters, Murnaghan, Neo-Hookean, Ogden, St Venant-Kirchhoff, Storakers, Varga, Yeoh, User Defined																	●									
Thermal Expansion and Damping																	●									
Linear Elastic Material	●																									
Bulk, Shear, Young's Modulus; Poisson's Ratio, Lamé Parameters, Pressure/Shear Wave Speed	●																									
Isotropic	●																									
Isotropic, Orthotropic, Anisotropic Loss Factor			●										●											●		
Orthotropic and Anisotropic			●										●											●		
Rayleigh Damping	●																									
Thermal Expansion													●											●		
Plasticity											●						●									
Isotropic, Kinematic and Perfectly Plastic Hardening											●						●									
Large Strain Plasticity											●						●									
Orthotropic Hill Plasticity																	●									
Thermal Expansion											●						●									
Tresca or von Mises Yield Criterion; User-Defined Flow Rule											●						●									

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