HIGHER GOALS

NUCLEAR FUEL TECHNOLOGY & PERFORMANCE

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Nuclear power plants have high initial investment costs but low fuel costs compared to electricity-generating plants burning fossil fuels. A 1000-megawatt nuclear plant, for example, uses about 30 tonnes of uranium a year, whereas a coal-fired plant of the same size requires about 2.6 million tonnes of coal and an oil-fired plant about 2 million tonnes of oil.

In today's changing energy marketplace, more countries are moving to introduce competition into formerly regulated electricity markets. For nuclear power development, this means, among other things, that fuel-related costs will have to be kept lower than the corresponding costs for fossil-fuelled plants to remain competitive. Economic pressures, alongside environmental demands, accordingly have become driving forces behind efforts to improve nuclear fuel technology and performance without compromising plant safety levels.

The search for better fuel economy at nuclear power plants involves extensive and detailed studies. They include evaluations of the design, behaviour, performance, and reliability of fuel elements under various operational conditions and at different types of power reactors. Particular interest has gone to extending the lifetime of nuclear fuels, and over the past decades there has been an upward trend in the achievement of "higher burnup" levels in most types of reactors. This has resulted in overall fuel-related savings and in the reduction of the amount of discharged spent fuel that must be managed. At the same time, high burnup also places greater demands on fuel performance. Therefore, research is in progress to assess fuel behaviour at different projected levels of burnup. The step-by-step increase in burnup is authorized only when evidence has been presented to licensing authorities that it can be achieved without compromising safety or fuel reliability. Research is focused on a number of phenomena that could potentially limit the lifetime of the fuel under different types of operating conditions.

Within the framework of the International Working Group on Water Reactor Fuel Performance and Technology, the IAEA has been supporting collaborative efforts of national and international experts in this field. It additionally organizes coordinated research projects involving national institutes investigating specific technical aspects, and conducts technical cooperation projects for transferring technologies and expertise. This article presents an overview of selected activities, particularly focusing on those related to the goals of achieving higher burnup of nuclear fuel.

FUEL EXPERIENCE

Under operating conditions, nuclear fuel assemblies are subjected to aggressive environments characterized by synergistic effects of stress, heat, coolant water chemistry, and irradiation. The effects lead to progressive degradation of the mechanical and physical properties of fuel cladding materials and other structural components of the fuel and control rod assemblies. Higher levels of fuel burnup add to these physical and mechanical demands, and much research and development is directed at developing advanced materials, including those that, for example, are more resistant to corrosion.

Overall, the reliability of nuclear fuel has been improving steadily over recent years. For light-water reactors, the main type in service worldwide, fuel failure rates have been 10^{-5}, which is about ten per year per million fuel rods in service. The mitigation and control of fuel defects are driven by economic and safety considerations. The goal of "zero fuel failures", which means in practice a reduction of the fuel failure rate to 10^{-6}, has

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been the target of utilities and fuel vendors over the near term.

Major causes of fuel failures to date have been mainly related to initial design and fabrication problems. New fuel rod and assembly designs are being developed and implemented in response. For example, at light-water reactors, metallic debris in the primary coolant system of the plant is known to cause a significant fraction, about 40% to 50%, of the fuel failures. As a result, utilities have developed programmes to identify and eliminate the sources of debris, and fuel vendors are offering "debris resistant" fuel designs.

To monitor fuel performance at higher burnup and to supply data for validating predictive computer codes, studies known as post-irradiation examinations are done. They apply to both surveillance-type, non-destructive examinations and to more sophisticated destructive examinations and measurements. Validation is needed for both new fuel concepts and for new cladding materials.

Fuel modelling studies are important from economic and safety perspectives. A reliable prediction of fuel behaviour in all conditions is required for safety calculations during design. Computer codes have been developed for this purpose. From a knowledge of fuel behaviour in both normal and abnormal conditions, operating rules are derived to prevent fuel failures and the possible release of fission products to the environment, or in extreme cases, to prevent serious fuel and core damage and any subsequent hazard. In this methodology, the fuel cladding is the first safety barrier.

Even with the simplest computer codes, adequate operating limits can be derived to ensure safe operation provided that conservative limits are set. The modelling of fuel performance, and inclusion of that knowledge in the codes, also are important to achieving more realistic predictions of fuel behaviour that will contribute to improving the economics of reactor operations.

JOINT RESEARCH

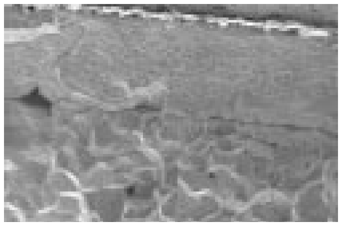
Through the IAEA's working group, experts have reviewed research results and operational experience, agreeing that fuel performance is satisfactory for current operational requirements at water reactors. Further research, however, is needed in several areas in light of ongoing efforts to achieve even higher burnup of nuclear fuels. They include studies related to:

Control of Water Chemistry. At high temperatures, water is an aggressive medium when in contact with structural materials. This means that the reliability of fuel assemblies, among other nuclear power plants systems, depends on the chemistry of water flowing in cooling systems. Corrosion is one of the most important processes leading to the degradation of fuel rods. During the 1980s, water chemistry specifications were gradually tightened, and this "purer is better" approach resulted in significant improvements, though it remained clear that corrosion had to be further reduced. More recently, chemists have been modifying specifications, usually by adding chemicals to the coolant. Investigations further allowed a better understanding of the mechanism of corrosion. Today, water chemistry regimes are getting more plant specific — for example, plant operators have new tools (calculation codes and programmes) to optimize water chemistry parameters and regimes within the specification, but taking into account the peculiarities of the plant. These issues further are being examined through two IAEA coordinated research projects.

Operational Anomalies. In the 1990s, several countries have reported problems with the bowing of fuel assemblies and lowering of control rods during plant shutdown operations. Although the drop time in these cases was still within the limits of technical specifications for the reactors involved, these anomalies were carefully analyzed and investigated. Studies of the anomalies, including the phenomenon of water gaps between fuel assemblies, are continuing. Some countermeasures have been implemented to prevent problems from recurring.

Irradiation and Other Effects. A number of phenomena related to the irradiation of nuclear fuel at higher levels of burnup are being investigated. Detailed characterization of the evolution of microstructures caused by irradiation is the key to understanding and predicting the degradation of physical and mechanical properties induced by radiation damage. *(See figure.)* Improvements in the fundamental theories of certain radiation-induced phenomena, among other developments, continue to improve the accuracy of predictions about the deformation of pressure tubes, and the knowledge is

STUDIES OF FUEL BEHAVIOUR & STRUCTURE



Rim layer

Normal fuel structure

Studies have shown that at high levels of burnup, the fuel structure is modified, as indicated by these highly magnified views using an electron microscope. A peripheral rim layer is formed that is characterized by ultra-fine grains, a high porosity of between 10% and 20%, and plutonium content. The circle at left is a closer view of the normal fuel structure.

contributing to the development of tubes having longer lifetimes.

The formation of fission gases is directly related to the length of time fuel is irradiated. At high levels of burnup, these gases can lead to undesirable consequences, including the buildup of internal pressure in rods. Studies of this phenomenon are identifying factors that need to be taken into account to improve predictions about fuel behaviour at high burnup. Contributing to this work are researchers participating in an IAEA coordinated research project on fuel modelling. Nineteen different codes were studied, resulting in the improvement and validation of elementary models and codes.

In parallel, a more advanced modelling code for fuel performance has been transferred to ten Eastern European countries, together with guidance on its application to reactor operation and safety assessments. This code's adaptation to predict the behaviour of fuel used in WWER-type reactors under normal and transient conditions is now being done within the framework of an IAEA technical cooperation project. Also being studied is another cause of structural modifications of fuel that is related to the formation of plutonium during irradiation. A number of countries are investigating this phenomenon as part of safety studies.

Fuel Behaviour under Accident Conditions. To improve knowledge about fuel behaviour under different types of conditions, tests of fuel are being conducted through simulated accident scenarios. Two scenarios under investigation are reactivity insertion accidents and loss-of-coolant accidents; both scenarios involve testing the performance of fuel at extended levels of burn-up. Early results of these research programmes in some countries were reported in May 1997 to the IAEA's working group. The final outcome of these programmes is expected to be a decisive factor in the achievement of the desired higher levels of fuel burnup over the coming years.

TECHNICAL CHALLENGES

Over the next decade, the trend of higher burnup levels for nuclear fuels is projected to continue, largely driven by economic incentives. Levels are expected to increase by 32% or more by the year 2010 for different types of fuels burned in water reactors. These incrementally higher levels will have to be tested and qualified before the use of the fuels can be licensed. In some areas, considerable research and development is required, as the cause of some fuel failures, even after examination, is not yet fully understood. Additionally, while there have been few fuel failures of mixed-oxide fuels, more experimental data are needed to study the behaviour of defective mixed-oxide fuel rods, especially at high burnups and for longer irradiation times.

The IAEA's Working Group on Water Reactor Fuel Performance and Technology includes experts from 26 countries and three international organizations. Through this group, among other avenues, the IAEA is assisting countries to benefit from each other's experience and technological development by focusing efforts on specific topics and needs. For example, jointly with the Nuclear Energy Agency of the Organization for Economic Cooperation and Development, the IAEA has established the International Fuel Performance Experiment Database, which includes data from experiments involving more than 300 fuel rods, that supports research in participating countries. These and other initiatives are contributing to collective efforts for meeting the technical challenges ahead and for improving the efficient operation of nuclear power plants. ❐