Nuclear fuel fabrication

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13.1 Introduction

Fabrication of nuclear fuel assemblies for nuclear power plants (NPPs) is the step in the front end of the nuclear fuel cycle when nuclear fuel is transformed from a fungible commodity (eg, natural or enriched uranium, or other fissile material) into a highly engineered product, with designs that are tailored to a specific NPP's needs. That is, fuel assembly designs are specific to a given reactor type (generally based on the nuclear steam supply system (NSSS)) and a specific NPP's fuel management strategy (which considers cycle length, capacity factor, existing fuel in the reactor core, etc.) The nuclear fuel fabrication market for light water reactor (LWR) fuel assemblies is the largest—approximately 82% of the operating NPPs in the world are LWRs. Among LWR designs, there are two general categories of plants: (1) pressurized water reactors (PWR), including Russian VVER designs, and (2) boiling water reactors (BWR), which made up 63.4% and 18.4% of operating units at the end of 2014, respectively, as shown Fig. 13.1. Non-LWR NPP designs include gas-cooled reactors (GCR), pressurized heavy water reactors (PHWR), Russian graphite-moderated reactors (RBMK), and liquid-metal-cooled fast reactors (LMR). PHWRs are the second largest segment of operating NPPs after LWRs, with 11% of all operating reactors worldwide, as shown in Fig. 13.1 (ANS, 2015).

Fig. 13.1 provides a comparison of the percentage of operating NPPs in each category of reactor as well as the percentage of operating MWe for each reactor category. LWRs, both PWRs and BWRs, dominate both the number of operating NPPs and the amount of electricity produced by NPPs worldwide. This trend is expected to continue to through 2035 as LWRs grow from 81.8% of total nuclear generation to 88.6% (ERI, 2015).

13.1.1 Fuel fabrication service suppliers

As the LWR market is by far the largest segment of the nuclear fuel fabrication market, it is the most competitive. At the present time, there are three principal international nuclear fuel fabricators that supply a broad range of LWR fuel assemblies of various designs to owners and operators of NPPs in Asia, Europe, and North America: AREVA NP (AREVA), Global Nuclear Fuel (GNF), and Westinghouse Electric Company (Westinghouse). All three companies operate production facilities in the US and Europe, and GNF and Westinghouse also operate fuel production facilities in Japan. In addition to the principal fuel fabricators, there are a number of other

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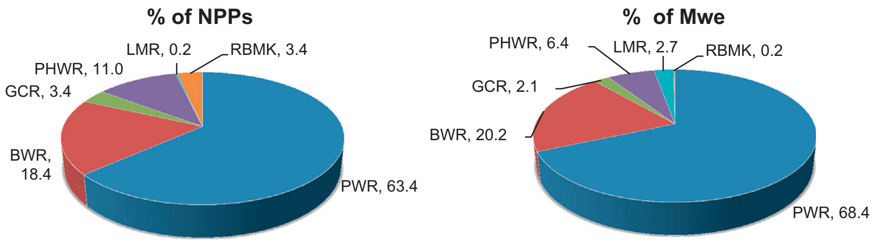

Figure 13.1 Types of NPPs, % of operating units and % of MWe.

companies that supply both LWR and non-LWR fuel to national and regional markets. The fuel fabricators are described next in alphabetical order.

AREVA NP is a wholly owned subsidiary of AREVA. AREVA is headquartered in Paris, France and has offices and manufacturing facilities around the world. AREVA's North American operations are administered by AREVA, Inc., which is currently headquartered in Charlotte, North Carolina. AREVA NP is a fully integrated fuel fabricator. In addition to fuel assemblies, it produces zirconium alloys, cladding, and other components through its subsidiary facilities in France and Germany.

AREVA operates two fuel fabrication facilities in Europe as well as several plants in France and Germany that produce zirconium alloys and fuel assembly components. AREVA's operating European plants for LWR fuel fabrication include the Romans, France plant that produces UO_2 powder and pellets as well as fabricated PWR fuel assemblies; and the Lingen, Germany fabrication facility that produces both BWR and PWR fuel assemblies. The Romans facility is rated at 1400 MTHM, or tonnes, per year with an annual dry UF_6 to UO_2 conversion capacity of 1800 MTHM and pelletization capability of 1400 MTHM/year. The capacity at Lingen is nominally 800 MTHM/year for conversion of UF_6 to UO_2, and 650 MTHM/year for pelletization and fuel assembly manufacturing. AREVA also operates a mixed oxide (MOX) fuel fabrication plant at Marcoule, in France, with an annual MOX fuel fabrication capacity of 195 MTHM.

AREVA's US fabrication operations are centered in Richland, Washington. The Richland plant manufactures both PWR and BWR fuel assemblies for US customers and BWR fuel for plants in Taiwan. Present capability at Richland for conversion of UF_6 to UO_2 powder is 1800 MTHM/year. Pellet manufacturing capacity is 1800 MTHM, and fuel assembly capacity is 750 MTHM/year. AREVA supplies UO_2 powder to Nuclear Fuel Industries of Japan from its Richland facility under a long-term supply contract. The Richland plant has also provided UO_2 powder in support of some of AREVA's European fabrication activities.

For almost two decades, AREVA NP and its predecessor companies have subcontracted with the Russian fabricator TVEL for the manufacture of fuel assemblies for NPPs in Germany, Sweden, and Switzerland. The fuel assemblies manufactured by TVEL contain reprocessed uranium (RepU) and are of standard AREVA designs using components supplied by AREVA. The RepU is blended with Russian HEU to the desired assays, processed, and fabricated by TVEL (ERI, 2015; WNA, 2013).

Cameco Corporation produces PHWR fuel for CANDU NPPs. It operates two manufacturing facilities: a fabrication facility in Cobourg, Ontario Province, for production of fuel bundle components and a fuel manufacturing plant in Port Hope, Ontario Province. One of the processes at the Port Hope conversion facility is to convert uranium trioxide (UO_3) to UO_2 powder, which the fuel manufacturing facility processes into UO_2 pellets for CANDU fuel assemblies. Capacity of the Port Hope fuel manufacturing facility is 1200 MTHM/year (Cameco, 2015a).

China National Nuclear Corporation (CNNC) has two nuclear fuel fabricators. The first is China Jianzhong Nuclear Fuel (CJNF), which through its subsidiary, China South Nuclear Fuel Co., Ltd (CSNFC), operates the fuel manufacturing facility at Yibin in Sichuan province. The second fabricator is China North Nuclear Fuel Co., Ltd (China Nuclear Northern, CNNFC), located in Baotou, Inner Mongolia. The CNNFC fuel fabrication facility in Baotou, also houses CNNC-Baotou Nuclear Fuel Company (CBNFC), which has been established to manufacture fuel for Westinghouse AP1000s built in China. CNNC has technology transfer agreements in place with AREVA, TVEL, and Westinghouse for PWR fuel supply (WNA, 2015a).

Precise fabrication capacity for various fuel designs being used in China is difficult to obtain. Data provided herein are estimates based on information from a variety of sources. In 2014, CSNFC announced that it expanded annual production capacity from 400 t to 800 MTHM. The facility is expected to continue to expand as fuel fabrication requirements grow. CNNFC fabricates fuel for two Canadian PHWRs in China, with an annual capacity of 200 MTHM/year and for Chinese-designed PWRs (including the Chasma PWRs in Pakistan), with estimated annual PWR fuel manufacturing capacity of 200 MTHM. It is also preparing to build a line to make pebble-bed fuel for high-temperature GCR. Baotou Nuclear Fuel Company has an initial capacity of 200 MTHM for production of AP1000 fuel assemblies (WNA, 2015a).

AREVA and CNNC have a joint venture in place to fabricate zirconium alloy in China and produce zirconium tubes for Chinese nuclear fuel production. The joint venture, CNNC AREVA Shanghai Tubing Company (CAST) entered production in 2012 (WNA, 2015a).

Enusa Industrias Avanzadas, SA (ENUSA) was created in 1972 with responsibility for the development of all commercial and industrial activities related to Spain's nuclear fuel cycle. The State Industrial Holding Company, SEPI, owns 60% of ENUSA and the Centro de Investigaciones Energeticas, Medioambientales y Technologiecas, CIEMAT, (Research Center for Energy, Environment, and Technology) owns the other 40%. ENUSA's headquarters are in Madrid, where it conducts fuel design and marketing activities. ENUSA's Fuel Division is responsible for fuel engineering and manufacturing and has been operating a PWR and BWR fuel fabrication facility in Juzbado since 1985. The facility has capacity of approximately 390 MTHM, with annual production of 300–350 MTHM/year for pellet and fuel assembly manufacturing. ENUSA has licensing agreements with Westinghouse (as the European Fuel Group (EFG)) and GNF (as GNF ENUSA

Nuclear Fuel SA (GENUSA)) for PWR and BWR fuel fabrication, respectively. With respect to PWR fuel, Westinghouse supplies fuel assembly components and tubing, and UO_2 powder. For BWRs, GNF supplies components and ENUSA has a contract with Westinghouse for the supply of UO_2 powder (ERI, 2015; ENUSA, 2014, 2015).

GNF was established in January 2000 as an international nuclear fuel joint venture limited liability company by General Electric Company (GE), Hitachi, Ltd and the Toshiba Corporation. Organizationally, 60% of GNF is held by GE, with the remaining 40% being shared equally between Hitachi and Toshiba. In establishing GNF, the three companies integrated their nuclear fuel marketing, design, development, and manufacturing functions. The US base for GNF is Global Nuclear Fuel-Americas, LLC (GNF-A), which is comprised of GE's former BWR fuel business, including marketing, design, development, and sales, together with the Wilmington, North Carolina manufacturing facility and the Joint Conversion Company (JCC). GNF Japan (GNF-J), formerly Japan Nuclear Fuel Company, Ltd (JNF), now includes all BWR marketing, design and development operations that GE, Hitachi, and Toshiba had previously been engaged in separately, together with the fuel manufacturing function of JNF, to serve the Japanese market (ERI, 2015).

The JCC was originally created to operate a new 1200 MTHM/year UF_6 to UO_2 powder production facility at GE's Wilmington, North Carolina site. Pellet and fuel assembly production at the Wilmington facility are 1000 MTHM annually. The JCC facility utilizes process equipment and dry conversion process technology licensed from AREVA. GNF-Canada, the maker of CANDU fuel, provides natural (eg, unenriched) UO_2 pellets used in the natural uranium ends (referred to as "blankets") in GNF BWR fuel assemblies. GNF-A also manufactures cladding and other fuel assembly components, fuel channels, control rod drives and blades in Wilmington. Because it does not have zirconium alloy production facilities of its own, GNF has purchased its zirconium alloy materials from Westinghouse, Wah Chang, and AREVA (ERI, 2015).

GNF-J supplies BWR fuel exclusively to the Japanese market. It operates a 750 MTHM/year fuel fabrication facility in the town of Kurihama of Yokosuka-shi in Kanagawa-ken, Japan. GNF-A supplies UO_2 powder and fuel assembly components from the Wilmington facility and GNF-J produces the fuel pellets and fabricates the fuel assemblies (ERI, 2015; NRA, 2013).

GNF-Canada operates a fabrication facility for PHWR fuel in Peterborough, Ontario. The facility has an annual capacity for pellet and fuel assembly production of 1500 MTHM (GNF, 2015b).

India's Department of Atomic Energy (DAE) Nuclear Fuel Complex (NFC) was established in 1971 and is responsible for the supply of nuclear fuel assemblies and reactor core components for all of the NPPs operating in India. The facility in Hyderabad fabricates both natural and enriched uranium fuel, zirconium alloy cladding and reactor core components. The facility has a 48 MTHM capacity for manufacture of LWR fuel, and a 435 MTHM capacity for manufacture of PHWR fuel. NFC will also manufacture FBR fuel for planned NPPs. NFC operates a 50 MTHM fabrication facility for MOX fuel in Tarapur (WNA, 2015b; NFC, 2015).

Industrias Nucleares do Brasil (INB) operates a PWR fuel fabrication plant in Resende, Brazil. The fuel fabrication facility, which as constructed with technology and support from Siemens-KWU, has operated since 1982. INB has technology transfer agreements with Westinghouse to produce fuel assemblies of Westinghouse design for Angra Unit 1 and with AREVA to manufacture fuel for use in Angra Unit 2, which is a Siemens-KWU PWR. According to INB, its fuel fabrication facility has 160 MTHM/year of powder production capability, 120 MTHM/year of pelletization capability, and 240 MTHM/year of assembly capability (INB, 2015).

Japan Nuclear Fuel Limited (JNFL) operates nuclear fuel cycle facilities at Rokkasho-Mura and is in the process of constructing a MOX fuel fabrication facility at the site. The facility will have a maximum MOX fuel fabrication capacity of 130 MTHM annually and is planned to begin operation in 2016 (NRC, 2013).

Kazatomprom operates the Ulba Metallurgical Plant (UMP) at Ust-Kamenogorsk, which provided UO_2 pellet production for both VVER and RBMK units for TVEL. UMP has a reported annual conversion capacity of 1200 MTHM and pelletization capacity of 1200 MTHM, but no assembly capability. Kazatomprom provides pellets for fuel manufacture in China, Japan, and India.

KEPCO Nuclear Fuel Company, Ltd (KNFC), a subsidiary of Korea Electric Power Corporation (KEPCO), began operating a fuel fabrication facility at Taejon, Republic of Korea in October 1988. The facility was built under a technology exchange agreement with Siemens-KWU. KNFC is responsible for all PHWR and PWR fuel fabrication activities and is presently supplying 100% of the Republic of Korea's PWR fuel fabrication requirements to reactors of Combustion Engineering, Framatome, Westinghouse and KEPCO design (Song et al., 2009).

KNFC has a capacity of 700 MTHM/year to convert UF_6 to UO_2 powder using a dry conversion process and for pelletization. Fuel assembly capacity is 550 MTHM annually. KNFC also provides nuclear fuel research and development activities, CANDU fuel fabrication, and all fuel and core design for both CANDU units and PWRs in the Republic of Korea. CANDU fuel fabrication capacity is 400 MTHM/year (KNFC, 2015; WNA, 2013).

KNFC's Techno Special Alloy (TSA) zircaloy tube mill began operating in November 2008. The fully operational plant has a production capacity of 1400 km of tubing per year. Current products include fuel tubes, thimble tubes, instrument tubes, as well as various sleeves and flanges. In addition, KNFC is building a new facility for the manufacture of zirconium alloy tubes. The facility will be capable of producing 600 km of nuclear fuel cladding tubes per year. Construction is expected to be complete in 2016, and the facility is expected to begin production in 2017 (ERI, 2015).

KNFC and Westinghouse formed a joint venture, KW Nuclear Components Company, Ltd (KWN), to manufacture Control Element Assemblies (CEA). Westinghouse holds 55% and KEPCO Nuclear Fuel Company (KNF) holds 45% of KWN. These CEAs would be for the Combustion Engineering (CE)-designed NPPs, including OPR1000 and APR1400 units in Korea and the United Arab Emirates (UAE). Manufacturing would take place at the KNFC fuel fabrication plant in Daejeon. Production of CEAs began in 2011 (ERI, 2015).

Mitsubishi Nuclear Fuel Co. Ltd (MNF) is owned by Mitsubishi Heavy Industries (MHI), 35%; Mitsubishi Materials Corporation (MMC), 30%; AREVA, 30%; and Mitsubishi Corporation, 5%. MNF operates a PWR fuel fabrication facility in Tokai Mura, Japan, including a 475 MTHM/year UF_6 to UO_2 conversion plant to produce powder for pellet manufacturing. The pelletization and fuel assembly manufacturing capacity is 440 MTHM/year. MNF provides fuel development, design, manufacturing, and sales (ERI, 2015; NRA, 2013).

Nuclear Fuel Industries, Ltd (NFI) is jointly owned by Westinghouse (52%), and NFI (48%—which is owned by Furukawa Electric Company, Ltd (50%) and Sumitomo Electric Industries, Ltd (50%)). NFI operates two fuel fabrication facilities, a 383 MTHM/year facility in Kumatori, Japan for PWR fuel, and a fuel plant in Tokai Mura that produces 250 MTHM/year of BWR fuel. Neither plant produces UO_2 powder. NFI has an agreement with Kazatomprom's UMP to supply UO_2 fuel pellets to NFI for its use in manufacturing fuel assemblies (ERI, 2015; NRA, 2013).

Joint Stock Company (JSC) TVEL, a Rosatom subsidiary, provides a wide range of services dealing with nuclear fuel design, development and manufacturing. All of Russia's uranium conversion, enrichment and fuel fabrication facilities operate within the TVEL organization. Fuel fabrication facilities include those operated by JSC Mashinostroitelny Zavod (MSZ) at Elektrostal outside of Moscow and JSC Novosibirsk Chemical Concentrates Plant (NCCP) that operates a fabrication facility at Novosibirsk in Western Siberia. The MSZ plant produces UO_2 powder and pellets, including pellet production using European RepU. MSZ fabricates fuel assemblies for VVER-440, VVER-1000 and for European reactors under agreement with AREVA. MSZ also has the capability to produce fuel assemblies for the RBMK units as well as LMR fuel for BN-600 and BN-800 fast reactors. The NCCP plant produces fuel for both the VVER-440 and VVER-1000 reactors. NCCP also has conversion and pelletization capacity. Reported TVEL fuel fabrication capacity varies widely from various sources, including the capacities at MSZ and NCCP. TVEL officials have reported LWR pellet manufacturing capability of 1760 MTHM and fuel assembly capacity of 2150 MTHM. Other organizations that report fuel fabrication capacity have shown TVEL's conversion capacity to be equal to its capacity for pellet manufacturing—thus, this report assumes a conversion capacity of 1760 in total at MSZ and NCCP. TVEL has reported a RMBK fuel manufacture capacity 460 MTHM and LMR fuel production capacity of 50 MTHM. TVEL is expected to increase its production capacity as needed to meet the requirements of new NPPs (TVEL, 2010; WNA, 2013).

Historically, UO_2 pellet production for both VVER and RBMK units took place at Kazatomprom's UMP. However, UO_2 powder and pellets are now being manufactured by TVEL to reduce Russian dependence on Kazakhstan. Zirconium production and manufacture of zirconium components is controlled by JSC Chepetsk Machine Building Plant in Glazov.

TVEL has historically provided almost 100% of fuel fabrication requirements to Russian-designed VVERs in Russia, Ukraine, and Eastern Europe. Recently TVEL developed a PWR fuel design for use in Western NPPs to expand its market, the TVS-K design (TVEL, 2014).

Westinghouse Electric Company is owned by Toshiba Corporation (87%), Kazatomprom (10%), and Japan's Ishikawajima-Harima Heavy Industries Co., Ltd (3%). Toshiba acquired Westinghouse from British Nuclear Fuels Limited (BNFL) in 2006. Westinghouse is headquartered in Cranberry Township, Pennsylvania, near Pittsburgh and operates a fuel fabrication facility in Columbia, South Carolina. Westinghouse is a fully integrated supplier. In addition to the Columbia fuel fabrication facility, Westinghouse operates the Western Zirconium Plant in Ogden, Utah, that produces zirconium and zirconium alloy materials for use in fuel components by Westinghouse and other fuel vendors. Tubing is produced by the Specialty Metals Plant (SMP) in Blairsville, Pennsylvania. Through earlier acquisitions by prior Westinghouse owners, the commercial nuclear power businesses of Asea Brown Boveri, Ltd (ABB), including ABB Atom, and CE, are owned by Westinghouse.

The Westinghouse fuel fabrication plant in Columbia, South Carolina has an annual capacity of 1500 MTHM for UF_6 to UO_2 conversion, pellet production and PWR and BWR fuel assembly manufacture. Westinghouse is the only Western fuel supplier that has produced fuel assemblies for Russian-designed VVER NPPs, having produced VVER-1000 fuel assemblies for the two Soviet-designed Temelin units in the Czech Republic until 2006 and for NPPs in Ukraine.

Westinghouse Electric Sweden operates a 600 MTHM/year fuel fabrication facility in Västerås, Sweden producing both PWR and BWR fuel. Westinghouse operates Springfields Fuels Limited in Lancashire, UK. The plant was has a capacity for UO_2 conversion of 730 MTHM, 380 MTHM pellet manufacturing capacity, and 640 MTHM assembly capacity. The facility also manufactures fuel for UK's Advanced GCR (AGR) NPPs with an annual production capacity 220 MTHM (WNA, 2013).

Other small fuel fabricators include the *Pakistan Atomic Energy Commission (PAEC)*, which produces PHWR fuel for Pakistan's Kanupp NPP. The facility is estimated to have a capacity of 20 MTHM/year. Argentina's *Combustibles Nucleares Argentinos (CONUAR) SA* operates a 160 MTHM/year fuel fabrication facility for fabrication of PHWR fuel for the Atucha and Embalse NPPs. Romania operates a 240 MTHM fabrication facility for PHWR fuel in Pitesti (WNA, 2015b).

13.1.2 Fabrication services market capacities

Nuclear fuel fabrication has several market segments as described previously. The largest segment is LWR fuel fabrication, which includes Russian VVER fuel fabrication. The other nuclear fuel fabrication markets include PHWR fuel, MOX nuclear fuel (which may be supplied to LWRs or fast reactors (LMR fuel), GCR fuel, RBMK fuel, and LMR fuel (which may include MOX fuel). Fuel fabrication facilities and their estimated capacities are summarized in the sections that follow.

13.1.2.1 LWR fuel fabrication

Fuel fabrication facilities and approximate capacities of the principal, national, and regional suppliers of LWR fuel are summarized in Table 13.1. The principal supplier facilities are arranged by their geographical location to provide a complete

Table 13.1 **Summary of all LWR fuel fabrication facilities and capacities (WNA, 2013; ERI, 2015)**

Country	Fuel fabricator	Location of fuel fabrication facility	Type of fuel	Production capacity, MTHM/year		
				Conversion	Pellet	Assembly
East Asia						
Japan	Global Nuclear Fuel—Japan	Yokosuka	BWR	0	750	750
	Mitsubishi Nuclear Fuel	Tokai Mura	PWR	475	440	440
	Nuclear Fuel Industries (W)	Kumatori	PWR	0	383	383
	Nuclear Fuel Industries (W)	Tokai Mura	BWR	0	250	250
Korea	KEPCO Nuclear Fuel Company	Taejon	PWR	700	700	550
China	CNNC-China South Nuclear Fuel Co.	Yibin, Sichuan	PWR	800	800	900
	CNNC-China Nuclear Northern Fuel Co.	Baotou, Inner Mongolia	PWR	200	200	200
	CNNC-Baotou Nuclear Fuel Co.	Baotou, Inner Mongolia	PWR	200	200	200
			Asia Subtotal	**2375**	**3723**	**3673**
Western Europe						
France	AREVA	Romans	PWR	1800	1400	1400
Germany	AREVA	Lingen	BWR/PWR	800	650	650
Spain	ENUSA	Juzbado	BWR/PWR	0	390	390
Sweden	Westinghouse Atom	Vasteras (a)	BWR/PWR	600	600	600
UK	Westinghouse	Springfields	PWR	730	380	640
			Europe Subtotal	**3930**	**3420**	**3680**

United States						
US	AREVA	Richland, WA	BWR/ PWR	1800	1800	750
US	Global Nuclear Fuel-Americas	Wilmington, NC	BWR	1200	1000	1000
US	Westinghouse Electric Company	Columbia, SC	PWR/ BWR	1500	1500	1500
			US Subtotal	**4500**	**4300**	**3250**
Total installed fuel fabrication capacity for East Asia, W. Europe and North America				**10,805**	**11,443**	**10,603**
Other						
Brazil	Industrias Nucleares do Brasil	Resende	PWR	160	120	240
India	Nuclear Fuel Complex (DAE)	Hyderabad	BWR	48	48	48
Russia	TVEL, JSC Machine Building Plant (MSZ)	Elecktrostal	PWR	1100	1100	950
	TVEL, Novosibirsk Chem. Conc. Plant (NCCP)	Novosibirsk		660	660	1200
Kazakhstan	Ulba Metallurgical Plant	Ust-Kamenogorsk	PWR	1200	1200	0
			Other Subtotal	**3168**	**3128**	**2438**
Total Installed LWR Fuel Fabrication Capacity for World				**13,973**	**14,571**	**13,041**

picture of LWR fuel fabrication supply capability on a world and regional basis. As shown in Table 13.1, present world annual LWR fuel fabrication capacity—based on UF_6 to UO_2 conversion capacity—from all identified sources is approximately 13,970 MTHM. While total assembly capacity is lower at approximately 13,000 MTHM, assembly capacity is widely recognized to be expandable, as it is generally limited only by the number of shifts being run at the plant.

In East Asia, total UF_6 to UO_2 conversion capacity is approximately 2375 MTHM—significantly lower than the capacity to manufacture pellets and LWR fuel assemblies, which is an estimated 3700 MTHM. Japanese fuel fabricators, which do not have conversion capability, import powder or pellets from other suppliers. China is expected to increase LWR fuel fabrication capacities significantly over the next decade to meet its growing requirements.

In Western Europe, annual conversion capacity for LWR fuel is approximately 3900 MTHM/year, with pelletization and assembly capacity for LWR fuel of 3420 MTHM and 3680 MTHM, respectively.

In the US, the annual conversion capacity is about 4500 MTHM, pelletization is about 4300 MTHM, and assembly capacity is 3250 MTHM. In the past, a substantial portion of UO_2 powder has been exported from the US to Japan to make up for the imbalance between UO_2 conversion capacity and fuel assembly capacity. This is expected to resume as fuel fabrication restarts to support NPP restarts in Japan.

LWR capacity in Russia is an estimated 1760 MTHM for UO_2 conversion and pellet manufacture and 2150 MTHM for fuel assembly production. As shown in Table 13.1, this capability is split between MSZ and NCCP. Kazatomprom's UMP has an annual production capacity of 1200 MTHM for UO_2 conversion and pellet manufacture. India and Brazil have small LWR fuel fabrication capacities to meet indigenous requirements.

13.1.2.2 PHWR fuel fabrication

As shown in Table 13.2, PHWR fuel fabrication is done on a national basis to support PHWR operations in the country in which the fabrication facility is located. In Korea, KNFC operates a 400 MTHM facility operated by KNFC in Taejon. CNNFC operates a 200 MTHM facility at Baotou, China. In Canada, two PHWR facilities are operational: Cameco's 1200 MTHM facility in Port Hope, Ontario and GNF-Canada's 1500 facility in Peterborough, Ontario. In Argentina, CONUAR operates a 160 MTHM facility in Cordoba and Ezeiza. In India, NFC operates a 435 MTHM facility in Hyderabad, A small 20 MTHM facility has been constructed in Pakistan, and a SNN operates a 240 MTHM facility in Pitesti, Romania. Total PHWR fuel production capacity is 4155 MTHM.

13.1.2.3 MOX fuel fabrication

MOX fuel has been utilized in LWRs in four European countries (Belgium, France, Germany, and Switzerland). In Japan, 12 NPPs are also licensed to utilize MOX fuel and a facility for MOX fuel fabrication is undergoing licensing.

Table 13.2 Summary of PHWR fuel fabrication facilities and capacities (WNA, 2015b)

Country	Fuel fabricator	Location of fuel fabrication facility	Type of fuel	Production capacity MTHM
East Asia				
Korea	KEPCO Nuclear Fuel Company	Taejon	PHWR	400
China	CNNC-China Nuclear Northern	Baotou, Inner Mongolia	PHWR	200
			Asia Subtotal	**600**
North America				
Canada	Cameco Corporation	Port Hope, Ontario	PHWR	1200
Canada	Global Nuclear Fuel—Canada	Peterborough, Ontario	PHWR	1500
			North America Subtotal	**2700**
Other				
Argentina	CONUAR	Cordoba and Ezeiza	PHWR	160
India	Nuclear Fuel Complex (DAE)	Hyderabad	PHWR	435
Pakistan	PAEC	Chashma	PHWR	20
Romania	SNN	Pitesti	PHWR	240
			Other Subtotal	**855**
Total Installed PHWR Fuel Fabrication Capacity for World				**4155**

MOX fuel has also been developed for other reactor types such as PHWRs and LMRs. Table 13.3 provides a summary of worldwide MOX fuel fabrication capacity.

In Japan, the MOX fuel fabrication facility at Tokai Mura, operated by Japan Atomic Energy Agency, is a demonstration facility that had a capacity of 5 MTHM annually. In 2014, JAEA announced that it would decommission the facility rather than expend capital to bring the plant up to the new regulatory standards. The larger JNFL MOX fabrication facility at Rokkasho-Mura, which will have a capacity of 130 MTHM, is undergoing review by Japan's Nuclear Regulatory Authority (NRA) and is currently expected to begin operation in 2017 (WNA, 2015d; JNFL, 2015; JAEA, 2015).

Table 13.3 Summary of MOX fuel fabrication facilities and capacities

Country	Fuel fabricator	Location of fuel fabrication facility	Type of fuel	Production capacity	
				Pellet	Assembly
East Asia					
Japan	Japan Nuclear Fuel Limited	Rokkasho-Mura	MOX (LWR)	130	130
			Asia Subtotal	**130**	**130**
Western Europe					
France	AREVA	Marcoule	MOX (LWR)	195	195
			Europe Subtotal	**195**	**195**
Other					
India	Advanced Fuel Fabrication Facility (DAE)	Tarapur	MOX (LWR, PHWR)	50	50
Russia	TVEL, Mining & Chemical Complex (MCC)	Zheleznogorsk	MOX (LMR)	60	60
			Other Subtotal	**110**	**110**
Total Installed MOX Fuel Fabrication Capacity for World				**435**	**435**

AREVA operates the 195 MTHM MOX fuel fabrication facility, Melox, at Marcoule. Melox began initial operation in 1995 and the facility achieved an annual production rate of 100 MTHM in 1997. AREVA, in partnership with the Shaw Group, as AREVA MOX Services, is building the MOX fuel fabrication facility (MFFF) at the Savannah River Site, in South Carolina, under contract to the US Department of Energy (DOE). If completed, the facility would manufacture MOX fuel from excess weapons plutonium for commercial NPPs. It is unclear when or if construction of this facility will be completed due to the rising cost of construction (AREVA, 2015a).

In India, DAE operates a MOX fuel manufacturing facility, Advanced Fuel Fabrication Facility (AFFF), at Tarapur. The facility has fabricated lead MOX fuel assemblies for irradiation in both BWRs and PHWRs to gain experience in MOX fuel fabrication for India's planned fast reactor program (Kamath, 2010; WNA, 2015e).

TVEL's Mining and Chemical Complex (MCC) at Zheleznogorsk operates a 60 MTHM/year MFFF that began operation in 2014. The MOX fuel will be used in Russian fast reactors the BN-800 and future BN-1200 reactors. First production of fuel assemblies for Beloyarsk 4 (BN-800) began in 2014, and full capacity is expected in 2016 (WNA, 2015c; TVEL, 2010).

13.1.2.4 Fuel fabrication capacity for other types of NPPs

The facilities that fabricate fuel for GCRs, RBMKs, and LMRs are country-specific in that the facilities only build these fuel types for use in its home country's nuclear power program. In the UK, Westinghouse operates the former BNFL fabrication facility at Springfields, which fabricates fuel for the UK GCRs (specifically AGR). Springfields capacity for GCR fuel is 200 MTHM annually. Springfields also fabricated GCR fuel for magnox reactors; however, the last magnox fuel was shipped from the Springfields site in 2011. Wylfa is the last operational magnox reactor and it is currently licensed to generate electricity until the end of 2015, when it is expected to begin defueling and decommissioning (Magnox, 2015; Westinghouse, 2015).

India's AFFF at Tarapur fabricates advanced fuel designs to support India's planned fast reactor program. In addition to fabrication of MOX fuel discussed previously, the facility is performing prototype research for MOX LMR fuel as well as mixed carbide fuels and metallic fuels for the fast reactor program (Kamath, 2010).

In Russia, TVEL's MSZ at Eleckrostal includes fabrication capacity for LMR fuel for the BN-600 and BN-800 fast reactors. LMR fuel fabrication capacity is estimated to be 50 MTHM. MSZ also includes capacity to fabricate 460 MTHM of fuel for Russia's RBMK reactors. At MCC in Zheleznogorsk, the facility has a 60 MTHM capacity for fabrication of MOX LMR fuel for the BN-800 reactor as shown in Table 13.3 (TVEL, 2010; WNA, 2015c).

13.1.3 World fabrication requirements

As illustrated in Fig. 13.2, world fuel fabrication requirements for all NPP types are expected to increase from an estimated 10,900 MTHM in 2015 to approximately 12,650 MTHM by 2025—a 16% increase. LWR fuel requirements are projected to continue to dominate other fuel forms—with NPP requirements increasing from an estimated 6700 MTHM to approximately 8600 MTHM in 2025—a 28% increase over the next 10 years. Both RBMK and AGR fuel fabrication requirements are expected to decline over the next 10 years assuming that RMBK reactors in Russia and AGRs in the UK begin to reach the decommissioning stage. There is also minor growth in PHWR fuel requirements—an increase of about 1%—with requirements rising to 3610 MTHM by 2025. LMR fuel requirements, which are a small segment of the fabrication market, increase by 400% to 32 MTHM as fast reactor development in Russia, China, and India increases and new fast reactors begin operation over the next 10 years (ERI, 2015) (Table 13.4).

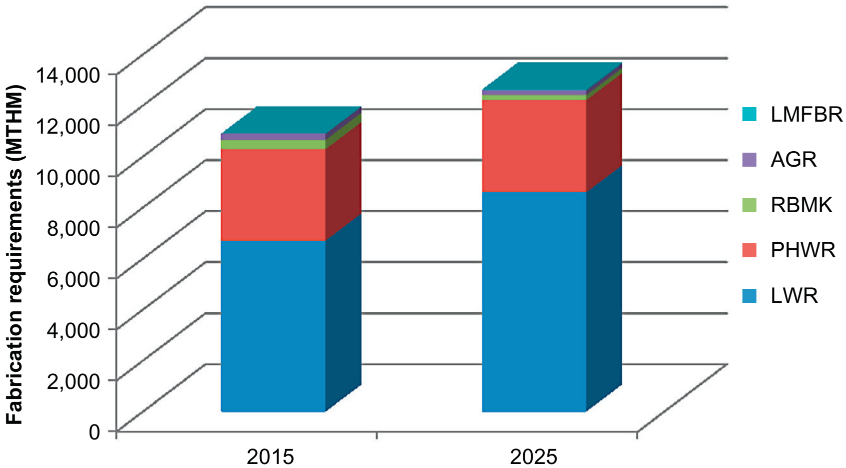

Figure 13.2 Fuel fabrication requirements by reactor type, 2015 and 2025.

Table 13.4 Summary of fuel fabrication facilities and capacities for other fuel types

Country	Fuel fabricator	Location of fuel fabrication facility	Type of fuel	Production capacity assembly
Western Europe				
United Kingdom	Westinghouse	Springfields	GCR	200
			Europe Subtotal	**200**
Other				
India	Advanced Fuel Fabrication Facility (DAE)	Tarapur	LMR	Prototype
Russia	TVEL, JSC Machine Building Plant (MSZ)	Elecktrostal	LMR (BN-600)	50
	TVEL, JSC Machine Building Plant (MSZ)	Elecktrostal	GMR (RBMK)	460
	TVEL, Mining & Chemical Complex (MCC)	Zheleznogorsk	MOX (LMR)	60
			Other Subtotal	**570**
Total Installed Other Fuel Fabrication Capacity for World				770

13.2 Fuel assembly design components

Nuclear fuel assembly designs are a function of the type of reactor in which the fuel will be used (PWR, BWR, VVER, PHWR, AGR, etc.), the fuel assembly lattice type, and the NSSS supplier of the NPP. LWR fuel assemblies typically consist of a fuel assembly skeleton, which is the hardware that provides structural support to the fuel, and fuel rods, which contain nuclear fuel, generally in the form of pellets. Fuel assembly components for non-LWR fuel are also discussed next.

13.2.1 PWR Fuel Assembly

The PWR fuel assembly skeleton includes spacer grids, top and bottom nozzles, guide tubes, and instrument tubes. Fuel rods are inserted into the skeleton to complete the fuel assembly. Spacer grids are structural elements along the length of the fuel assembly that provide structural and flow mixing functions. Spacer grids contain cells in a so-called "egg crate" design through which fuel rods are inserted and held into place in a square array. PWR assembly arrays range from 14×14 rods to 18×18 rods, depending upon the NSSS supplier of the NPP. The primary purpose of the top and bottom grids is to provide structure support for the fuel rods, while the spacer grids along the remaining length of the assembly provide not only structural support but also have a flow mixing function. Many modern PWR fuel designs also incorporate debris-resistant lower grids that are located between the bottom nozzle and bottom structural grid to prevent debris from damaging the fuel rod cladding. (NEI/ERI, 2008; AREVA, 2010; Westinghouse, 2005).

The top and bottom nozzles provide structural support for the fuel during fuel handling and operation. The top nozzle provides a grappling function for use during fuel handling operations and includes hold-down springs that offset the upward force of the coolant flow and prevent the assemblies from lifting off the bottom core plate during operation. The bottom nozzle directs coolant flow into the assembly and provides housing for debris filters in many of the modern PWR fuel designs. The debris filters are designed to minimize the amount and size of the debris particles entering the assemblies and hence minimize the potential for debris fretting failures. Current PWR fuel designs also incorporate easily removable top nozzle designs to facilitate fuel assembly reconstitution. The ability to reconstitute assemblies during refueling outages eliminates the necessity of premature assembly discharge due to minor fuel rod or structural skeleton damage (NEI/ERI, 2008).

Guide tubes are cylindrical metal tubes that provide axial positioning for the spacer grids, structural support to the fuel assembly, channels for insertion of control rods, and channels for burnable absorber rods, if used. Instrumentation tubes, which are generally a central guide tube in the fuel assembly, provide structural support for the fuel assembly as well as channels for the insertion of in-core monitoring instrumentation. Guide tubes and instrumentation tubes are typically fabricated of a zirconium alloy such as M5 or ZIRLO (NEI/ERI, 2008).

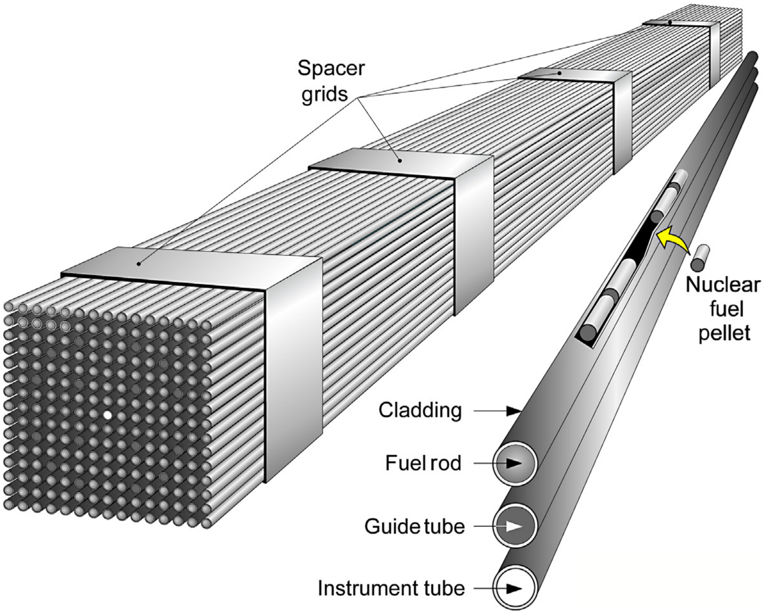

Figure 13.3 PWR fuel assembly (DOE, 2015).

In addition to the PWR fuel designs described previously that are used in Western-designed NPPs, VVER fuel assemblies are also a PWR fuel. However, in VVER fuel assemblies, the fuel rods are grouped in a hexagonal array rather than a square array. Depending upon the NSSS design, PWR fuel assemblies range in length from 4.06 to 4.80 m, and VVER fuel assemblies range from 3.20 to 4.57 m (NEI Magazine, 2014).

Fig. 13.3 provides a cutaway design of a typical fuel assembly showing the nuclear fuel pellets inside of fuel rods, fuel assembly array, and spacer grids. This particular graphic does not include the top and bottom nozzles (DOE, 2015).

13.2.2 BWR Fuel Assembly

The BWR fuel assembly skeleton includes the spacer grids, the upper and lower tie plates, the tie rods and the water rods or water channels. Fuel rods are inserted into the skeleton to form the fuel assembly. A fuel channel is placed over the fuel assembly and secured with a channel fastener. BWR spacer grids are similar in form and function to those in PWR fuel assemblies. However, rather than an "egg crate" design, some vendors use a grid in which cylinders are welded together to form the grid structure. A typical BWR fuel assembly may contain between six and eight spacer grids, depending on the manufacturer, and the grids support 9×9, 10×10 or 11×11 fuel rod arrays. BWR fuel assembly length ranges from 4.081 to

4.481 m depending upon the NSSS design of the NPP (NEI/ERI, 2008; NEI Magazine, 2014).

The lower and upper tie plates provide structural support for the fuel during fuel handling and operation. The lower tie plate of a BWR assembly provides structural support for the lower end of the fuel rods and also serves to distribute and direct coolant flow entering the assemblies. Debris filters are integral with the lower tie plate or may be attached to it. The upper tie plate provides structural support for the upper end of the fuel rods and contains a lifting fixture for use in fuel handling operations (NEI/ERI, 2008).

BWR tie rods are fuel rods that have specially designed end plugs that are screwed into the lower tie plate and also affixed to the upper tie plate to provide structural support for the fuel assembly. Water rods provide additional moderation to BWR assemblies and provide axial positioning of the spacer grids. Fuel designers will utilize water rods to optimize the neutron flux shape within a fuel assembly. The actual configuration of water rods in a BWR fuel assembly will vary depending upon the specific BWR fuel design. AREVA employs a square water channel that displaces nine fuel rods in its ATRIUM 10 and ATRIUM 11 designs. GNF utilizes two large cylindrical water rods displacing eight fuel rods in its GNF2 design. The Westinghouse BWR design consists of four 5×5 mini-assemblies in its SVEA-96 Optima3 design. To form the water channel, one fuel rod (in the center of the larger fuel assembly) is removed from each of the mini-assemblies to form a water cross (NEI/ERI, 2008; AREVA, 2015b; GNF, 2015a; Westinghouse, 2013).

BWR fuel channels are four-sided structural elements, which are the length of the fuel rods and are typically fabricated of Zr-4 or another zirconium alloy. The fuel channel encloses a BWR fuel assembly and performs three primary functions of providing a channel for through-bundle water flow path, acting as a guide for BWR control blades, and providing structural support to the fuel assembly. At one time BWR fuel channel designs were sold separately from fuel assemblies. However, today, BWR fuel channels complement specific fuel assembly designs to enhance flow mixing in the assembly and improve fuel performance (NEI/ERI, 2008).

13.2.3 PHWR Fuel Bundle

PHWR fuel assemblies include a circular zircaloy end support plate, that provides support to the fuel tubes, fuel tubes (referred to as fuel sheath in Fig. 13.4), zircaloy bearing pads, interelement spacers, and a pressure tube that surrounds the fuel assembly. The bearing pads maintain the spacing between the fuel assembly and the pressure tube. In addition, the interelement spacers maintain the separation of the fuel tubes from one other without the need to utilize spacer grids. The fuel tubes, which contain UO_2 pellets, are closed with zircaloy end caps and have a graphite inner layer (referred to as "Canlub") that is used to reduce the stresses within the fuel tube. The fuel tube end caps not only provide a seal for the fuel tubes, but they also provide a means of attaching the tubes to the end support plate.

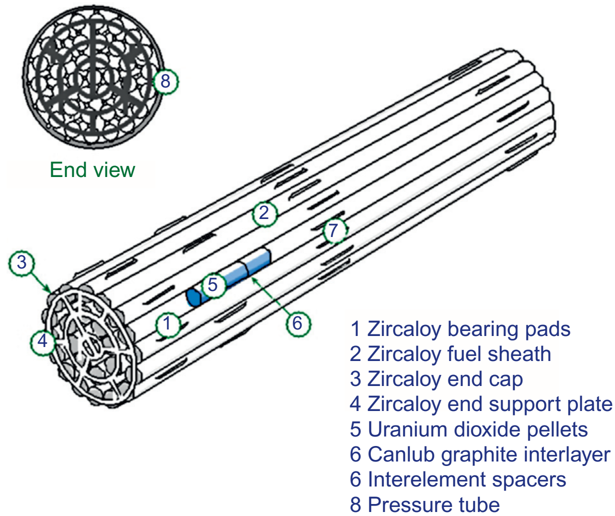

Figure 13.4 CANDU fuel assembly (CANDU.ORG, 2015) waiting for response regarding permission.

CANDU PHWR fuel assemblies utilize 28, 37, or 43 fuel tubes, which are typically made of a zirconium alloy and are grouped into a cylindrical fuel bundle roughly 10 cm in diameter and 50 cm in length around a central axis. Unlike LWR fuel which resides in the NPP core in a vertical position, PHWR fuel assemblies are loaded into horizontal channels or pressure tubes which penetrate the length of the reactor vessel (called the calandria) (Cameco, 2015a; CANDU.ORG, 2015; Ferenbach and Miller, 2009).

13.2.4 GCR Fuel Assemblies

GCR fuel assemblies, such as those used in AGRs in the UK, have a circular configuration, in which 36 stainless steel clad fuel pins are grouped. Each fuel pin contains 20 enriched UO_2 fuel pellets. The AGR fuel assemblies are covered with a graphite sheath that acts as a moderator during reactor operation. Fuel assemblies are stacked in a vertical configuration in a fuel channel, with eight assemblies per channel (Westinghouse, 2015; WNA, 2015e).

13.2.5 RBMK Fuel Assemblies

RBMK fuel assemblies, such as those used in RBMK NPPs in Russia, include two “subassemblies” that each contain 18 fuel rods and 1 carrier rod. The lower subassembly includes an end grid and ten spacer grids. The top subassembly has 10 spacer grids. The spacer grids provide structure support as well as improving heat transfer. The zircaloy fuel rods in each subassembly are arranged within two concentric rings around a central carrier rod. The two subassemblies are joined by a cylinder along the plane of the center carrier rod. Each fuel assembly in the reactor core is housed in an individual pressure tube. The total length of the fuel assembly is 10.025 m with 6.862 m being the active region. The fuel rods contain enriched UO_2 fuel pellets and may utilize a burnable absorber (INL, 2015).

13.2.6 Uranium dioxide production

There are three conversion processes used by fuel fabricators to convert UF_6 gas to UO_2 powder for the production of UO_2 pellets: (1) the "dry" process, (2) the ammonium diuranate (ADU) process, a wet process, and (3) the ammonium uranyl carbonate (AUC) process, also a wet process. The dry process results in significantly lower quantities of liquid waste than either of the wet processes and it is the most commonly used conversion process used today. In each of these processes, the first step is the heating of the UF_6 cylinders in an autoclave and the removal of the UF_6 in gaseous form. The remaining steps in the various UF_6 to UO_2 conversion processes are described briefly next (NEI/ERI, 2008).

The dry process was originally developed by Siemens, now part of AREVA, and has been licensed to several other fabricators. It consists of the hydrolyzation of the UF_6 with steam in a gas-phase reaction. This step is followed by the reduction of the resulting uranyl fluoride (UO_2F_2) with hydrogen and steam in a fluidized bed reactor to produce the UO_2. The initial powder product is then calcined in a rotary kiln with more steam and hydrogen to drive off any remaining fluoride and to dry the powder (NEI/ERI, 2008).

In the ADU process, the UF_6 gas is hydrolyzed by solution in water. Ammonia is added to the solution producing a precipitate of ammonium diuranate (ADU). The ADU is subsequently filtered, dried, calcined in the presence of steam and reduced in the presence of hydrogen to produce the UO_2 powder. In an earlier version of the wet process, ammonium carbonate was used instead of ammonia, producing AUC that was then treated in a similar manner to the ADU described previously (NEI/ERI, 2008).

In the *AUC process*, gaseous UF_6, carbon dioxide (CO_2) and ammonia (NH_3) are combined in water resulting in a precipitate of AUC. The AUC is then processed in a manner similar to ADU to produce the UO_2 powder (NEI/ERI, 2008).

13.2.7 Fuel pellet production

Following conversion of UF_6 gas into UO_2 powder, the next step in the fuel fabrication process pellet production of UO_2 pellets. The UO2 pellet manufacture involves the following steps: (1) mixing of the UO_2 powder with binding and lubricating agents, (2) compaction or cold pressing, (3) sintering, and (4) precision grinding. Binding and lubricating agents that are commonly employed in pellet manufacture are organic compounds such as aluminum or zinc stearate and stearic acid. These agents enhance the formation of pores to facilitate the increase in density during the sintering process. The binding agents provide additional strength to the cold pressed pellets and assist in reducing dust hazards associated with the handling of UO_2 powder. The lubricating agents assist in a uniform cold pressing operation (NEI/ERI, 2008).

Once the UO_2 powder has been mixed with the binding and lubricating agents, the next step is to cold press the resulting mixture to produce "green" pellets, which have a density of approximately 55−60% of theoretical density. The green pellets are then sintered in a high-temperature furnace to form a stable ceramic with the necessary heat transfer properties. The sintering process also drives off the remaining additives. Final pellet densities of about 96−97% of theoretical density are typically achieved. Once the sintering process is complete, the pellets are ground to their final dimensions in a grinder, inspected and stored for future fuel rod loading (NEI/ERI, 2008).

MOX fuel pellet manufacture can be accomplished via two methods: (1) dry mixing and (2) coprecipitation. In the dry mixing process, UO_2 powder and plutonium oxide powder (PuO_2) are ground together. Depleted UO_2 powder is typically used along with rejected UO2 pellets that have been ground into a powder. The mixture is then cold pressed into pellets, sintered, and ground to meet final specifications in similar processes used to produce UO_2 pellets. In the coprecipitation process, a mixture of uranyl nitrate and plutonium nitrate is converted by treatment with a base such as ammonia to form a mixture of ammonium diuranate and plutonium hydroxide. After the mixture undergoes a heating process, it will form a powder containing uranium dioxide and plutonium dioxide. The resulting powder is then pressed into pellets, sintered, and ground as in the formation of UO_2 pellets (Collins et al., 2011; AREVA, 2015c).

13.2.8 Use of burnable absorbers

Burnable absorbers are neutron-absorbing materials that are commonly incorporated in LWR fuel designs as a means of power shaping, local power-peaking control and overall long-term reactivity control. Burnable absorbers used for long-term reactivity control, such as gadolinium (GdO_2) in BWR fuel assemblies, depletes as the fuel assembly remains in the reactor core, thereby providing greater reactivity control during initial use of the fuel (when the new fuel assembly's reactivity is highest) and providing less reactivity control for the fuel assembly late in a cycle (when the fuel assembly's reactivity has decreased). The use of burnable absorbers varies among vendors and fuel designs, but can be generally grouped into three classifications: (1) discrete absorbers, (2) intimately mixed absorbers, and (3) surface coating absorbers (NEI/ERI, 2008).

The discrete absorbers, which are rarely used today, are only employed in PWR fuel designs and are typically incorporated in the form of an absorber-filled rod that is inserted into a vacant rod control cluster assembly (RCCA) guide tube. Typical absorber materials employed in these designs are Boron-10 (B^{10}) doped Pyrex glass or aluminum oxide-boron carbide (Al_2O_3-B_4C) pellets. Reactivity control is achieved through variation in the absorber loading per rod, the number of absorber rods per fuel assembly, and the total number of absorber-loaded fuel assemblies in the core (NEI/ERI, 2008; Westinghouse, 2010).

Intimately mixed absorbers, gadolinium (GdO_2) and erbium (ErO_2) oxides, are combined with the UO_2 powder prior to pelletization. This burnable absorber technology has been successfully employed in both PWR and BWR fuel designs by essentially all fuel fabricators. BWRs use exclusively gadolinia, while both gadolinia and erbia are employed in PWRs. Reactivity control is achieved through variation of absorber loading per fuel rod, absorber distribution within fuel rods, number of absorber-loaded fuel rods per assembly, and/or total number of absorber-loaded assemblies per core.

Surface coating absorbers, such as Westinghouse's Integral Fuel Burnable Absorber (IFBA), are applied as thin coatings of boron compounds such as zirconium diboride (ZrB_2) on the surface of individual pellets in PWR fuel rods. The coating is typically applied to specific pellets of like enrichment within a fuel rod, or to pellets spanning a wide region of a fuel rod to achieve specific power-peaking control (Westinghouse, 2010; NEI/ERI, 2008).

13.2.9 Fuel rod fabrication process

While the specifics of fuel rod design vary among individual fabricators and fuel type, a typical LWR fuel rod is composed of a zirconium alloy cladding tube (such as Zr-2, Zr-4, ZIRLO, M5, etc.), a UO_2 pellet column, two end plugs and an internal plenum spring. Each fuel rod has a unique identification number to provide the ability to trace the history of each rod manufactured. The internal plenum spring prevents pellet movement and possible damage during handling operations. A typical fuel rod manufacturing procedure consists of the following steps: (NEI/ERI, 2008).

- The bottom end plug is inserted into cladding tube and welded in place
- The UO_2 pellet column is loaded into the cladding tube. It may be pushed into horizontally positioned tubes or gravity loaded with the tubes tilted at an angle depending upon the manufacturing process
- The length of the pellet column is confirmed to be in accordance with manufacturing specification through insertion of a gauge is inserted into the cladding tube
- A plenum spring is inserted into the cladding tube on top of the pellet stack
- The top of the cladding tube is placed in a sealed chamber for pressurization. Helium is introduced into the fuel rod to a specified internal fuel rod pressure. If it had not been done previously, the top end plug is inserted into the cladding tube once rod pressurization has been achieved. The end plug is then welded to the tube. If the plug contained a hole to achieve rod pressurization, the hole is seal welded as well
- Inspections of the completed fuel rod are performed

Fuel rod weld integrity is generally verified through visual, ultrasonic, and/or X-ray inspection techniques. Each fuel rod may be weighed for gross loading verification and/or gamma scanned to provide verification of pellet enrichments and orientation (Kok, 2009; NEI/ERI, 2008).

13.3 Current and future trends

A number of fuel cycle trends are worth noting including the continued emphasis on fuel reliability and increases in NPP cycle length, capacity factor, and fuel assembly burnup. The development of fast reactors in Russia, China, and India, along with fuel for these plants is also expected to experience continued growth. Each of these topics is discussed briefly next with references to other resources.

13.3.1 Fuel reliability

The nuclear industry continues to make progress in the reduction of fuel failures. In the US, there was a concerted effort to meet the Institute of Nuclear Power Operation's (INPO) goal for zero fuel defects by 2010. This *Zero by Ten Initiative* is now called *Driving to Zero*. The Electric Power Research Institute (EPRI), INPO, NPP operators and fuel fabricators worldwide have worked together to develop guidelines to address the known failure mechanisms, which include: PWR corrosion and crud, BWR corrosion and crud, grid-to-rod fretting (GTRF), pellet-cladding interaction (PCI), and foreign material induced failures. EPRI published an updated Fuel Surveillance and Inspection Guidelines in 2012 and continues to review its five fuel reliability guidelines periodically to reflect the most recent knowledge gained through fuel surveillance and inspection programs. According to EPRI, when the industry began the *Zero by Ten Initiative* in 2007, 30% of US reactors were experiencing fuel failures. By the end of 2010, this figure was reduced to 6% and has remained constant (EPRI, 2005, 2008, 2013a).

Even though fuel failures have been significantly reduced over the last decade, fuel reliability remains a major industry focus. Improved debris-resistant fuel designs and better in-plant housekeeping have contributed to reductions in debris-related fuel failures. Vendor research and development have been focused on eliminating or at least significantly reducing other types of failures while continuing to increase fuel assembly discharge burnup. However, fuel failures resulting from materials corrosion and hydriding, grid-rod fretting, pellet-clad interaction, etc., have not yet been totally overcome in either BWRs or PWRs, and axial growth and distortion of PWR fuel assemblies and distortion of BWR channels remain major problems for operators at some plants.

EPRI established a fuel reliability database (FRED) in 2004 to better share fuel reliability information across the industry. FRED contains information on the fuel types in core, the reliability of the fuel during operation, and other fuel-related issues that affect operation. For PWRs, GTRF remains the dominant failure mechanism in US reactors. For US BWRs, debris-related failures have been the dominant failure mechanism since 2008. With most PWRs having transitioned to fuel designs with grid fretting resistance, debris-related failures are expected to become the dominant failure mechanism in US PWRs in the future (EPRI, 2006, 2014c).

Higher fuel duty and longer cycle lengths have increased the severity of BWR channel distortion problems in recent years. Channels may bow, bulge or twist, altering the clearance that allows the control rod to move freely, resulting in potential safety implications due to degraded control rod performance. According to EPRI, 17 out of 35 BWRs in the US have reported control blade interference due to channel distortion in the last decade. Affected fuel designs include Zircaloy-2 channels manufactured by all three US fuel vendors. EPRI, US utilities, the BWR Owners Group, fuel vendors, and INPO developed a Channel Distortion Industry Action Plan (CDIAP) to coordinate research in this area to better understand the mechanisms associated with channel distortion. Lead Channel Test programs have been initiated to evaluate alternative channel materials and fuel vendors have introduced enhanced BWR fuel channel designs to enhance bundle flow characteristics (EPRI, 2012, 2014a,d).

13.3.2 Fuel cycle trends

Worldwide NPP operating/refueling cycle lengths are generally increased over the past two decades—from nominal 12-month cycles up to 24-month cycles. Regarding operating/refueling cycle lengths, almost all US NPPs are on nominal 18- or 24-month cycles. However, one US plant has found it economical to return to an annual cycle. In Europe, PWRs generally operate on 12- to 18-month refueling cycles, depending upon the country and BWRs generally operate on 24-month cycles. NPPs in Eastern Europe, Russia, and former Soviet countries continue to operate on 12-month refueling cycles. In Korea and Taiwan, NPPs typically operate on 18-month cycles and China is moving a number of its NPPs in this direction. Prior to the Fukushima Daiichi accident in 2011, Japanese utilities received approval to increase the allowed operating period from 13 months to as much as 18 months, equivalent to cycle lengths of 21 months when the refueling outage is included, but these plans have not been implemented. Longer operating cycles allow NPP operators to maximize power generation, reduce the number of outages, lower outage costs, and make more efficient use of outage personnel. As cycle length increases, the fraction of fuel assemblies replaced at each outage also increases. As a result, longer cycles require higher enrichments even with the same design burnups, resulting in an increase in fuel cycle requirements. Generally, non-fuel operating cost factors, and not the fuel cost, determine a NPP's cycle length (ERI, 2015).

In 2014, the worldwide NPP capacity factor continued to be negatively impacted by the ongoing reactor outages in Japan, with a world average capacity factor of 73.9%. Excluding the reactor outages in Japan, the worldwide capacity factor was 83% in 2014. US capacity factors increased in 2014 to reach a record 91.7% as no plants were in long-term outages. The average world capacity factor is expected to improve slowly to an estimated 85%, as Japanese reactors resume operation or decisions are made regarding further plant closures (ERI, 2015).

Average design discharge exposure (also called fuel assembly burnup) for fuel loaded in LWRs is estimated at 49.5 GWD/t for fuel loaded in 2014. The actual discharge exposures are often slightly below the design discharge exposures. While new "Gen-3" reactors such as AREVA's EPR and Westinghouse's AP1000 are expected to use design discharge exposures of 60 GWD/t, most reactors are expected to remain near their current burnup levels (ERI, 2015). According to research conducted by ANT International, batch average discharge burnups for PWRs in the US are an estimated 43−58 GWD/t and for US BWRs are 43−52 GWD/t. In Western Europe, batch average burnups range from 45 to 65 GWD/t, in Asian countries—from 45 to 50 GWD/t, and in Russia and Eastern Europe—from 50 to 60 GWD/t (ANT International, 2014).

Interest in high burnup fuel is driven by longer cycle lengths, reductions in spent fuel generation, more efficient use of uranium and enrichment services on a unit energy production basis, and improved fuel cycle costs. While requiring higher initial enrichment assays, higher burnup designs result in fewer assemblies in each reload, and a decline in the nuclear fuel cycle requirements in the range of 4−8%, compared to a situation where no advances in fuel design take place and the same cycle length is maintained. Ongoing concerns about fuel performance at high discharge burnup and the industry-wide push for zero fuel failures are likely to restrict increases in discharge burnup beyond the current levels in the near term. If discharge exposures were pushed higher than 60 GWD/t, enrichment assays would be required to increase above the current licensed limit of 5.0 w/o ^{235}U for most fuel facilities (ERI, 2015).

13.3.3 Fast reactor fuel

Fast reactors can utilize a wide range of fuel types, a mixture of transuranic elements as fuel, and various chemical forms. Fast reactor fuel can be made from UO_2, MOX, single or mixed nitride ceramics, and metallic fuels. Fast reactor fuel can be made from pellets, in a manufacturing process similar to that for LWR fuel described previously, or it can be manufactured using a method called vibro-packing. Fast reactor development is expected to continue to grow as certain countries look to close the fuel cycle either to address fuel resource needs or to reduce growing quantities of spent nuclear fuel.

Vibro-packed MOX fuel is made by agitating a mixture of granulated uranium and plutonium oxides with uranium powder, with binding oxygen and other gases added during the agitation process. Vibro-packed MOX fuel can be more easily recycled than pelletized MOX fuel and there are reportedly fewer interactions between the fuel and cladding (WNN, 2014a).

A reactor core in a fast reactor is much smaller than that of an LWR and the cores will typically have two different fuel regions—the seed fuel uses fuel with a high fissile content and a higher power level, and the blanket fuel has a low fissile content but utilizes fuel material with high neutron absorption cross sections (in a "breeder" fast reactor) or actinide material to be transmuted (in a "burner" fast reactor) (WNA, 2015e).

The BN-600 at Beloyarsk operates as "breeder" with a central bundle that includes 127 rods (2.4 m in length and 7 mm in diameter). The rods contain ceramic pellets in three uranium enrichment levels: 17%, 21%, and 26%. Blanket fuel bundles have 37 rods containing depleted uranium. The BN-600 has utilized mostly

UO_2 fuel, but vibro-packed MOX fuel has been successfully used in the BN-600 reactor for the past decade. Vibro-packed MOX fuel assemblies have also been fabricated for the BN-800 NPP at Beloyarsk 4, which began operation in 2014. The assemblies were produced at the Research Institute of Atomic Reactors (NIIAR) in Dimitrovgrad (NIIAR, 2010; WNA, 2015e; WNN, 2014).

Many of the early fast reactors, such as EBR-II in the US, utilized metallic fuel and some fast reactor designers, such as GEH, are developing metallic fuel designs. In metallic fuel, a metallic fuel slug is loaded into the fuel cladding and the gap between the fuel slug and cladding is filled with sodium. The sodium acts as a thermal bond until the fuel swells to meet the cladding. Fuel slugs can be the full length of the fuel cladding tube or multiple slugs can be stacked—much in the way that ceramic UO_2 pellets are stacked in LWR fuel. The Mark-I and Mark II fuel utilized in EBR-II was made with 95% uranium metal and a 5% fissium alloy. Fissium is a mixture of fission products. Subsequent fuel was made from recycling the metal fission products along with recovered uranium metal. The General Electric-Hitachi PRISM fast reactor design, which is based on the EBR-II design, would utilize metallic fuel such as an alloy of zirconium, uranium, and plutonium (Chang, 2007; GEH, 2015).

A new Russian fast reactor that is under development, the BREST fast neutron reactor, will utilize lead as the primary coolant. The fuel type considered for the first core of the BREST fast reactor is a nitride of depleted uranium mixed with plutonium and minor actinides (MA). Reprocessing is limited to the removal of fission products without separating plutonium and MA from the mix (U-Pu-MA). One of the notable characteristics of the BREST plant and other planned fast reactors is that a reprocessing plant is colocated with the reactor, eliminating in principle any accident or problem due to fuel transportation (Alemberti et al., 2014; WNN, 2014b).

13.3.4 Expansion of fuel fabrication markets and new market participants

The past two decades saw consolidation of fuel suppliers in the US and Western Europe resulting in the three major Western fuel suppliers that exist today: AREVA, GEH, and Westinghouse. The next decade may be characterized as one of expansion of existing fabricators into new regions or the introduction of new fuel products from new market entrants.

TVEL has historically provided almost 100% of fuel fabrication requirements to Russian-designed VVERs in Russia, Ukraine, and Eastern Europe but it did not provide fuel to Western-designed NPPs. Recently TVEL developed a PWR fuel design for use in Western NPPs to expand its market. In February 2012, TVEL announced that it had signed a contract with Vattenfall Nuclear Fuel of Sweden that covers Lead Test Assemblies (LTAs) of square 17×17 lattice TVS-Kvadrat. Conversely, Westinghouse is the only Western fuel supplier that has produced fuel assemblies for Russian-designed VVER NPPs, having produced VVER-1000 fuel assemblies for the two Soviet-designed Temelin units in the Czech Republic until 2006. Under an the initial 2008 contract between Westinghouse and Energoatom of Ukraine, the first Westinghouse fuel assemblies were loaded into the South Ukraine NPP in 2010. In December 2014, Westinghouse and Ukraine's Energoatom agreed to significantly increase future deliveries of Westinghouse-supplied fuel assemblies to Ukrainian NPPs through 2020.

There is also expansion of fabrication capacity in China for Western-designed NPPs that are under construction in China. CNNC has put in place technology transfer agreements with AREVA, TVEL and Westinghouse so that China will be capable of fabricating fuel for its Western-designed NPPs. Kazatomprom is also exploring joint ventures with a number of fuel manufacturers that would allow fabrication of fuel assemblies in Kazakhstan. Kazatomprom already exports fuel pellets to a number of countries including China and India.

In April 2015, the Nuclear Utility Fuel Advisory Board (NUFAB), whose members include several of the largest US nuclear operators—Dominion, Duke Energy, Exelon, and Southern Nuclear, sent a letter to the US Nuclear Regulatory Commission (NRC) regarding a new fuel product under development by Lightbridge Corporation (Lightbridge). According to Lightbridge, its metallic fuel rod design includes three components: a- central displacer of zirconium (Zr), which serves to reduce centerline temperatures and allows for the incorporation of burnable poison material within the rod; a four-lobed fuel core composed of a Zr-U alloy, and a Zr-1Nb cladding alloy that is metallurgically bonded to the fuel core. The metallurgical bonding that takes place during the fuel rod fabrication process results in each fuel rod being a monolithic form composed entirely of metal. According to Lightbridge, the fuel rod design is more robust than current tubes that utilize ceramic pellets. NUFAB members are working with Lightbridge to submit an application to the NRC in 2017 for the use of LTA, with insertion of LTA's into a US PWR as early as 2020 (NUFAB, 2015; WNA, 2015e).

13.4 Sources of further information and advice

There are a wide variety of sources that provide information on fuel fabrication processes, capacity, and fuel cycle trends. Documents from many of these sources are cited herein and are included in the references to this chapter. Additional resources include:

- Addition information regarding fuel fabrication can be found at the various web sites for the fuel fabricators.
- The World Nuclear Association also provides a high-level overview of the fuel fabrication process and fuel cycle facilities in countries with nuclear power programs.
- ANT International, which provides training in the area of nuclear fuel, has very informative information available on its web site, for purchase or through various seminars that the company holds periodically.

- EPRI's Fuel Reliability Program provides information regarding fuel assembly failure mechanism, ongoing research programs, and plant specific experience.
- The proceedings of technical meetings sponsored by the International Atomic Energy Agency, TopFuel, and other conferences also provide a wealth of information on fuel for existing NPPs, fuel cycle innovations, and research into new fuel designs and new reactor types.

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