INTRODUCTION TO SAFETY ATTRIBUTES OF THE LIGHTBRIDGE METAL FUEL TECHNOLOGY

April 2011

Prepared by: J. Malone, N. Shapiro, S. Vaidyanathan, and A. Totemeier

Lightbridge Corporation
1600 Tysons Blvd.
Suite 550
Mclean, VA 22102 USA
P +1 571.730.1200
F +1 571.730.1259

The Basics of Nuclear Power Generation

Commercial nuclear power plants produce electricity by heating water to steam and using that steam to turn a turbine-generator. This is the same process used in all steam-driven power systems. Nuclear reactors are unique in that they create heat via a process known as nuclear fission or the splitting of an atom into two smaller atoms. Most of today's commercial power reactors are light water reactors (LWRs)[1] which utilize uranium, specifically the isotope U-235, as a solid fuel which undergoes fission. The fission process occurs when a uranium nucleus absorbs a free neutron of the right energy and splits into two lighter nuclei along with a few excess free neutrons. Those free neutrons can cause fission in other U-235 nuclei, thereby creating a self-sustaining chain reaction. Nuclear power plants are complex systems which control the nuclear chain reaction and use the energy released by fission to create electricity without releasing carbon dioxide to the environment. A good summary of the basics of nuclear electricity generation is provided by the U.S. Nuclear Regulatory Commission[2].

The remnants of the fission process, the so-called fission products, are generally highly unstable and undergo various atomic processes to achieve a more stable state. These atomic processes are termed radioactive decay, and are what is referred to when people use the term radiation. There are several radioactive decay processes and many forms of radiation. The type of radiation that most commonly comes from radioactive decay is termed ionizing radiation because it has the ability to "strip" electrons from atoms, leaving the atom with a positive ionic charge. Ionizing radiation can be harmful to biological tissue depending on where the radiation is received and the dose rate or how much radiation is received in a given period of time. The radiation from fission products is high during reactor operation and shortly after shutdown but decreases with time as the atoms decay to a stable state.

Overview of Nuclear Power Plant Safety Principles

The safety systems in a nuclear power plant are designed to protect the environment, the public, and plant workers from the harmful effects of radiation. These systems include the design of the fuel, the power plant safety systems, and the containment structure[3] around the reactor. Nuclear power plant safety follows a defense-in-depth principle, such that multiple systems are designed to provide the same

---

[1] Light water is the term used to refer to the water that we all use every day for cooking, cleaning, and drinking. Alternatively, heavy water utilizes an isotope of hydrogen that has an extra neutron.

[2] Available online at http://www.nrc.gov/reading-rm/basic-ref/students/reactors.html

[3] Some older plant designs, such as the RBMK reactor in Chernobyl, did not have a containment structure around the reactor core.

basic function of containing radioactive material. Each successive level of safety is designed specifically to deal with a failure in the previous system.

Three primary barriers to fission product release are present in nuclear power plants: the fuel cladding[4], the reactor vessel and primary coolant system, and the containment structure around the reactor[5]. Fuel is the first and foremost barrier; if fuel rod integrity is maintained, significant amounts of radioactivity cannot be released to the environment. Diverse and redundant engineered safety features also are incorporated to prevent the failure of these three barriers. Examples are the reactor protection system, the emergency core cooling system, and the containment cooling system.

Fuel failure is specifically related to the temperature of the fuel. In general terms, if the fuel cladding can be kept at a low enough temperature during accidents, fuel integrity will be maintained and the risk of radioactive release is low. Therefore the multiple engineered safety systems of the power plant are designed to remove heat from the fuel. Other safety systems, such as pressure relief valves and containment cooling, are incorporated to prevent failure of the primary coolant system and the containment. The redundant safety systems provide assurance that there are no single point failures in the plant that can compromise safety, and the defense-in-depth approach is designed to provide plant operators time to restore internal cooling systems or provide external cooling to the plant.

As noted above, the fuel cladding is the first barrier to radioactive material release. Some of the radioactive elements created in the fission process are gaseous or volatile and try to escape from the fuel material. The cladding around the fuel acts as the *first level of containment*. One consequence of the radioactive decay of the fission products is heat generation, so-called decay heat. The amount of decay heat produced depends primarily on the operating power of the reactor. Decay heat is constantly generated while the reactor is operating and, although decreasing with time, persists long after the reactor is shut down and the nuclear chain reaction has stopped. Although the amount of decay heat at the time the reactor is shutdown[6] is generally only ~5-7% of the reactor's normal output, it is a

---

[4] Cladding refers to the hermetically sealed metal tube that surrounds the fuel material; together the fuel material and cladding are referred to as a fuel rod.

[5] These three barriers are present while the fuel is in the reactor core. Used (or spent) fuel is removed from the reactor core and stored in a spent fuel pool. Although the used fuel is less radioactive and generates less heat than the fuel in the reactor, spent fuel pools lack the additional barriers afforded by the reactor pressure vessel and the containment structure. Consequently, for spent fuel, increased importance is placed on the fuel integrity as a barrier to radiation release.

[6] The amount of decay heat decreases to ~ 1% of the reactor's normal output within one day of shutdown and to ~ 0.25% by the end of the first week.

significant energy source and more than capable of heating the fuel and cladding beyond their safety limits. Therefore some form of cooling the fuel must be maintained so the cladding, the first level of containment, doesn't fail due to overheating. This cooling is necessary when the reactor is shut down and for several years after the fuel has been removed from the reactor and is stored in the spent fuel pool.

The cladding in LWRs is a zirconium-based alloy tube that is hermetically sealed around the fuel pellets. There is a region of empty space between the fuel pellet and the inner wall of the cladding, known as the fuel-clad gap. This gap allows the fuel pellets to swell during reactor operation. Above and below the stack of fuel pellets is an empty space known as the plenum. This region is designed to accommodate the pressures that develop due to fission product gases that escape the oxide fuel. In the event of a cladding breach, the fuel-clad gap provides a direct path for fission gases in the plenum to escape the first level of containment and enter the reactor's primary coolant system. This occurs occasionally during operation of the reactor and does not in itself represent a significant radiological threat when there are a few isolated fuel failures. However, in the event that the cladding of many fuel rods fails, a large amount of radioactivity can be released into the coolant.

The primary reactor coolant loop is the *second level of containment* as a fuel failure could result in the release of radioactive material to the coolant water. The primary coolant loop is comprised of the reactor pressure vessel (RPV), piping, pumps and heat exchanger which circulate coolant (i.e. water) around the fuel. The RPV is a large steel tank, several inches thick, that houses the core of the nuclear reactor. The RPV and primary coolant system contain the high pressure and high temperature of the reactor coolant.

The *third level of containment* is the air-tight containment, a robust, steel-lined and steel-reinforced concrete structure. The containment is designed to withstand the high pressures and temperatures that can develop during accident scenarios if the primary coolant system fails and coolant escapes. The containment provides reactor operators with more time to restore internal cooling systems or provide external cooling to the reactor.

The myriad safety systems in nuclear power plants are designed to ensure the integrity and extend the capabilities of the various containment systems. This is another defense-in-depth feature of all commercial nuclear power plants. However, no system is failure proof. Nuclear power plant designers and regulatory agencies realize this and have worked extensively to show that safety is maintained during various anticipated operational occurrences[7] and design basis accidents[8].

New reactor designs incorporate several advanced safety systems that weren't available when most of the current plants were built decades ago. These systems are called *passive safety systems* since they don't require any actions on the part of plant systems (i.e. pumps or electricity) or plant workers to perform their function. There are several types of passive safety that have been developed and various new nuclear power plant designs incorporate different systems. It is important to note that although passive safety systems can provide increased safety or increased time to deal with an accident, they do not mean that an accident can never happen.

Safety Attributes of Lightbridge's Metal Fuel Technology

Lightbridge is developing two types of advanced fuel for LWRs with improved safety benefits compared to conventional UO2 fuels. The first fuel is an evolutionary metallic fuel with significantly improved heat transfer and fuel robustness; the second is a mixed thorium-uranium dioxide fuel with enhanced proliferation resistance[9]. This paper focuses on the safety attributes of Lightbridge's metallic fuels. As described above, a major purpose of the nuclear power plant safety systems is to prevent the fuel from reaching a failure point (i.e. cladding breach) wherein the radioactive material inside can be released to the environment. There are several mechanisms for cladding breach in conventional UO_2 fuels and the primary coolant loop and containment building are designed to retain the radioactive material released in such an event, known as the *radioactive source term*. The radioactive source term is determined by the type and quantity of radioactive material that is released to the environment and is directly related to the amount of material that can escape the first level of containment, the fuel cladding. The fuel-clad gap and fission gas plenum in conventional fuels provide an immediate source of radioactive gases that can be released in the event of a cladding breach. The safety benefits of Lightbridge's metal fuel improve the robustness of the first level of containment, the cladding, to prevent or significantly minimize the release of fission products from the fuel. The increased safety of Lightbridge's metal fuel

---

[7] Anticipated operational occurrences (AOOs) are events that are beyond the normal operation of the power plant but are expected to occur at least once during the plant's lifetime. Plant design must prevent fuel failure during such events.

[8] Design-basis accidents are events outside of normal operation and AOOs that the power plant must be designed to withstand without losing its safety systems and exposing the public to excessive levels of radiation; for example, a severe natural disaster or targeted terrorist attack.

[9] A previously published white paper on Lightbridge's thorium-based fuels is available on Lightbridge's website. http://goo.gl/sNm1c

technology (MFT) can be attributed primarily to two key features, the increased heat transfer capability of the fuel and the strong metallurgical bond between the cladding and the fuel material.

Lightbridge's metal fuel utilizes a unique geometry and fuel composition to increase the heat transfer capability of the fuel, which results in lower fuel operating temperatures, and a unique fabrication process that eliminates the fuel-cladding gap that exists in conventional fuel. These features are responsible for the retention of the gaseous fission products within the fuel material rather than in a plenum or gas gap. The metallurgical bond and lower operating temperature are responsible for reducing the potential for cladding failure during normal operation and a reduced source term in the event that a cladding breach should occur.

Improved Heat Removal

The process of heat removal from a nuclear fuel rod can be simplified into three steps, 1) heat generation in the fuel; 2) heat conduction to the surface of the rod; and 3) convective heat transfer to the coolant (i.e. water) and away from the rod. Heat generation is dependent on the power of the fuel rod, generally described by linear power density (e.g. kW/ft). As mentioned, heat removal and maintaining a low fuel temperature are the primary concern of the reactor safety systems.

Lightbridge's MFT has increased heat removal compared to conventional UO_2 fuels as the metal has a much higher thermal conductivity and the bonded cladding is a better conduction pathway than the fuel-clad gap in conventional fuel.

The unique geometry of the MFT decreases the distance the heat has to travel to reach the coolant, provides approximately 35-40% more surface area for heat transfer than equivalent cylindrical fuel rods, and increases coolant mixing which reduces the likelihood of localized hot spots in the fuel during normal operation. Therefore, heat generated in Lightbridge's metal fuel can move through the fuel rod and be removed by the reactor coolant more efficiently.

During normal reactor operation the increased heat transfer allows Lightbridge's MFT to operate at a higher power density[10] than UO_2 fuels and at a significantly lower temperature. The average operating temperature of Lightbridge's MFT operating at 130% of the power density of standard UO_2 fuel is approximately 380 °C, compared to approximately 1500 °C for the UO_2 fuel. The lower fuel operating temperature provides several benefits to the fuel's performance during normal operation, such as

---

[10] Power density is the amount of power generated per unit volume of nuclear fuel.

markedly decreased fission product mobility and less sensible heat[11] that needs to be removed during reactor shutdown.

The increased thermal conductivity of the MFT is important during certain accident scenarios when providing adequate cooling to remove the decay heat of the fuel becomes a concern. For instance, if the reactor (or spent fuel pool) coolant level decreases below the top of the fuel, the increased thermal conductivity of the MFT can more easily transfer heat to the covered region of the fuel providing more time before the zirconium cladding overheats.

Metallurgically Bonded Cladding

Fabrication of the MFT results in a metallurgically bonded fuel and cladding with no gas gap. This metallurgical bond provides increased cladding robustness as the cladding benefits from the mechanical strength of the fuel material and there are no mechanisms for fuel-cladding mechanical interaction that could lead to high localized strains in the cladding and the development of potential cladding breach points.

The cladding of conventional fuel can fail if it is overheated or if it is suddenly cooled while overheated. As mentioned above, the fuel-clad gap and fission gas plenum provide a mechanism for immediate fission gas release in the event of fuel failure in conventional fuel. This source of radioactivity is markedly reduced in Lightbridge's MFT. In the event of a cladding breach the only fission products available for immediate release are those that are located near the breach. This reduces the radioactive source term for cladding breach events both during reactor operation and while the fuel is stored in a spent fuel pool.

Conclusion

The inherent characteristics of the Lightbridge MFT contribute to increased safety margins during normal reactor operation and certain off-normal events, such as anticipated operational occurrences and design basis accidents. Lightbridge is carrying out a comprehensive fuel qualification program that includes advanced computer modeling and various fuel demonstration tests and experiments that will establish direct quantitative benefit of the safety attributes of Lightbridge MFT.

---

[11] Sensible heat is the amount of heat required to change the temperature of a body. http://en.wikipedia.org/wiki/Sensible_heat

About the Authors

James P. Malone - Chief Nuclear Development Officer, Lightbridge Corporation

Jim Malone has more than four decades of high-level experience in the nuclear industry, including extensive experience in all aspects of fuel procurement and management. In late 2009, Mr. Malone retired after a decade with Exelon Generation Company, where as vice president, Nuclear Fuels he provided strategic direction and tactical guidance for Exelon's nuclear fuel cycle activities. He was responsible for procurement (uranium, conversion, enrichment and fuel fabrication) for seventeen operating nuclear reactors - PWRs and BWRs - and his expertise guided the management of used fuel. The Nuclear Fuel department's responsibilities also included special nuclear material accounting and safeguards, economics, and fuel cycle costs. Under Mr. Malone's supervision, the Nuclear Fuels department provided reload bundle and core design, safety analysis, and plant technical support, including fuel reliability, component procurement strategy, and decommissioning strategy.

Before joining Exelon, Mr. Malone served for ten years as vice president and senior consultant at NAC International, where he consulted on fuel reliability and the front and back ends of the nuclear fuel cycle, among other issues. One of his last projects at NAC was the international safeguards system for the Rokkasho Mura reprocessing plant in Japan. Mr. Malone also worked for many years at SWUCO, Inc. first as a nuclear fuel broker, then as manager of technical services, and finally as vice president. Prior to SWUCO, Mr. Malone was manager of economic analysis at Yankee Atomic, where his work led to important decisions on fuel type and design. Mr. Malone began his career in nuclear power in 1968 as an engineer in the utility reactor core analysis section of the Nuclear Engineering Department of Unted Nuclear Corporation, where his duties included bundle and core design for the Dresden 1 and Yankee Rowe reactors.

Mr. Malone is a member of the American Nuclear Society and past chairman of its Fuel Cycle Waste Management Division. He holds a bachelor's degree in chemical engineering (nuclear) from Manhattan College and an MBA from Iona College, where he was awarded the Graduate School of Business Award for Academic Excellence.

Norton Shapiro, Ph.D – Member of the Technical Advisory Board, Lightbridge Corporation

An expert in fuel technology, Dr. Norton Shapiro is one of the top nuclear fuel scientists in the world. He is considered an authority on subjects including uranium utilization, plutonium recycle, thorium utilization, and proliferation-resistant fuel cycles. Dr. Shapiro has been a member of Lightbridge Corporation's Technical Advisory Board since 2006.

Dr. Shapiro is a former engineer for Westinghouse Electric Company, the world's leading nuclear corporation, specializing in pressurized and light water reactors. Dr. Shapiro chaired the Technical Review Committee at Westinghouse Electric, where he led safety and systems analysis within the Nuclear Services Business Unit. He is also the former head of the Nuclear Engineering Department of ABB Combustion Engineering, where he was responsible for the design of nuclear reload cores as well as for the power plants under construction. At ABB, Dr. Shapiro was manager of advanced design projects, leading the development of advanced fuel cycle designs and innovative thermal reactor concepts; he also carried out U.S. Department of Energy contracts relating to the development of advanced fuel cycles and fuel designs in CE reactors. Dr. Shapiro has authored several scientific papers, including "Assessment of Thorium Fuel Cycles in Pressurized Water Reactors," which was published by the Electric Power Research Institute. He is a former member of the Executive Committee of the Reactor Physics Division of the American Nuclear Society.

Dr. Shapiro earned his Ph.D. in nuclear engineering from the University of Illinois.

Sam Vaidyanathan, Ph.D. – Member of the Technical Advisory Board, Lightbridge Corporation

Dr. Sam Vaidyanathan, an expert on plutonium disposition and advanced nuclear fuel development, has more than thirty years' experience with the development, testing, and engineering of nuclear fuels, materials, and core components. He has an extensive background in both light water reactors and fast reactors. Dr. Vaidyanathan has been a member of Lightbridge Corporation's Technical Advisory Board since 2006.

As one of the top fuel technology leaders at GE Nuclear, Dr. Vaidyanathan was senior program manager and principal engineer for fuel development and plutonium disposition. Among many accomplishments, he coordinated the GE Astro-Space Division's highly successful national task force for the multidisciplinary effort to qualify uranium nitride fuel for space reactor applications. He also worked in GE's Nuclear Systems Technology Operation, where he collaborated with scientists from the U.S. nuclear laboratories. Dr. Vaidyanathan, who has led studies on plutonium conversion and on mixed oxide (MOX) fuel fabrication, has also pioneered technical strategies for the disposition of weapon-grade plutonium as MOX fuel in boiling water reactors and has developed methods to better evaluate safeguards during the disposition process. As a consulting engineer, Dr. Vaidyanathan served as an expert on space nuclear reactor power systems and concepts, published in scientific journals on topics such as reliable space reactors, and researched fuel additives in relation to pellet-cladding interaction in nuclear reactors.

Dr. Vaidyanathan earned his Ph.D. in mechanical engineering from the University of California at Berkeley.

Aaron Totemeier - Director of Fuel Cycle Technology & Fuel Fabrication, Lightbridge Corporation

Mr. Totemeier provides technical oversight and review of Lightbridge's fuel research, development and demonstration activities. He is the technical lead for Lightbridge's programs with Texas A&M University and Idaho National Laboratory. Currently a Ph.D. candidate at Texas A&M University, Mr. Totemeier's primary research focus is the design, performance, and fabrication of metallic nuclear fuels for advanced reactor designs. He presently participates in various Lightbridge projects as a nuclear technology expert.

Mr. Totemeier has developed fabrication technologies for zirconium-based cermet nuclear fuels and analyzed radiation shielding for nuclear space propulsion systems. His areas of interest also include radiation damage evolution in nuclear fuels and structural materials and the safeguards of special nuclear material.