Realistic Simulation Assists Nuclear Power Plant Certification

From the onset of the civilian nuclear era, there has been a strong awareness of the importance of safety within the nuclear energy industry. Experts have devoted much time and effort to ensuring the integrity of reactor cores and facility containment.

Wolfgang Hienstorfer, TÜV SÜD ET

Global cooperation on nuclear safety issues is widespread. The U.N.'s International Atomic Energy Agency (IAEA) has established mandatory benchmarks for nuclear plant siting, design, construction, operation, resourcing, assessment, and verification of safety, quality assurance, and emergency preparedness. All countries with operating nuclear power facilities are expected to bring their plants up to the latest IAEA standards.

Aging nuclear facilities

An integral part of reactor safety assurance is the mitigation of facility aging. Designed for 30- to 40-year operating lives, the systems, structures, and components of nuclear plants can change with time and use. Components can wear out, corrode, or degrade; instrument and control systems may become obsolete as technologies evolve. Complicating the issue, the properties of critical materials may change through heat and neutron irradiation.

Identifying and correcting longevity issues can extend the operating license of a plant by several decades, which is why upgrading older facilities is a major focus of nuclear regulatory bodies and plant operators. In addition, new facilities are held to the highest standards of quality to ensure a lifetime of safe operation.

"The structural integrity and operational management of nuclear facilities must be secured far into the future—whatever the type or age of the plant," says Wolfgang Hienstorfer, head of the department of structural analysis at TÜV SÜD ET, a leading global technical service corporation in Filderstadt, Germany.

Hienstorfer's team independently tests, inspects, and certifies nuclear facilities for licensing by the German government. He is also chairman of the advisory group on nuclear facility aging management to Germany's Nuclear Safety Standards Commission, and a technical consultant to the IAEA on nuclear facility aging. Many of his recommendations developed during his work at TÜV have been incorporated into existing international standards.

"On behalf of the regulatory bodies, we encourage the power utilities to follow the latest relevant research findings whether they are maintaining an older plant or designing and building a new one," says Hienstorfer.

FEA assists safety evaluation

To assist in the evaluation of nuclear plant integrity, Hienstorfer's group employs Abaqus FEA software. "Abaqus is a very useful and powerful tool for many aspects of our work," says Hienstorfer. "The processes of sensitive industrial facilities are very complex, and FEA helps us evaluate the safety margins in a more sophisticated way."

TÜV uses Abaqus to analyze stress loads over a wide range of scenarios such as rapid temperature and/or pressure changes, airplane impact, earthquakes, and radiation embrittlement. The software is used to analyze everything from key mechanical components—including pumps, piping systems, vessels, supports, and tanks—to fuel assemblies, building structures, and lifting devices.

Strict standards for nuclear reactors

An ongoing focus of regulators is the reactor pressure vessel (RPV), the steel "heart" of the power plant that houses the nuclear fuel rods (Figure 1). A nuclear power plant using fission to produce steam that drives electric generators is subject to temperature and pressure stresses similar to those at any kind of steam facility. But the possibility of pressurized thermal shock (PTS) affecting a radiation-embrittled RPV is unique to the nuclear industry: bombardment from neutrons can, over time, alter the molecular makeup of the metal from which an RPV is built, making the vessel more prone to structural damage

Figure 1: A nuclear reactor pressure vessel that houses the fuel rods. Exterior view of the nozzles (with red caps) through which hot and cold water circulate into and out of the vessel. (Photo courtesy of Westinghouse)

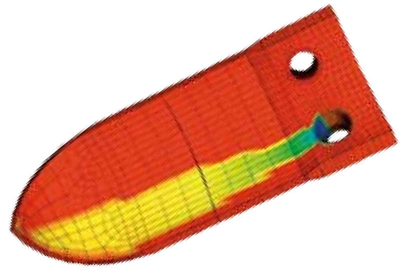

Figure 2: Cutaway view of reactor pressure vessel (RPV) at the start of a pressurized thermal shock (PTS) simulation by TÜV, using Abaqus FEA. The vessel, which normally operates at 300º C (indicated in red), is shown as cooler water (30º C) begins pouring in through the nozzle on the top right. (Image courtesy of TÜV)

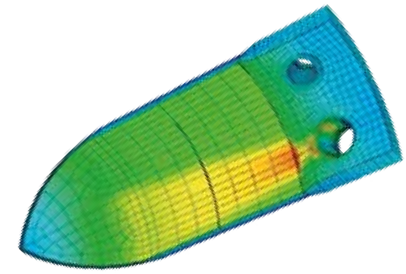

Figure 3: The same reactor vessel in pressurized thermal shock (PTS) simulation shows the stress distribution on the inner wall (from red to blues and greens). TÜV uses Abaqus FEA to evaluate the ability of RPVs to withstand such an event. (Image courtesy of TÜV)

under stress. In a classic loss-of-coolant (LOC) scenario, a broken pipe in the primary system deprives the reactor core of vital coolant, and the hot vessel (300º C) is then subjected to extreme PTS as colder water (at 30º C) is rapidly piped into the vessel to cool the core and shut the reactor down.

IAEA standards require that RPVs have a proven ability to withstand this kind of event in order to receive certification for operation. "You have to document the damage tolerance of the systems, structures, and components of a plant to pass inspection," says Hienstorfer. "FEA is integral to that analysis. FEA can be used for virtual testing to provide guidance for new designs in the early stages of product development, as well as for performance assessment of existing components under simulated stress conditions."

A typical FEA analysis of an RPV takes into account temperature transients, internal pressure fields, and radiation embrittlement behavior of the vessel during a simulated LOC event. The simulations examine stresses at vessel walls and entry points of the hot and cold water nozzles feeding into the RPV.

Modeling an RPV with Abaqus

To create their FEA models, TÜV engineers first obtained component condition data for the vessel and nozzles from nondestructive x-ray and/or ultrasound testing. Every vessel is plant-specific—in the case described here, the material was ferrite steel coated with austenitic cladding to protect the load-carrying ferrite layer from corrosion. Embrittlement of the metal over time was represented by end-of-life calculations based on existing data from irradiated material.

Next, Abaqus/CAE was used to build and mesh computer models of the vessel and the four water pipe nozzles that fed into it. Using larger, linear hexahedral elements reduced computation time for solving the global model (Figure 2), while smaller, quadratic hexahedral elements were used in the submodels (Figure 4) for more accurate depiction of stresses at the edges of nozzles.

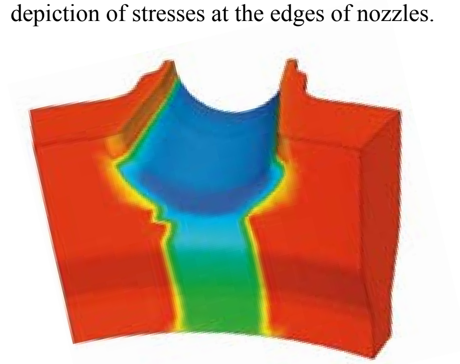

Figure 4: Abaqus FEA half-model of an RPV nozzle opening (shown as holes in Figures 2 and 3) through which cold water is quickly introduced to shut down the reactor, resulting in pressurized thermal shock (PTS). (Image courtesy of TÜV)

Simulating pressurized thermal shock

The TÜV team then used Abaqus/Standard for linear elastic simulation of the rapid cooling of the vessel, calculating the effects of a large increase in tensile stresses on the inner vessel wall. This increase is the result of two phenomena. First, the thermal conductivity of the two materials is different, so each reacts differently to the rapid temperature change. Second, the emergency injection of colder water creates a temperature plume that produces stress buildup at its leading edge (Figure 3).

The effect of the high pressures under which the system would operate was also incorporated into the models; an elastic/plastic Abaqus simulation predicted where the greatest surface and/or volumetric stresses would occur in the system. The simulations were run beyond the required tolerance levels to the point at which cracking would occur. Such data is useful for fracture mechanics analyses, and can be used in the future by inspectors, says Hienstorfer.

FEA facilitates regulatory compliance

The RPV in this example passed TÜV's simulation testing, indicating that its walls and nozzles would withstand the extreme conditions of an LOC event over a 40-year lifespan. "The Abaqus FEA calculations helped evaluate compliance of the vessel to regulatory safety requirements," says Hienstorfer.

Successful design, development, and maintenance of nuclear power facilities are challenges that must be managed from both an organizational and an engineering viewpoint, says Hienstorfer. He sees FEA as playing an integral role in both operational evaluation and ongoing monitoring of nuclear facilities to help comply with regulations designed to ensure the world's growing energy needs can be met safely.

"We depend on FEA for computer modeling and virtual testing of reactor pipelines, vessels, and materials under extremes of stress and time," he says. "It definitely provides guidance to engineers building safety and longevity into their nuclear power plant designs."

For More Information

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