Consortium for Advanced Simulation of Light Water Reactors

Relevance of Scope and Execution Plan to Nuclear Reactor Safety

The Consortium for Advanced Simulation of Light Water Reactors (CASL), a U.S. Department of Energy (DOE) Energy Innovation Hub for Modeling and Simulation of Nuclear Reactors, brings together a multidisciplinary team of researchers from national laboratories, industry, and universities to address critical challenges to the nuclear power industry through modeling and simulation. This team is taking advantage of advances in high-performance computing, mathematics, and high-fidelity models of physical phenomena to develop new tools for enhancing the performance of existing reactors and improving the design of next-generation systems.

The vision for CASL is to confidently predict the safe, reliable, and economically competitive performance of nuclear reactors through comprehensive science-based modeling and simulation technology that is deployed and applied broadly throughout the nuclear energy enterprise. To achieve this vision, CASL's mission is to provide forefront and usable modeling and simulation capabilities needed to address phenomena that limit the operation and safety performance of light water reactors (LWRs).

Given budget and time constraints, CASL has elected to focus on challenges that originate within the reactor vessel of a pressurized water reactor (PWR), the most common type of LWR in the U.S. nuclear power industry, with an emphasis on the reactor core, the vessel itself, and the in-vessel components. In particular, the CASL team is working to understand the behavior of nuclear fuel during both normal operation and upset conditions. Since the nuclear fuel is the first barrier to the release of radioactive fission products, precisely simulating its behavior will help to identify modifications to plant operating regimes and fuel design that will ensure and enhance nuclear safety while improving economic performance.

Nuclear fuel elements for PWRs typically include cylindrical pellets of uranium oxide fuel that are placed in thin tubes of zirconium alloy cladding material to create a fuel rod. A small gap between the pellets and cladding is filled with helium gas to improve heat transport from the fuel pellets to the reactor coolant. Fuel rods are then arranged into a grid assembly to enhance coolant mixing and to restrict fuel vibration and movement. The number of assemblies in a reactor core depends on reactor type, but a typical PWR contains 193 fuel assemblies, nearly 51,000 fuel rods, and about 18 million fuel pellets. These elements perform in a high-temperature, high-pressure, high-radiation environment for 3 to 5 years.

Even during normal operation of a nuclear power plant, these hostile service conditions lead to radiation damage, material property changes, and mechanical distortion in the fuel pellets, rods, and assemblies. This fuel system transformation is accelerated under accident conditions, which can result from human (e.g., operator error), mechanical (e.g., pipe burst), or external (e.g., earthquake) events.

To improve the fundamental understanding of nuclear fuel behavior, CASL is developing advanced modeling and simulation capabilities in neutron transport, thermal hydraulics (coolant flow), materials science, and structural mechanics, and the mechanism to collectively account for the interactions between them. These new modeling and simulation capabilities, which are being incorporated into CASL's "virtual reactor," the Virtual Environment for Reactor Applications (VERA), will make it possible to confidently predict nuclear fuel performance under a range of conditions, even with limited experimental observations. This predictive simulation capability is a key tool for designing more robust nuclear fuel that is tolerant of upset conditions, since there is a lack of experimental observations under such conditions.

Although CASL is not currently developing a modeling and simulation capability for severe accidents like the events that took place at Japan's Fukushima Daiichi reactors in 2011, its focus on high-precision predictions of the onset and evolution of fuel damage directly supports the analysis of such incidents. For example, the amount of damage to nuclear fuel that will result from a severe accident depends on the properties of the fuel at the beginning of the accident. These properties are likely to be substantially different from those of fresh fuel because of fission-induced transformation that occurs during normal operation. An early focus for CASL has been the prediction of fuel property changes during normal operation. The large body of experimental observations under normal or slightly off-normal operating conditions is being used to validate the modeling capabilities now being developed. In the future, CASL will use these capabilities to examine fuel behavior under accident conditions, including a loss-of-coolant accident (LOCA).

CASL challenge problems

Challenge Problem	*Description*
CRUD	Buildup of CRUD (corrosion and wear products) on outside of fuel cladding influences mechanical and reactivity behavior, with potential for clad damage
Grid-to-rod fretting	Interactions of fuel rods with the support grid of a fuel assembly, induced by flow vibration and amplified by irradiation-induced grid spacer growth and spring relaxation, can cause clad damage
Fuel assembly distortion	Irradiation and thermal creep of fuel assembly can lead to distortion resulting in slow or incomplete control rod insertion
Departure from nucleate boiling	Under some accident conditions, fuel clad surfaces can dry out, dramatically reducing their heat transfer capability and resulting in clad melting
Pellet-clad interaction failure	Normal reactor operation results in pellet swelling and cladding creep down, which quickly eliminate the pellet-cladding gap, providing better heat transfer characteristics for the rod. Once in contact, local stresses imposed on the cladding by rapid power changes or missing pellet surfaces can result in clad cracks.
Cladding integrity during LOCA	Many fuel failure modes can result in fission product release and degradation of coolable geometry
Cladding integrity during reactivity insertion accident	Rapid high power response of the fuel pellet can lead to pellet disintegration and clad failure due to loads imposed by the pellet
Reactor internals integrity	Thermal fatigue, mechanical fatigue, radiation damage, and stress corrosion cracking can damage internal components
Reactor vessel integrity	Radiation damage decreases temperature for onset of brittle failure, increasing chance of failure due to thermal shock stresses induced during emergency coolant injection
Advanced fuel forms	New cladding material, fuel material, and fuel pin geometries have potential to provide more resistance to damage and provide economical operating cycles at the same time

In fact, the "challenge problems" that CASL is addressing during its initial 5-year operating period were selected to provide the nuclear power industry with tools for delivering improved performance with enhanced safety. They include a number of safety-related issues, including fuel behavior under accident conditions. CASL will also provide modeling capability that will enable fuel designers to assess the performance of advanced fuel designs that are more resistant to damage under normal and abnormal operating conditions, with the potential to mitigate some of the problems associated with the events at the Fukushima Daiichi reactors.

In its early days, the nuclear power industry was a leader in the development and use of modeling and simulation in a demanding setting. CASL's intent is to reassert and strengthen this leadership role by deploying a technology step change (VERA) that supports today's nuclear energy industry and accelerates future advances of this low-carbon energy source.

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