PACE GLOBAL
A Siemens Business

4401 Fair Lakes Court
Fairfax, VA 22033 USA
Phone: 1.703.818.9100
www.paceglobal.com

LIGHTBRIDGE METALLIC PWR FUEL EVALUATION OF PROLIFERATION RESISTANCE PROPERTIES

Prepared for:

Lightbridge

March 18, 2013

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TABLE OF CONTENTS

EXHIBITS

TABLES

INTRODUCTION

Lightbridge is developing a new nuclear fuel design for use in U.S pressurized water reactors (PWR). The new fuel consists of a uranium/zirconium metallic material extruded into fuel rods that possess a cruciform cross-section enclosed by zirconium cladding. The uranium used in the resulting fuel assemblies is enriched to a maximum of 19.7 wt % U-235 rather than the 5 wt % maximum enrichment used in current uranium dioxide fuel designs.

This report presents a review of the non-proliferation aspects of this fuel at several stages in the life cycle in comparison with current fuel designs. New fuel and used fuel for Westinghouse four-loop plants operating at their original 100% power level, as well as at a level of 117% of their original power, are compared. The quantitative evaluation is based on Lightbridge supplied data.

The report considers the government and regulations in effect in the United States in 2013.

PROLIFERATION RESISTANCE

The classic definition of (non-) proliferation as defined by the Department of Defense (DoD) is given as:

Those actions (e.g., diplomacy, arms control, multilateral agreements, threat reduction assistance, and export controls) taken to prevent the proliferation of weapons of mass destruction by dissuading or impeding access to, or distribution of, sensitive technologies, material, and expertise.

In this review, the (non-) proliferation aspects of Lightbridge fuel are limited to an analysis of the physical properties of the fuel itself. In order to remain within the scope of the project, political, institutional, and/or organizational aspects of non-proliferative strategies, requirements, and safeguards are necessarily not considered. To compare the Lightbridge fuel with current designs, critical physical characteristics of the two Lightbridge fuel designs (100% and 117% of original plant power rating) under consideration will be compared at different stages in their life cycle with a generic PWR UO_2 fuel which would serve to power an equivalent reactor with identical power level and cycle length. The following physical characteristics which can be associated with possible diversionary activities were considered, and those most applicable to the analyses were discussed in detail:

- Quantity of material – Is the amount of fuel on hand at this stage sufficiently different to affect its proliferation characteristics?
- Quality of material – Do the fuel materials have different amounts of enrichment that might affect the usefulness in construction of a nuclear explosive device?
- Ease of processing into an explosive device – Is there a difference in the physical or chemical properties of the fuel that would affect the ease of processing it into an explosive device?
- Radiological properties – Are the radiological properties of the material such that the usefulness of constructing an explosive device are enhanced or reduced?
- Nuclear criticality issues – Is either material subject to inadvertent criticality during processing or handling?
- Material handling properties – Are any of the material properties that affect material handling (weight, radiation level, size, shape) sufficiently different to affect non-proliferation?
- Timing of material transfer(s) – Does the frequency or duration of material transfers differentiate between the Lightbridge and generic PWR UO2 fuel types?

The evaluation considers this comparison within the regulatory framework of the United States. The U.S. is a signatory to the international Nuclear Non-Proliferation Treaty, which serves to constrain signatory countries from developing nuclear weapons. Regulatory guidance and compliance inspection is provided by the International Atomic Energy Agency (IAEA), an agency of the United Nations.

Within the U.S., regulatory authority resides with the Nuclear Regulatory Commission (NRC), an agency of the Federal government. Regulations restrict ownership and control of nuclear material. NRC regulations assure that nuclear material is physically secure and that materials are carefully accounted for. Verification of these activities is provided by the NRC through inspections and document reviews. In addition, steps such as video surveillance and seals on containers of radioactive material assure that material security is preserved.

IAEA and NRC regulations classify nuclear material with less than 20 wt % U–235 as Low Enriched Uranium (LEU). This material cannot be used directly for the construction of nuclear weapons, which require uranium enrichments at about the 90% level. Current U.S. reactor fuels and the proposed Lightbridge design are all classified as LEU.

NEW FUEL

This section compares the characteristics of the Lightbridge metallic fuel with uranium oxide PWR fuel that is similar to current designs at the stage when the fuel has been manufactured but has not been irradiated or used in any way.

QUANTITY OF MATERIAL FOR LIGHTBRIDGE NEW FUEL

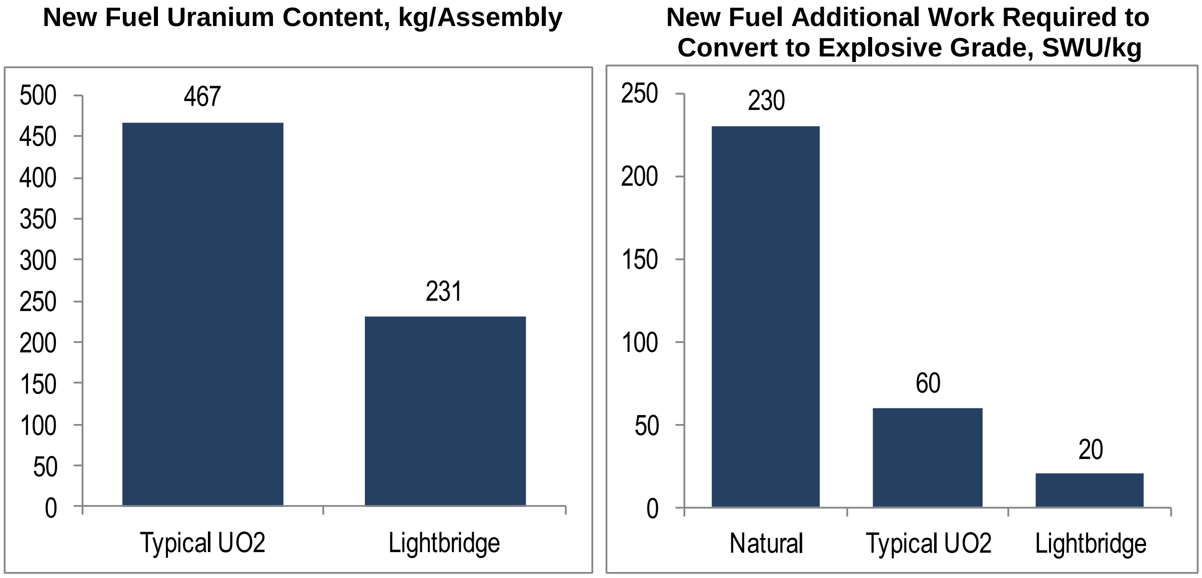
A review of Lightbridge-supplied data indicates that the Lightbridge fuel assemblies contain significantly less total uranium than standard PWR fuel assemblies (Exhibit 1). Based on this data, for a generic average 17x17 PWR fuel assembly, each reload batch requires 80 fuel assemblies with an enrichment of approximately 4.4 wt % U-235 for an 18 month cycle. This results in a mass of U-235 of approximately 20.3 kilograms contained in a total mass of about 470 kilograms of total uranium in each fuel assembly. This uranium is contained in the ceramic UO_2 matrix of the conventional fuel pellets.

In contrast, a Lightbridge fuel assembly is composed of two types of uranium fuel; a metallic uranium-zirconium region is composed of a 15x15 lattice wholly surrounded on the periphery by a single row of conventional UO_2 fuel rods. For a standard 18-month cycle, Lightbridge indicates that approximately 18.7 kilograms of U-235 are contained in the metallic fuel region at an enrichment level of approximately 14 wt % U-235. However, total mass of uranium in the metallic fuel region is only about 134 kg. For the conventional UO_2 rods on the periphery, an approximate enrichment of 3 wt % U-235 in the UO_2 is used. This results in a peripheral mass of U-235 of about 3 kilograms in the UO_2 of each assembly. This gives a total of about 21.7 kilograms of U-235 contained in the entire fuel assembly, for a total of about 231 kilograms of uranium.

For a Lightbridge design for 117% uprated power, the metallic fuel enrichment is increased to near 17 wt % U-235 by using about 22.8 kilograms of U-235 for a total uranium mass of about 134 kg in the metallic portion of the fuel. The peripheral UO_2 rods are the same as those used in the non-uprate Lightbridge design. The total mass of uranium in the fuel assembly remains the same at about 231 kilograms of uranium, but now a portion of this uranium has a higher enrichment in U-235.

As can be seen, the total uranium content of Lightbridge fuel assemblies is far less than that contained in standard fuel. This is balanced by the increased enrichments of the metallic portions of the Lightbridge fuel assemblies. The reload batch size for both conventional and Lightbridge fuel for 18-month cycles is estimated at 80 assemblies. Although the total uranium mass is significantly less in the Lightbridge design, the additional zirconium used in the metallic regions results in fuel assemblies that are only about 70 kg lighter (mass) than conventional fuel.

Exhibit 1: Lightbridge New Fuel Uranium Comparison



New Fuel Uranium Content, kg/Assembly

New Fuel Additional Work Required to Convert to Explosive Grade, SWU/kg

Note: See Table 1 in the Appendix for detail.

Source: Per data supplied by Lightbridge

QUALITY OF MATERIAL FOR LIGHTBRIDGE NEW FUEL

Overall, Lightbridge metallic fuel will be enriched to a maximum of 19.7 wt % U-235 (depending on fuel design requirements), while standard uranium oxide fuel is assumed to be enriched to the current regulatory maximum limit of 5 wt % U-235 for power uprate applications.

The increased enrichment of the Lightbridge metallic fuel would be of preliminary interest to a potential diverter. However, it has been shown in the general literature that the 19.7 wt % U-235 cannot be fashioned into a nuclear device without further enrichment (increase) processing. The diverter organization would have to have access to an enrichment facility in order to gain this advantage.

In the United States, enrichment facilities are closely regulated. Nuclear material entering and leaving such facilities is carefully tracked and accounted for, making it extremely difficult to divert either fuel type for additional enrichment. The size, cost, and use of specialized equipment in an enrichment facility assure that none could be designed and constructed in the U.S. without the cognizance and oversight of the regulatory agencies.

If these safeguards could be somehow overcome, the Lightbridge fuel would be somewhat more desirable for an organization endeavoring to construct a nuclear device because it would require less separative work units (SWU) in the (additional) enrichment process to reach a highly-enriched state than if starting with lower-enriched uranium oxide fuel. However, it has been shown that the amount of separative work *savings* required to enrich the Lightbridge material to an explosive grade above 5 wt % U-235 is only about 40 SWU per kilogram of final product above that required for 5 wt % U-235. This savings result occurs since it takes approximately 60 total SWU (to enrich to an explosive grade) if starting from an initial feed enrichment of 5 wt % U-235, and 20 total SWU if starting from a feed enrichment of ~20 wt % U-235. Natural enrichment feed (0.711 wt % U-235) requires approximately 230 SWU per kilogram of product to enrich to an explosive grade.

Consequently, there is little advantage to be gained by a potential diverter to focus on fresh Lightbridge fuel as a diversionary target over the vastly more prevalent supplies of fresh UO_2 fuel. The additional required complex chemical processing of the metallic portion of the fuel would make the diversion even less likely. In fact, if a diverter had the necessary access to enrichment facilities, it would actually be more efficient and stealthy for the diversionary organization to process natural uranium to the highly-enriched state as it could then easily bypass national safeguards on enriched uranium emplaced by all the world's recognized nuclear states.

EASE OF PROCESSING INTO EXPLOSIVE DEVICE FOR LIGHTBRIDGE NEW FUEL

The Lightbridge fuel is comprised of a metallic combination of zirconium and uranium coated with a zirconium layer to form the fuel rod cladding. Converting this material to UF_6 feedstock material for an enrichment facility would be extremely difficult, as it is believed no industrial-scale process has been developed for this purpose.

As stated above, the converted uranium (to UF_6) would then have to be further enriched by some process with a similar difficulty to that derived from conventional UO_2 LWR fuels, and a subversion of national in-place safeguards required.

RADIOLOLGICAL PROPERTIES/NUCLEAR CRITICALITY/MATERIAL HANDLING ISSUES FOR LIGHTBRIDGE NEW FUEL

Lightbridge fuel with enrichments near 20 wt % may require special containers to ensure exclusion of water (or other hydrogenous materials) to prevent inadvertent low-level, subcritical multiplication or exceeding $k_{eff} < 0.98$ requirements. This concern would be confirmed in the final fuel assembly design process. No other special constraints over conventional new fuel assemblies are envisioned. In any event, this would have little bearing on proliferation concerns.

TIMING OF MATERIAL TRANSFERS FOR LIGHTBRIDGE NEW FUEL

No issues of transport or time requirements are associated with new Lightbridge fuel assemblies that would be different from conventional UO_2 fuel assemblies with respect to non-proliferation concerns.

POWER LEVEL: 100% VS. 117% FOR LIGHTBRIDGE NEW FUEL

Although fuel for a reactor that is modified to operate at an increased power level will contain more U-235 than a reactor at 100% power, the remainder of its mechanical and nuclear parameters remains the same. Therefore, there is no change in proliferation resistance for fuel designed to operate at a higher power level.

NEW FUEL SUMMARY

Using new Lightbridge fuel as a source of material for a nuclear device would require a sophisticated chemical/physical process to convert the metallic fuel material into supply feedstock to an enrichment plant. A complex chemical processing system would have to be developed and implemented prior to any utilization of the Lightbridge fuel for a diversionary activity. Conversely, the process to convert UO_2 into material (UF_6) for further enrichment processing is relatively well-defined for uranium oxide fuel.

After the conversion, the nuclear material would need additional enrichment processing in a highly-regulated and sophisticated enrichment facility. The Lightbridge fuel would require slightly less SWU energy than the equivalent uranium oxide fuel, but the development of the chemical conversion process required for the Lightbridge metallic fuel would most likely send a potential diverter to consider standard UO_2 fuel. In actuality, it would be more efficient and stealthy to use natural uranium as an enrichment feed.

SPENT FUEL

This section compares the characteristics of spent Lightbridge fuel with that of uranium oxide fuel similar to current designs using calculated parameters of the fuel materials after the fuel has been used for generating power. As a result of the fission process in the reactor, the spent fuel contains fission products, which are generally highly radioactive isotopes of the remnants of the heavy fuel nuclei which have fissioned. In addition, some of the U-238 in the fuel is converted to plutonium during reactor operation and a portion remains after discharge in the spent fuel. Depending on the irradiation history of a reactor, this plutonium may be, in some cases, used for the construction of a nuclear weapon, albeit a different type than that constructed using high-enriched uranium.

QUANTITY OF MATERIAL (URANIUM/PLUTONIUM) IN LIGHTBRIDGE SPENT FUEL

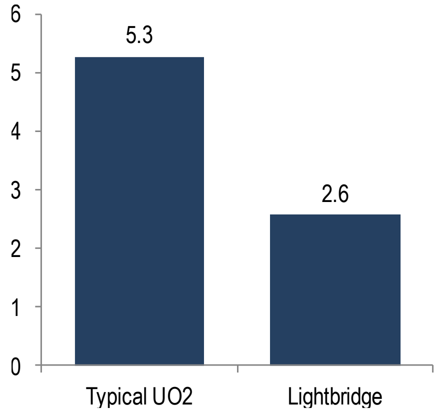
Current uranium dioxide PWR fuel and the Lightbridge metallic fuel designs contain approximately the same amount of U-235 when they are new for a given core power level. The Lightbridge fuel design requires the use of a higher percentage of the U-235 for power generation but also creates a significantly smaller amount of fissile Pu-239 in spent fuel. Spent fuel compositional masses and isotopes for typical UO_2 and Lightbridge PWR fuel designs are shown in Exhibit 2.

In a standard 18-month cycle UO_2-fueled PWR, approximately 78% of the original U-235 atoms are consumed. In contrast, a Lightbridge metallic fuel 18-month cycle results in the consumption of approximately 86% of the original U-235 atoms. The case of Lightbridge fuel used in a power uprate of 117% results in an even higher consumption of the original U-235 atoms, to almost 89%.

The amount of residual plutonium at the end of the cycle is significantly smaller in the Lightbridge designs as compared to UO_2 fuels. For example, for a PWR 18-month UO_2 fuel cycle with a core power level of 3,400 MWt, approximately 5.3 kg of plutonium is left in each assembly at discharge. In comparison, only about 2.6 kg of plutonium remains in a Lightbridge fuel assembly at discharge.

The low residual amount of plutonium in Lightbridge fuel, therefore, means that a potential diverter would actually have a greater interest in a standard UO_2 spent fuel assembly than a spent Lightbridge fuel assembly. The extremely low residual U-235 in the Lightbridge fuel would only compound this disinterest of the diverter.

Exhibit 2: **Lightbridge Spent Fuel Actinide Masses – kg per Assembly**



Note: See Table 2 in Appendix for detail.

Source: Per data supplied by Lightbridge.

QUALITY OF MATERIAL (PLUTONIUM) IN LIGHTBRIDGE SPENT FUEL

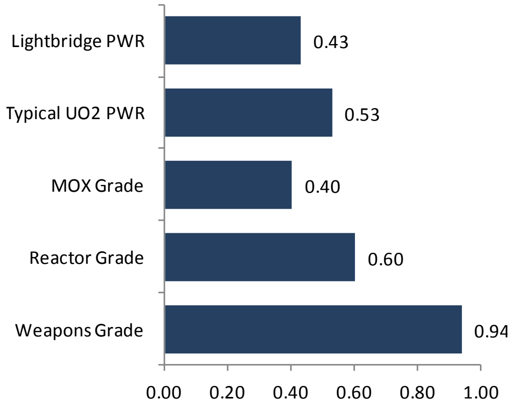
As noted above, spent UO_2 or Lightbridge fuel has little remaining U-235 that would be of interest to a potential diverter. The remaining enrichment is in some cases less than that of natural uranium. In addition, this remaining U-235 is embedded in the highly radioactive fission product matrix of the spent fuel. Therefore, in the case of spent fuel, the remaining plutonium becomes a possible target for diversionary activity. Plutonium consists of several isotopes which are co-produced during the operation of the reactor. Pu-239 and Pu-241 are fissile and are of interest to a diverter. Pu-240 and Pu-242 are neutron poisons and tend to denature the ability of Pu-239 to create an explosion.

The ratio of the plutonium isotopes Pu-238/Pu-239/Pu-240/Pu-241 and Pu-242 define the ‘grade’ of the plutonium for use in a possible nuclear device. Exhibit 3 presents a simplified analysis of plutonium grade materials, and shows the Lightbridge fuel and the comparative UO_2 fractions at the end of an 18-month cycle.

In Exhibit 3, it can be seen that weapons-grade Pu has a large fraction of Pu-239 and little other Pu isotopes. This is produced in special nuclear reactors which have very low burn-up before the matrix containing the Pu is discharged for processing. Pu-239 is produced before the other Pu neutron poisons can build in. Reactor-grade Pu, as shown in the Exhibit 3 is similar to the compositions found in LWRs, including PWRs. It is reasonably comparable to the Lightbridge-supplied data for a generic PWR using UO_2 fuel. MOX grade is similar to plutonium that has been reprocessed and formed into new fuel assemblies for reuse in a power reactor. MOX grade, as can be seen in Exhibit 3, has the least amount of Pu-239 and a relatively large amount of the neutron poisons Pu-240 and 242. The Lightbridge spent fuel most closely resembles this grade of plutonium.

We can conclude that with the low fraction of residual Pu-239 and relatively large fractions of neutron poisons, Lightbridge metallic fuel would be a poor choice for a plutonium weapon. In fact, the Pu ratios demonstrate that on this basis, a potential diverter would also have less interest in Lightbridge fuel than the equivalent UO_2 fuel.

Exhibit 3: Plutonium Fractions and Grades, Pu-239



Note: See Table 2 in Appendix for detail.

Source: Per data supplied by Lightbridge.

EASE OF PROCESSING INTO EXPLOSIVE DEVICE FOR LIGHTBRIDGE SPENT FUEL

Per the IAEA, reactor-grade plutonium from civil spent fuel has a lower fraction of Pu-239 than weapons-grade due to the relatively high levels of burn-up in civil nuclear power reactors. It has a greater quantity of undesirable isotopes of plutonium that would complicate the use of civil nuclear materials in nuclear weapons, decreasing the reliability of a nuclear explosion. In addition, Pu-238 decays relatively rapidly, generating significant amounts of heat. Pu-240 could set off the chain reaction prematurely through its high rate of spontaneous fission characteristic, substantially reducing explosive yield as the weapon could blow itself apart and cut short the chain reaction. Pu-241, although fissile, decays to Am-241, which absorbs neutrons and emits intense gamma radiation. These isotopes require careful management and extensive shielding to protect personnel when handling these materials, and they could damage other components in a nuclear weapon. There is no well-defined threshold for this higher burn-up above which plutonium becomes unusable for weapons, so the working hypothesis is that all reactor grades of plutonium pose a proliferation risk. Further, a plutonium device would require a highly sophisticated configuration and triggering device as compared with an enriched uranium device.

The above nuclear characteristics make the construction of a plutonium device technologically more complex for a diverter when compared to an enriched uranium device. However, as also demonstrated above, considering the residual quantity and quality plutonium in Lightbridge fuel, it can be observed that a potential diverter would have a greater interest in UO_2-based spent fuels than Lightbridge spent fuel.

RADIOLOGICAL/CRITICALITY/ MATERIAL HANDLING PROPERTIES FOR LIGHTBRIDGE SPENT FUEL

Regardless of the spent fuel assembly origin, working with spent nuclear fuel is difficult because of the high radiation fields near unshielded fuel. In a nuclear power plant spent fuel pool, where fuel is typically stored for at least five years after use, fuel is normally covered by at least 20 feet of water to maintain the areas near the fuel pool as safe working environments for the plant employees. These radiological properties are sufficiently adverse such that there is no differentiation made between fuel designs regarding proliferation resistance from this parameter.

The primary radiological properties of spent fuel are radiation and heat generation. Based on Lightbridge-supplied data, it is demonstrated that the Lightbridge spent fuel would have slightly higher decay heat emanation (~4%) for a period of three years to 20 years post-discharge from a reactor. This additional decay heat would have to be accommodated by the spent fuel cooling systems of nuclear power plants or storage casks in which the spent Lightbridge fuel is stored. It is judged that this additional decay heat would have little effect on the non-proliferation characteristics of the Lightbridge fuel, particularly so when it has already been demonstrated above that Lightbridge fuel is less attractive to a diverter than UO_2 fuel, based on its isotopics.

Post-irradiation Lightbridge spent fuel would have no special criticality characteristics apart from spent UO_2 fuel, and therefore no difference from a non-proliferation perspective.

From a material handling perspective, the high radiation levels from spent fuel dictate that fuel is stored in massive casks or containers. These casks are typically made from multiple layers of high strength stainless steel, with layers of high density concrete used for added shielding. They may weigh 100 tons or more. Although this is a significant deterrent to theft, the differentiation between fuel types is small.

TIMING OF MATERIAL TRANSFERS FOR LIGHTBRIDGE SPENT FUEL

Due to the low residual U-235 content, low post–irradiation Pu amount and quality as compared with conventional UO_2 fuels, Lightbridge spent fuel would have almost no attractiveness to a potential diverter over UO_2 spent fuel assemblies. As such, material transfer and handling concerns would be the same as, or less than, conventional UO_2 LWR fuels.

POWER LEVEL: 100% VS. 117%

Spent fuel for a reactor that is modified to operate at an increased power level will contain more U-235 and Pu-239 than that from a reactor at 100% power. However, this difference does not make the spent fuel from a 117% uprated generating unit substantially more desirable for weapons construction.

SUMMARY

As demonstrated above, the low residual amount of plutonium, the poor explosive grade per calculated plutonium ratios, and scant remaining uranium in Lightbridge fuel suggests that a potential diverter would actually have a greater interest in standard UO_2 spent fuel than Lightbridge spent fuel.

Further, spent fuel from any power reactor in the U.S. exhibits potentially lethal high radiation levels and must be maintained in large, very heavy containers. These features make spent fuel undesirable as a source of weapons material.

In addition, Lightbridge fuel is constructed of a metal mixture that has not been studied for reuse of its nuclear constituent materials. This comparison applies for plants uprated to 117% of original power level, as well as for plants that have not been uprated.

PROLIFERATION POTENTIAL DURING NUCLEAR FUEL LIFE CYCLE

A comparison of the proliferation potential of the Lightbridge metallic fuel design compared with the current UO_2 fuel is presented in Exhibit 4, below:

Exhibit 4: Comparison of the Proliferation Potential of Lightbridge Metallic Fuel and Current UO2 Fuel

Life Cycle Element	Material Description	Current Fuel	Lightbridge Fuel	Proliferation Comment
Conversion	Ore is converted to UF_6 gas.			No difference. UF_6 not useful for weapons without enrichment.
Enrichment	UF_6 is processed to increase amount of U-235.	5 wt % enrichment. Cannot directly be made into a weapon.	19.7 wt % maximum enrichment. Cannot directly be made into weapon.	Higher Lightbridge enrichment would need only slightly less SWU energy to process into weapons grade material than 5 wt % UO_2. Enrichment facility has security per regulations to deter proliferation.
Fuel Fabrication	Fuel assemblies approx. 4 meters long.	UO_2 pellets in Zircaloy tubes. 17x17 array.	Extruded zirconium/ uranium metal rods. Also uses UO_2 blanket rods around periphery in a 17x17 compatible array.	Difficult to separate uranium from metal rods (Lightbridge). Fabrication facility has security per regulations to deter proliferation.
Transportation	Fuel assemblies in shipping containers. 4-6 bundles per shipment.	UO_2 pellets in Zircaloy tubes. 17x17 array.	Extruded zirconium/ uranium metal rods. UO_2 blanket rods around periphery in a 17x17 compatible array.	Shipping process controlled to prevent diversion of nuclear material.
Storage at Power Plant	Fuel assemblies in fuel pool or storage areas.	UO_2 pellets in Zircaloy tubes. 17x17 array.	Extruded zirconium/ uranium metal rods. UO_2 blanket rods around periphery in a 17x17 compatible array.	Fuel moved to fuel pool or storage after receipt inspection. Power Plant has excellent security.

Life Cycle Element	Material Description	Current Fuel	Lightbridge Fuel	Proliferation Comment
Reactor Operation	Fuel assemblies in reactor.	UO_2 pellets in Zircaloy tubes. 17x17 array.	Extruded zirconium/ uranium metal rods. UO_2 blanket rods around periphery in a 17x17 compatible array.	Reactor head bolted on. No personnel access to fuel. Power Plant has excellent security.
Spent Fuel Storage	Highly radioactive fuel assemblies in spent fuel pool (~5 years). Highly radioactive fuel assemblies in casks at on-site fuel storage facility (> 5 years).	UO_2 pellets in Zircaloy tubes. 17x17 array. ~5.3 kg Pu per spent fuel assembly.	Extruded zirconium/ uranium metal rods. UO_2 blanket rods around periphery in a 17x17 compatible array. ~2.6 kg Pu per spent fuel assembly.	Less Pu (Lightbridge). Power Plant has excellent security. Dry storage casks are heavy and robust. Storage facility has security.

Source: Pace Global, Lightbridge data

NON PROLIFERATION SUMMARY

For the Lightbridge fuel designs as compared to typical PWR UO_2 fuels, it is observed that:

- The overall total uranium content of Lightbridge fuel assemblies is far less than that contained in equivalent PWR UO_2 fuel. The nuclear design fissile requirement is met by the increased enrichments used in the metallic portions of the Lightbridge fuel assemblies such that the number of fissile uranium atoms contained in the two types of fuel assemblies is about the same.
- There is little advantage to be gained by a potential diverter to focus on fresh Lightbridge fuel as a diversionary target over the vastly more prevalent supplies of fresh UO_2 fuel. The additional required complex chemical processing of the metallic portion of Lightbridge fuel would make the diversion less attractive and easily overcomes a slightly reduced separative work unit (SWU) requirement associated with Lightbridge higher initial enrichments.
- The amount of residual plutonium at the end of the operating cycle is significantly smaller in the Lightbridge designs as compared to UO_2 fuels. The low residual amount of plutonium in Lightbridge fuel results in a potential diverter having a greater interest in a standard UO_2 spent fuel assembly than a spent Lightbridge fuel assembly. The extremely low residual U-235 in the Lightbridge fuel would only compound this disinterest of the diverter.
- The low fraction of residual Pu-239 and relatively large fractions of neutron poisons in Lightbridge metallic fuel means that the Lightbridge fuel would be a poor choice for processing into a plutonium weapon. In fact, the Pu ratios demonstrate that on this basis, a potential diverter would have more interest in a standard UO_2 spent fuel assembly than a spent Lightbridge fuel assembly.

- Security systems and regulatory controls are in place to minimize proliferation from power reactor fuel facilities. Where differences are identified, the Lightbridge design is favored in comparison with standard UO2 fuel. This comparison applies for plants uprated to 117% of original power level, as well as for plants that have not been uprated.

APPENDIX

Table 1: Lightbridge New Fuel Uranium Masses – Kg per Assembly

	Typical 18 Month Cycle UO_2 PWR @3400 MWt		Lightbridge 18 Month Cycle Metallic PWR Fuel @3400 MWt						Lightbridge 18 Month Cycle Metallic PWR Fuel @17% Power Uprate					
			Metallic Seed		Peripheral Rod Blanket		Fuel Assembly Composite		Metallic Seed		Peripheral Rod Blanket		Fuel Assembly Composite	
Uranium Isotope	mass	wt %	mass	wt %	mass	wt %	mass	wt %	mass	wt %	mass	wt %	mass	wt %
U-235	20.3	4.4	18.7	14.0	2.9	3.0	21.7	9.4	22.8	17.1	2.9	3.0	25.7	11.1
U-238	446.7	95.6	114.9	86.0	94.6	97.0	209.4	90.6	110.8	82.9	94.6	97.0	205.4	88.9
Total U	467.0	100.0	133.6	100.0	97.5	100.0	231.1	100.0	133.6	100.0	97.5	100.0	231.1	100.0

Source: Per data supplied by Lightbridge

Table 2: Lightbridge Spent Fuel Actinide Masses – Kg per Assembly

	Typical 18 Month Cycle UO_2 PWR @3400 MWt		Lightbridge 18 Month Cycle Metallic PWR Fuel @3400 MWt						Lightbridge 18 Month Cycle Metallic PWR Fuel @17% Power Uprate (3980 MWt)					
			Metallic Seed		Peripheral Rod Blanket		Fuel Assembly Composite		Metallic Seed		Peripheral Rod Blanket		Fuel Assembly Composite	
Uranium Isotope	mass	wt %	mass	wt %	mass	wt %	mass	wt %	mass	wt %	mass	wt %	mass	wt %
U-235	4.3	1.0	2.5	2.3	0.5	0.5	3.0	1.5	2.5	2.4	0.4	0.4	3.0	1.5
U-238	431.3	99.0	108.7	97.7	90.8	99.5	199.5	98.5	104.1	97.6	90.2	99.6	194.2	98.5
Total U	435.7	100.0	111.2	100.0	91.3	100.0	202.5	100.0	106.6	100.0	90.6	100.0	197.2	100.0
Plutonium Isotope	mass	wt %	mass	wt %	mass	wt %	mass	wt %	mass	wt %	mass	wt %	mass	wt %
Pu-238	0.1	2.3	0.1	6.8	0.03	2.5	0.1	5.1	0.2	9.2	0.03	2.7	0.2	6.5
Pu-239	2.8	52.9	0.7	41.9	0.5	45.0	1.1	43.1	0.7	41.2	0.6	47.7	1.3	43.9
Pu-240	1.2	23.5	0.4	24.0	0.3	27.1	0.6	25.2	0.4	21.8	0.3	23.7	0.7	22.6
Pu-241	0.8	14.6	0.2	14.4	0.1	14.7	0.4	14.5	0.3	15.5	0.2	15.8	0.5	15.7
Pu-242	0.3	6.6	0.2	12.9	0.1	10.8	0.3	12.1	0.2	12.2	0.1	10.0	0.3	11.3
Total Pu	5.3	100.0	1.6	100.0	1.0	100.0	2.6	100.0	1.8	100.0	1.2	100.0	3.0	100.0

Source: Per data supplied by Lightbridge

Table 3: Plutonium Fractions and Grades

	Per J. C. Mark*			Per Lightbridge-Supplied Data						
					Lightbridge 18 Month Cycle Metallic PWR Fuel @3400 MWt			Lightbridge 18 Month Cycle Metallic PWR Fuel @17% Power Uprate		
Plutonium Isotope	Weapons Grade	Reactor Grade	MOX Grade	18 Month Cycle UO_2 PWR @3400 MWt	Metallic Seed	Peripheral Rod Blanket	Fuel Assembly Composite	Metallic Seed	Peripheral Rod Blanket	Fuel Assembly Composite
Pu-238	.00012	.013	.019	0.023	0.068	0.025	0.051	0.092	0.027	0.065
Pu-239	.938	.603	.404	0.529	0.419	0.450	0.431	0.412	0.477	0.439
Pu-240	.058	.243	.321	0.235	0.240	0.271	0.252	0.218	0.237	0.226
Pu-241	.0035	.091	.178	0.146	0.144	0.147	0.145	0.155	0.158	0.157
Pu-242	.00022	.050	.078	0.066	0.129	0.108	0.121	0.122	0.100	0.113

* “Explosive Properties of Reactor-Grade Plutonium”, J. Carson Mark, Science and Global Security, (2009).

Source: Per data supplied by Lightbridge