THE NEED TO ADDRESS THE LARGER UNIVERSE OF HEU-FUELED REACTORS, INCLUDING: CRITICAL ASSEMBLIES, PULSED REACTORS AND PROPULSION REACTORS [1]

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ABSTRACT

The RERTR program has focused on ending shipments of HEU fuel to research reactors. Highest priority has been given to reactors with steady thermal powers ≥ 1 megawatt. Since the cores of critical assemblies and pulsed reactors can contain huge amounts of HEU, they should be a second focus. Also, since many aging and specialized HEU-fuelled reactors may no longer be needed, more emphasis should be given to initiatives that could assist in their shutdown and decommissioning, including providing access to regional reactors with superior facilities.

HEU-fuelled ship-propulsion reactors should also be addressed. Russia's civilian icebreaker reactors are of particular interest because their fuel design is considered less sensitive than that of naval reactor fuel. Moreover, Russia's KLT-40 icebreaker reactor is being adapted for a floating nuclear power plant and LEU icebreaker fuel could be used for converting Russian research reactors such as PIK and SM-3, that operate at power-reactor temperatures.

1. Introduction

The U.S. and Soviet RERTR programs were originally established to eliminate their shipments of weapon-usable uranium to foreign research reactors. Reactors that operate continuously at high power are the largest consumers of ^{235}U [2]. Therefore, the highest priority was given to developing fuel for reactors with steady thermal power outputs ≥ 1 megawatt(thermal) [MWt] [3]. This approach has been successful in reducing U.S. HEU exports from an average of over 1000 kg/year to less than 100 kg/yr [4].

The effort to prevent nuclear terrorism also should be concerned, however, with research reactors with large inventories of lightly irradiated HEU, even if they have lifetime cores. Critical assemblies used to mock up the cores of fast-neutron reactors and pulsed reactors can have core inventories larger than the 60 kilograms of approximately 80% enriched HEU used to make the Hiroshima gun-type bomb.

Most naval-propulsion reactors are HEU fuelled. Conversion of these reactors is not often publicly discussed because their designs are considered sensitive. The fact that Russia became interested in developing LEU fuel for the KLT-40 reactor used in its nuclear-powered icebreakers in order to be able to use the reactor in an exportable floating nuclear power plant has, however, provided an opportunity to explore the conversion of a propulsion reactor.

2. Critical assemblies

A large fraction of the HEU-fuelled reactors not currently targeted for conversion by the RERTR program are critical assemblies. Those that have the largest inventories of HEU are used to mock up fast-neutron reactors. Typically, large HEU-fuelled fast reactors, such as Russia's BN-600, are fuelled with 20-30 % enriched uranium. Fast critical assemblies, however, often contain fuel elements with enrichments up to 90% [5].

Today, it is possible to do accurate computer calculations of criticality for irradiated as well as fresh fuel. Critical assemblies are needed only for "benchmark experiments" to check the computer models. The results of many such experiments are already available and they can be shared between research institutes. It is important to consider, therefore, how many critical assemblies the world needs. This could be a subject for a session at next year's RERTR meeting.

3. Pulsed reactors

Pulsed reactors containing large inventories of HEU are standard equipment at many nuclear-weapon design institutes. It is a therefore a welcome development that the All-Russia Institute of Experimental Physics (VNIIEF), whose BIGR pulsed reactor contains 833 kg of 90% enriched uranium, has submitted a proposal to the International Science and Technology Centre [ISTC] in Moscow to conduct a study of the feasibility of converting BIGR and a second pulsed reactor (VIR-2M) to LEU fuel [6].

4. Convert or decommission?

Overall, there are many more research reactors than are needed today. In 2003, 272 were listed as operating [7]. In the spring of 2004, the IAEA put out a press release in which Iain Ritchie was quoted as estimating that there will be only 30-40 research reactors needed 15 years hence [8]. Three quarters of the research reactors in operation today will be more than 40 years old in 2020, others are highly specialized and no longer needed, and only nine are under construction and eight planned.

Because of the RERTR program, very few HEU-fuelled research reactors have been built in the past 25 years. The approximately 120 HEU-fuelled reactors are therefore older on average than the LEU-fuelled reactors. Most of the newer HEU-fuelled reactors are either Slowpoke and MNSR reactors, whose lifetime cores each contain only about 1 kg of weapon-grade uranium, or specialized Russian critical assemblies and pulsed reactors.

Thus, a large fraction of the currently operating HEU-fuelled research reactors will probably soon no longer be needed. International assistance should be made available to help decommission them where needed. Decommissioning would remove the threat of HEU diversion as effectively as conversion and removal of spent HEU fuel.

For critical assemblies or pulsed reactors that contain large inventories of lightly-irradiated HEU, the value of the HEU could provide an economic incentive to decommission. The HEU can be blended down to low-enriched uranium and sold for power-reactor fuel. One metric ton of 90% enriched uranium, if blended with natural uranium, could produce 25 tons of 4.3% enriched natural uranium worth about $25 million. Of course, some fraction of this value would be spent on the blend-down services and transaction costs.

Another incentive to shut down excess research-reactor capacity would be to provide the users access to superior facilities elsewhere. In the U.S. and Western Europe, access to high-energy particle accelerators, synchrotron radiation sources, and research reactors is provided to outside "user groups" on a competitive basis. If similar access were available to qualified users worldwide, then regional research-reactor-users could sit down together and think through how many of what types of research reactors they need. The IAEA already is promoting the idea of "regional centres of excellence." The RERTR community could help advance this idea.

5. Naval propulsion Reactors

The world's nuclear fleets contain about 200 operating reactors -- each with a power in the 100-MWt range and the vast majority fuelled with HEU. U.S. and U.K. submarine and aircraft carrier reactors are fuelled with 90+% enriched HEU. It is reported that currently operating Russian submarine reactors are fuelled with 21-45% enriched HEU [9]. By contrast, France reportedly uses "Caramel" fuel enriched to less than 10% in its newer nuclear submarines, which are refuelled at approximately 5-year intervals [10]. These submarines include the *Rubis*-class attack submarine, which is by far the world's smallest nuclear-powered attack submarine (2650 tonne displacement).

Converting U.S. naval reactors to LEU will probably constitute the greatest challenge. The fuel in the cores in new U.S. nuclear submarines and aircraft carriers is being designed to last the lifetime of the vessels -- up to 45 years at expected rates of use. In 1995, the U.S. Director of Naval Nuclear Propulsion reported to Congress,

> "no more uranium could be packed into a modern long-lived core without degrading structural integrity or cooling of the fuel elements…Therefore, using LEU…offers only two design choices:
>
> - "Using the same core volumes…reduce the fissile loading and substantially reduce the endurance of the core.
> - "Alternatively, in redesigned ships, substantially increase the volume of the core…" (emphasis in original).

It is also stated in the report that converting to a lifetime LEU core would require increasing the core volume by a factor of three. The resulting increase in the overall cost of building a nuclear ship was estimated at about 25% [11].

It could well be that some possibilities were ignored in the analysis. Unfortunately, because of military secrecy, it is impossible for outsiders to review the basis for these statements. An independent group with the appropriate security clearances should do this. However, if lifetime cores are required, the testing of replacement LEU fuel would take on the order of 10 years (assuming that the capacity factors of naval reactors are about 20%).

Nevertheless, conversion of all naval reactors as well as civilian reactors must be seriously pursued. The risks associated with stockpiling of hundreds of tons of weapon-grade uranium for naval reactors and the flow of thousands of kilograms per year through their fuel cycles should not be accepted indefinitely.

6. Icebreaker reactors

There is somewhat less secrecy about the design of civilian ship propulsion reactors. Today, Russia is the only country operating such reactors. It has 11 HEU-fueled reactors on seven icebreakers based near Murmansk. Together, their cores contain about 2000 kg of ^{235}U and they require about one fifth that amount annually for refuelling. Some information is available about the core design of one of these reactors, the KLT-40, as a result of a safety report provided to the Norwegian government in connection with a port visit by an icebreaker/container ship, the *Sevmorput,* to Norway in 1991 [12]. That report states that the reactor is fuelled with 90% enriched uranium. However, the operator of the nuclear-powered icebreakers, the Murmansk Shipping Company, reportedly has stated more recently that most of the fuel currently used in Russian icebreakers is 30-40% enriched [13].

Russia is interested in adapting the ≈150 MWt KLT-40 for a floating nuclear power plant that could be exported. The Bochvar Institute therefore applied for and received ISTC funding to explore possible high-uranium density fuels that could be used to convert the reactor to LEU fuel. The results of this project were reported at the 1997 RERTR meeting. Two types of high-uranium-density fuels were examined:

1) Particles of porous UO_2 imbedded in aluminium alloys (melting temperatures 580 ^{o}C and up) gave fuel densities of 4.6-5.1 grams U/cc; and

2) Particles of uranium alloy coated with zirconium (melting temperature 855 ^{o}C) gave fuel densities of 9.3-10.9 grams U/cc [14].

In 2001, the Bochvar Institute applied to the ISTC for funding for the next stage of the project but received only approval without funding [15]. The Nuclear Threat Initiative Foundation is currently considering funding the project.

Based on the incomplete information that the Soviet Union provided Norway about the design of the *Sevmorput* core, a Norwegian group developed a family of core models with hollow cylindrical fuel rods [16]. A colleague and I showed that, if the rods were solid, with a fuel density of 4.5 grams U/cc, this core model could be converted to LEU fuel with a core life of 10,000 full-power hours equal to that obtained with 90% fuel [17]. A group affiliated with the Moscow Institute of Physics and Technology has done a series of calculations assuming twisted cruciform-shaped fuel rods of the type used in the PIK reactor core [18] and concluded that the KLT-40 could be converted to LEU using a fuel with densities ranging from 4.5 - 6.9 grams U/cc, depending upon the assumed thickness of the fuel fins [19].

7. Conclusions

Recently, the U.S. Congress authorized the U.S. Secretary of Energy to fund the development of

> "alternative fuels and irradiation targets based on low-enriched uranium to convert research and *other* reactors fuelled by highly-enriched uranium to such alternative fuels, as well as the conversion of [such] reactors and irradiation targets" [emphasis added] [20].

Thus any HEU-fuelled reactor can now be considered for conversion if its fuel or fuel cycle is seen as potentially vulnerable to diversion -- and all are. The Bochvar Institute is already pioneering in broadening the RERTR program mission in its effort to develop LEU fuels for the KLT-40 reactor.

Critical assemblies and pulsed reactors *are* research reactors and should be given appropriate priority in the RERTR program even if it is necessary to replace lifetime HEU cores.

Finally, given the large number of research reactors that are expected to become obsolete or superfluous during the next decade, there should be a parallel international program to assist in decommissioning unneeded HEU-fuelled research reactors and providing researchers who shut down their research reactors access to operating research reactors with superior facilities.

References and notes

[1] Amore detailed paper, "A comprehensive approach to elimination of high-enriched-uranium from all nuclear-reactor fuel cycles," is in press at *Science & Global Security 12* (2004).
[2] At 80% capacity factor, approximately 0.35 kg of ^{235}U will be fissioned or transmuted into ^{236}U per megawatt of capacity per year.
[3] Of the 38 research reactors converted to LEU as of the end of 2003, 27 had steady powers ≥ 1 MWt, 6 were lower-power U.S. research reactors whose conversion was mandated by the U.S. Nuclear Regulatory Commission, and 2 lower-power reactors outside the U.S. were TRIGA reactors, for which HEU replacement cores became unavailable.
[4] A. J. Kuperman, "Civilian Highly Enriched Uranium and the Fissile Material Convention" in *Nuclear Power& the Spread of Nuclear Weapons,* P. L. Leventhal, ed., Brassey's, 2002, p. 249.
[5] The BFS facility at the Institute of Physics and Power Engineering in Obninsk, Russia has 8700 kg of 36% and 90% enriched uranium, I.P. Matveyenko et al, "Physical inventory of nuclear materials on BFS facility," *MPC&A-2000 conference, Obninsk, Russia, 22-26May 2000*.
[6] "Use of low enriched uranium in VNIIEF pulse nuclear reactors," ISTC project proposal # 3128, submitted in 2004.
[7] P. Adelfang and I.G. Ritchie, "Overview of the status of research reactors worldwide," *Proceedings of the International Meeting on Reduced Enrichment for Research and Test Reactors, Chicago, Illinois, USA, 5-10 October 2003*.
[8]"New life for research reactors? Bright future but far fewer projected," IAEA press release, March 8, 2004.
[9] C. Ma and F.N. von Hippel, "Ending the production of highly enriched uranium for naval reactors," *Nonproliferation Review 8* (2001) p. 86. France has both LEU and HEU-fueled naval reactors. China's are believed to be LEU fueled.
[10] Y. Girard, Technicatome, Saclay, unpublished transcript, conference on "The implications of the acquisition of nuclear-powered submarines by non-nuclear weapons states," MIT, March 27-28, 1989.
[11] Director, Naval Nuclear Propulsion, *Report [to the U.S. Congress] on use of low enriched uranium in naval nuclear propulsion,* June 1995, p. 8 (unclassified).
[12] *Information of Safety of Icebreaker-Transport Lighter/Containership with Nuclear Propulsion Plant Sevmorput* (undated).
[13] *Sources of radioactive contamination in Murmansk and Arkhangel'sk counties* by Thomas Nilsen and Nils Bøhmer (Bellona Foundation, 1994), p. 79.
[14] A. Vatulin, V. Lysenko and A. Savchenko, "Designing a new generation fuel element for different purpose water reactors," *Proceedings of the International Meeting on Reduced Enrichment for Research and Test Reactors, Jackson Hole, Wyoming, USA, 5-11 October 1997.*

[15] A.M. Savchenko, *Low Enrichment Uranium Core for Floating Nuclear Power Plant Reactor (FNPP) as a way of Resolving Weapon's Nuclear Material Nonproliferation Problem*, ISTC Project #2016.

[16] M. Bremer Maerli, S. Børresen, K. Gussgard, S. Høibråten, and M. M. Sobieska, *Criticality considerations on Russian ship reactors and spent nuclear fuel,* Norwegian Radiation Protection Authority, Report 1998:7.

[17] J. Kang and F. N. von Hippel "Feasibility of converting Russian icebreaker reactors," presentation at the *Global 2001 International Conference on the Back End of the Fuel Cycle,* Paris, Sept. 9-13, 2001.

[18] Yu. V. Petrov, A.N. Erykalov and M.S. Onegin, "The Fuel Cycle of Reactor PIK," *Proceedings of the International Meeting on Reduced Enrichment for Research and Test Reactors, Bariloche, Argentina, 3-8 November 2002***.** Conversion to 36% enriched UO_2-Al fuel with a density of 3.6 grams U/cc is discussed. The PIK reactor operates at pressures up to 50 bars, corresponding to temperatures up to 270 ^{o}C, K.A. Konoplev, "Status of construction of PIK reactor," http://nrd.pnpi.spb.ru/base/pik_en.html.

[19] A. M. Dimitriyev, A. C. Diakov, and A.M. Shuvayev, "An assessment of possibility to convert ship reactors to LEU fuel," (June 15, 2004, in Russian) http://www.armscontrol.ru.

[20] *National Defense Authorization Act for Fiscal Year 2005,* Section 3132: "Acceleration of removal or security of fissile materials, radiological materials, and related equipment at vulnerable sites worldwide."