November 2004 marked fifteen years since the fall of the Berlin Wall. In a program known as "Megatons to Megawatts", the United States and Russia have eliminated over nine thousand nuclear weapons-worth of Russian highly-enriched uranium [1]. Despite a promising diplomatic start to a different program to eliminate excess weapons-grade plutonium, the fifteenth anniversary of the Berlin Wall falling has passed with none disposed-of thus far. This paper examines the history of the plutonium-disposition program and describes current developments in a thorium fuel program that show great promise for this mission.

Thorium fuel as a superior approach to disposing of excess weapons-grade plutonium in Russian VVER-1000 reactors

by Seth Grae, Dr Alexei Morozov & Dr Andrey Mushakov

According to a June 2004 Carnegie Endowment report [2], the United States and Russia have each produced over 100 metric tons of weapons-grade plutonium, an equivalent of over 10,000 nuclear weapons in each country. While some of this fissile material is still deployed in the nuclear arsenals of the United States and Russia, with the end of the Cold War, a large portion of this plutonium has become excess to each country's defence needs.

The United States and Russia have taken the first steps to reduce the amount of plutonium that might otherwise become available for diversion into the wrong hands. In 2000, the U.S. and Russian governments signed a bilateral agreement [3] whereby each country committed to dispose of 34 metric tons of excess weapons-grade plutonium over the next two decades.

Both parties agreed to proceed in parallel with the disposition effort in each country and to seek to begin operation of disposition facilities by December 31, 2007 and to achieve a disposition rate of no less than 2 metric tons of this fissile material per year. At this rate, it would take 17 years to dispose of the entire 34 tons in each country after the start of the disposition process.

Russia made it clear that proceeding with plutonium disposition was dependent upon financial assistance from the United States and other industrialised countries [4], and the 2000 plutonium disposition agreement included $200 million in U.S. funding for Russia to jump-start the program. Russia agreed to contribute its excess weapons-grade plutonium and provide other in-kind contributions.

Current Approach

Initially, the U.S. Department of Energy (DOE) selected a mixed oxide (MOX) fuel technology for the Russian part of the disposition program, and MOX and immobilisation in a ceramic form for the U.S. part. In 2002, the immobilisation approach was eliminated from the disposition program, leaving MOX as the only plutonium disposition technology for both countries.

In 2000-2002, DOE estimated that the entire plutonium disposition program using MOX would cost nearly $6billion, with the Russian part being approximately $1.7-$1.9 billion [5, 6]. Since then, these cost estimates have escalated substantially and DOE is now revising the estimates [7, 8].

In fiscal years 2000-2004, the U.S. Congress appropriated over $1.8billion for plutonium disposition [9-13]. Of that amount, a little over $500million was appropriated for construction activities relating to the MOX plutonium disposition facilities. Having already cost U.S. taxpayers over an estimated $1billion, the MOX program has not made substantial progress toward the goal of beginning the operation of disposition facilities by December 31, 2007, as called for in the 2000 plutonium disposition agreement. According to the DOE budget request for fiscal year 2005 [8], the MOX program is still in the design stage, and no construction activities have been initiated. The MOX program is now virtually stalled over many unresolved issues. The United States and Russia have been at an impasse for over one and a half years over nuclear liability standards for contractors.

MOX fuel is estimated to produce approximately two-thirds as much new plutonium in its spent fuel as it eliminates (although the plutonium embedded in the spent fuel would be in an isotopic mix that would make it more difficult to use in weapons, and it would be more difficult to access plutonium in spent fuel than pure weapons-grade plutonium in a stockpile). There are technical issues with MOX that need to be addressed, including a more negative moderator temperature coefficient, a less negative Doppler coefficient and hotter, i.e., more decay heat, fuel rods in MOX and higher fission gas release in MOX as compared with standard uranium fuel [14]. MOX fabricated from reprocessed LWR fuel is used successfully in commercial Electricité de France (EdF) reactors. However, MOX fuel has never been used in Russian VVER-1000 reactors and the cost of modifying Russian reactors to use MOX fuel has not been adequately examined.

Furthermore, some members of the United States Congress are becoming frustrated with the little progress achieved by the MOX program to date. For instance, the House of Representatives proposed to reduce the funding in fiscal year 2005 for the MOX program by over $165million in the United States, or approximately by 25% from the DOE budget request [15]. At the same time, the Russian MOX program funding was proposed to be cut by half, from the requested $64million to $31.5million [15].

Despite these difficulties, MOX continues to be pushed by DOE as the best and only approach to plutonium disposition in the United States and Russia. There are also powerful business interests having a large stake in the MOX program. A consortium of Duke Project Services Group, Cogema, Inc., and Stone & Webster (DCS) has won the government contracts for the MOX program in the United States. Areva, which is mostly owned by the French government and is the parent company of Cogema, Inc., is the lead contractor for Russia. Duke Project Services Group is a wholly-owned subsidiary of Duke Energy. Duke Power is the electric utility business of Duke Energy and operates nuclear power plants in North and South Carolina in which MOX fuel could be used. Cogema has the MOX nuclear fuel technology. Stone & Webster plans to build the plants in South Carolina to produce MOX fuel.

The U.S. government contracts awarded to the DCS consortium are structured as “cost plus a fixed fee” contracts [16]. With the cost estimates for the MOX program now exceeding $6billion, the fixed fee part of these government contracts could be worth up to several hundred million dollars or more to the DCS consortium if the MOX program overcomes its current difficulties and moves forward. It has been estimated that Duke Power would save $160million in nuclear fuel costs from participating in the program [17].

Thorium fuel approach

Thorium fuel based on the seed-and-blanket fuel assembly geometry is a nuclear fuel technology that promises to offer practical and superior means to dispose of weapons-grade plutonium in Russian VVER-1000 reactors.

The technology is being developed by Thorium Power Inc. in collaboration with the Russian Research Centre "Kurchatov Institute", which has been leading the research and development effort on the thorium fuel in Russia since 1994. Kurchatov Institute is a premier nuclear research facility with full product development cycle capabilities and extensive nuclear reactor and nuclear fuel experience.

There are currently approximately five hundred Russian nuclear scientists and engineers from several leading Russian nuclear research institutes and fuel fabrication plants working on the development, testing, and demonstration of this thorium fuel technology. The current plan is to have lead test assemblies (LTAs) in an operating VVER-1000 nuclear power plant in 2006. If all goes as anticipated, this thorium fuel technology can be ready to begin plutonium disposition in Russian VVER-1000 reactors as early as in 2010.

The late Dr. Alvin Radkowsky invented Thorium Power's original nuclear fuel designs. Dr. Radkowsky was a pioneer nuclear scientist in the early U.S. commercial nuclear power programs, and he studied under "father of the hydrogen bomb" Dr. Edward Teller. Dr. Radkowsky was the first Chief Scientist for the U.S. Naval Nuclear Propulsion Program, which was headed by Admiral H.G. Rickover. Dr. Radkowsky led the design teams for the U.S. Navy's nuclear surface and submarine fleet and the first commercial nuclear power plant in Shippingport, Pennsylvania. He headed the team that invented the light water breeder reactor, which was based on an earlier version of the thorium fuel seed and blanket concept, and was demonstrated in the Shippingport reactor in the 1980s.

The development of the technology has been funded primarily with private capital from Thorium Power, Inc. Some early funding support also came from several DOE grants. In fiscal year 2004, the project received a $4million U.S. government appropriation that is now funding development of thorium fuel technology for disposing of weapons-grade plutonium in Russian VVER-1000 reactors. Oak Ridge National Laboratory, on behalf of DOE, oversees the work performed by the Russian institutes on this technology under a government

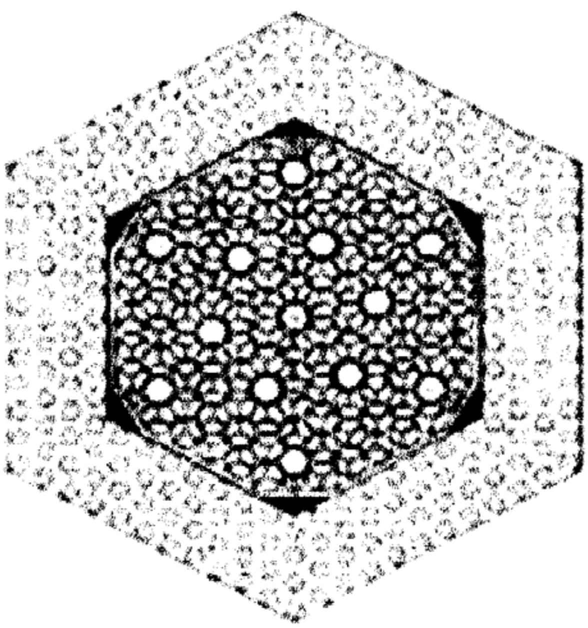

Figure 1: The top view of a seed-and-blanket fuel assembly for a VVER-1000 reactor

contract and audits the results of that work. Westinghouse Electric Company also participates in this project as a reviewer of the technical work and results achieved by the Russian nuclear scientists and engineers.

The thorium fuel technology being developed for the plutonium disposition mission incorporates a demountable two-zone heterogeneous fuel assembly. The central, or inner, region is called the seed, and the outer region is called the blanket (see Figure 1). The seed supplies neutrons to a sub-critical blanket [18]. The seed fuel rods are made of a metallic plutonium-zirconium alloy using a relatively inexpensive co-extrusion fabrication process. The blanket fuel rods are composed of thorium-uranium oxide fuel pellets sealed in standard zirconium tubing utilising the fuel fabrication technology used for standard uranium fuel for VVER-1000 reactors.

The co-extrusion process has been used in Russia for many years to fabricate nuclear fuel for navy ships [21]. The co-extrusion fuel fabrication technology was demonstrated for the thorium fuel project in September 2004 when the first plutonium fuel samples based on both metallic plutonium-zirconium and Cermet plutonium-zirconium fuel composition were fabricated at existing fuel fabrication facilities at Siberian Chemical Combine in Russia. The blanket fuel fabrication technology was demonstrated in Russia several years ago for the thorium fuel project, and since then, several thorium-uranium blanket fuel samples have been undergoing irradiation experiments at the IR-8 research reactor at the Kurchatov Institute. Several members of the U.S. Congress have visited these tests in Russia. The seed has an operating lifetime in the reactor's core of three years, the same as standard uranium fuel, whereas the blanket can be irradiated in reactor for up to nine years, at which time it must be replaced with fresh blanket fuel.

	Loaded		Discharged	
	kg/yr	%	kg/yr	%
Isotope:				
^{238}Pu	1.06	0.13	1.97	0.95
^{239}Pu	745.30	91.72	62.36	30.04
^{240}Pu	53.22	6.55	86.24	41.54
^{241}Pu	9.51	1.17	41.52	20.00
^{242}Pu	3.49	0.43	15.51	7.47
Total:	**812.60**	**100.00**	**207.60**	**100.00**

Table 1: Isotopic composition of plutonium in thorium fuel for VVER-1000 reactors

Table 1 illustrates the amount of weapons-grade plutonium that can be loaded each year in a VVER-1000 reactor using thorium fuel and the isotopic composition of the residual plutonium contained in spent seed fuel. (Most of the residual plutonium remaining in spent thorium fuel is contained in the seed. The amount of residual plutonium - all isotopes of Pu - present in spent blanket fuel is about 128kg, or 14kg on an annualised basis).

	Loaded		Discharged	
	kg/yr	%	kg/yr	%
Isotope:				
^{238}Pu	0.37	0.13	1.16	0.62
^{239}Pu	248.40	91.72	88.23	47.43
^{240}Pu	17.74	6.55	54.44	29.26
^{241}Pu	3.17	1.17	31.16	16.75
^{242}Pu	1.16	0.43	11.04	5.93
Total:	**270.84**	**100.00**	**186.00**	**100.00**

Table 2: Isotopic composition of plutonium in MOX fuel for VVER-1000 reactors

The information about the amount and isotopic composition of loaded and discharged plutonium for MOX fuel presented in Table 2 takes into account only the MOX fuel assemblies, which occupy one-third of a standard VVER-1000 reactor core. It excludes the regular uranium fuel assemblies occupying the other two-thirds of the core, which produce additional plutonium and other isotopes in their spent fuel.

Similar information for MOX fuel for VVER-1000 reactors is presented in Table 2. As can be seen, thorium fuel allows for 812.6kg of plutonium to be loaded into a VVER-1000 reactor each year (based on a standard fuel reloading scheme of three years), whereas MOX can only handle a plutonium load of 270.8kg per year. One reason why thorium fuel can dispose of plutonium up to three times as fast as MOX is the fact that, for safety and reactivity concerns, MOX fuel assemblies can occupy only one-third of a reactor core, with the other two-thirds filled with regular uranium fuel assemblies, whereas thorium fuel assemblies are being designed to be loaded into the entire core of a standard VVER-1000 reactor, because neutrons produced by the seed are captured by the blanket.

The plutonium disposition rate for thorium fuel could be increased to about 1,220kg per year if the irradiated plutonium-zirconium seed were discharged from the reactor after reaching a lower fuel burn-up rate comparable to the 20,000 megawatt days thermal per metric ton of heavy metal standard for irradiated MOX fuel specified in the 2000 plutonium disposition agreement [3]. At this rate it would take only approximately 28 reactor-years to dispose of the entire 34tons of weapons-grade plutonium in Russian VVER-1000 reactors using thorium fuel. Using four VVER-1000 reactors and starting actual plutonium disposition in 2010, the whole 34tons of Russian excess weapons-grade plutonium could be disposed of with thorium fuel by 2017.

As the data in Tables 1 and 2 illustrate, thorium fuel bums 75% of the originally loaded plutonium, compared with 31% for MOX. The lower plutonium elimination rate for MOX is further exacerbated by the fact that the other two-thirds of the reactor core filled with regular uranium fuel produce new plutonium, which is not the case with thorium fuel. If that newly-produced plutonium were taken into account, the total quantity of plutonium discharged per year for MOX would amount to about 336kg per reactor, or 65kg more plutonium than what was originally loaded into the reactor with MOX fuel. The isotopic composition of residual plutonium in spent fuel is also more favourable for thorium fuel, which has a significantly lower plutonium fissile (i.e. Pu-239 and Pu-241 - key isotopes for a nuclear weapon) as compared with MOX.

In addition to a significantly higher rate of plutonium disposition and increased proliferation-resistance of spent fuel, thorium fuel is expected to have significant cost advantages over MOX. Substantial cost savings could be achieved in the following three major areas:

- Capital investment in the construction of plutonium disposition facilities;
- Operating costs during the plutonium disposition phase of the program;
- Cost of reactor modifications.

As mentioned above, fabrication of the metallic plutonium-zirconium seed and the thorium-uranium oxide blanket can be done at existing - but modified - fuel fabrication facilities in Russia, and that has already been demonstrated. The estimated cost of upgrading these facilities to an industrial-scale production level, which would be required for converting tons of excess weapons-grade plutonium into fresh seed fuel, is approximately $100million, which is a fraction of the estimated over $1billion investment required to build a new MOX fuel fabrication plant. A substantially higher rate of plutonium disposition with thorium fuel as compared with MOX reduces by a factor of three the costs for the operating phase of the plutonium disposition program in Russia. Finally, thorium fuel is designed to be compatible with existing Russian VVER-1000 reactors without requiring as significant and costly reactor modifications as needed for MOX.

In addition to a significantly higher rate of plutonium disposition and substantially lower costs compared with MOX, the thorium fuel approach has the following benefits:

- The thorium fuel technology to be used in Russian VVER-1000 reactors is being developed by Russian nuclear scientists and engineers, who have nuclear fuel and VVER-1000 reactor knowledge and expertise and who have developed nuclear fuels for Russian reactors in the past.
- With the blanket part of the fuel assembly staying in-reactor up to three times as long as the seed, the amount of spent fuel can be significantly reduced - by about half by volume, or by 70% by weight - compared with standard uranium or MOX fuel.
- Radio-toxicity of spent thorium fuel is lower than that of MOX.

Finally, the spent blanket fuel, which is discharged once every nine years, contains approximately 693kg of U-233 [19]. This translates to about 77kg of U-233 on an annualised basis, which is less than half of the amount of plutonium produced by a 1000MWe nuclear power plant using standard uranium fuel. Some experts say that U-233 may represent a major proliferation concern. This concern is addressed in the thorium fuel design through denaturing of the U-233 in the blanket by the initial addition of almost 20% enriched uranium. During the long in-core residence time, the following additional uranium isotopes are created: U-232, U-234, U-235 and U-236. U-238 also remains in the blanket.

As Dr Radkowsky explained it, "Isotopic separation of the U-233 will be far more difficult and costly than the separation of U-235 from natural uranium. This is because of the several non-fissile isotopes mixed with the U-233 and contamination by the hard gamma emitter Tl-208" [20].

Conclusion

Thorium fuel offers a promising means to dispose of excess weapons-grade plutonium in Russian VVER-1000 reactors. Using this thorium fuel technology, plutonium can be disposed of up to three times as fast as MOX at a significantly lower cost. Spent thorium fuel would be more proliferation-resistant than spent MOX fuel.

The thorium fuel technology is being developed by Russian nuclear scientists and engineers to be fully-compatible with their standard VVER-1000 reactors and will not require significant and costly reactor modifications. Thorium fuel also offers additional benefits in terms of reduced weight and volume of spent fuel and therefore lower disposal costs.

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