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On the Importance of Ending the Use of HEU in the Nuclear Fuel Cycle: An Updated Assessment

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Abstract. The events of September 2001 have created a renewed urgency with regard to the disposition and future use and management of nuclear-weapons-usable materials. Highly enriched uranium (HEU) has received particular attention because it is relatively easy to use in a nuclear weapon and therefore an obvious candidate for diversion or theft by state or non-state actors. The role of the RERTR program in this context and its contribution to global security can hardly be overemphasized. This article reviews existing or proposed activities to reduce the threat posed by HEU, how these activities are linked to the RERTR program, and outlines the most urgent steps to be taken to approach the ultimate objective of eliminating non-weapons HEU inventories in the world.

Introduction

When serious concern about nuclear terrorism and new concern about proliferating states emerged recently, highly enriched uranium (HEU) began to attract considerable public and political attention.

Several characteristics of HEU make it the material of choice for low-tech proliferators, and possibly also for sub-state actors. In contrast to plutonium, it is relatively easy to handle due to its low level of radioactivity and, most importantly, only HEU can be used in the most basic weapons design, the so-called gun-type design.[1] There is little disagreement that a terrorist group would be able to design a gun-type device and that such a device could be expected to work without prior testing.

The only effective barrier to prevent nuclear terrorism as well as other proliferation scenarios is therefore to block the acquisition of HEU in the first place — and the only approach likely to be successful in the long-term is to eliminate HEU to the largest extent possible. A sustainable nonproliferation strategy must therefore address both production of HEU and theft or diversion of existing material, which includes the important category of HEU associated with the nuclear fuel cycle.[2]

Production of HEU vs. existing HEU stocks

To our knowledge, the enrichment of uranium to HEU is currently halted in the U.S., Russia, U.K., France, and China.[3] Table 1 summarizes the estimated world inventory of HEU in the military and civilian sector. Production of HEU is extremely difficult to do by states without detection — and impossible to do at all by non-state actors. Recent events related to the acquisition of centrifuge technologies have raised the awareness of front-end proliferation risks. They also demonstrated, however, that with the heightened vigilance of intelligence services since the discovery of Iraq's program in 1991, detection of clandestine production or even acquisition of related technology is likely even at an early stage. The main focus of concern, therefore, is on the possibility of diversion of already existing material in stocks or use.

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[1] The U.S. did not consider necessary a nuclear test of the "Little-Boy" device in 1945 before its use in Hiroshima. Due to the apparent simplicity of the design, the U.S. has subsequently declassified many characteristics of the weapon, including the dimensions of the uranium projectile and target, as well as other materials used in the weapon. Several scientists who participated in the Manhattan project have emphasized the simplicity of assembling a gun-type HEU device.

[2] For a more detailed discussion of strategies to prevent nuclear terrorism, addressing both HEU and plutonium, see [von Hippel, 2001].

[3] China has no declared policy, but stopped producing HEU more than a decade ago. Pakistan is producing HEU for its nuclear weapons program and North Korea has recently admitted to having an HEU program.

Military HEU stocks		Military HEU consumption	
Russia	735–1,365 t	Russia	1.3 t/y
United States	580–710 t	United States	2.0 t/y
France	20–30 t	France	?
China	15–25 t	China	0.0 t/y
United Kingdom	6–10 t	United Kingdom	$<$ 0.2 t/y
Pakistan	0.6–0.8 t		
South Africa	0.4 t		
Subtotal	1,360–2,140 t	Subtotal	$\sim$ 3.5 t/y

Civilian HEU stocks		Civilian HEU consumption	
Subtotal	$\sim$ 20 t	Subtotal	$<$ 1.5 t/y

Table 1: Estimated HEU world inventory and annual consumption in reactors. Military reactor use in nuclear-powered submarines and surface vessels, civilian use in research reactors and some Russian icebreakers. Estimates for HEU stocks and consumption from [Albright et al. 1997] and [Ma and von Hippel, 2001], respectively.

Some of the proliferation risks associated with existing HEU stocks are being addressed in various international programs and have received additional attention from independent analysts lately [Bunn et al., 2002], [Civiak, 2002]. They urge that it is essential to increase the rate of upgrades in the security of military and civilian stocks, to accelerate the disposition of declared excess HEU stocks (“Accelerated HEU Blend-Down”), to consolidate civilian “orphan” stocks such as that recently removed from the shutdown Vinča research reactor in Yugoslavia, and to provide incentives to facilities around the world to give up their HEU or plutonium (“Global Cleanout & Secure”).

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The reactor use of HEU is associated with a variety of proliferation risks, which are discussed in some more detail below. Furthermore, the use of HEU in the fuel cycle justifies the maintenance of stocks and, ultimately, also of production capacities. The ultimate objective therefore must be to eliminate the use, trade, and storage of HEU associated with any reactor use of the material. To this end, the conversion of research *and* naval reactors to low-enriched fuel is important — and both types of reactors are addressed in the last sections of this paper.

Proliferation risks associated with the use of HEU in the nuclear fuel cycle

The total amount of HEU present in the civilian nuclear fuel cycle has been estimated to be approximately 20 metric tonnes while operation of research reactors currently requires an annual HEU supply in the order of 1,000 kg.[4] These quantities are small compared to the military stocks, but 20 metric tonnes is still enough to make about one thousand fission weapons. Furthermore, there is an extra risk associated with the presence of this material at large number of civilian sites. There are still nearly 50 operational HEU-fueled research reactors with a thermal power of at least 1 MW in the world [IAEA, 2000]. If smaller reactors, shut-down facilities, and critical assemblies are included, the number of civilian sites with non-trivial (more than kilogram quantities) of HEU is likely to approach or exceed 100.

Irradiated HEU fuel also represents a serious proliferation risk because the uranium contained in spent 93-percent enriched fuel remains nuclear weapons-usable even for relatively high burnups. Table 2 shows the approximate uranium isotope vectors and corresponding critical masses for some reference burnup levels. The critical masses of uranium compositions of enrichments between 76 wt% and 81 wt% are still lower than 20 kg for the given simulation conditions — comparable to the value of approximately 15 kg for the reference case of fresh HEU enriched to 93 wt%.

	HEU 93%	20% Burnup	40% Burnup	50% Burnup	HEU 50%	LEU 20%
U-235	93 wt%	88 wt%	81 wt%	76 wt%	50 wt%	19.75 wt%
U-236	—	4 wt%	10 wt%	14 wt%	—	—
U-238	7 wt%	8 wt%	9 wt%	10 wt%	50 wt%	80.25 wt%
Critical Mass	14.9 kg	16.3 kg	18.2 kg	19.9 kg	41.4 kg	220 kg

Table 2: Uranium composition and critical masses for different uranium-235 burnup and enrichment levels. Critical mass values are for a beryllium-reflected metallic uranium sphere (reflector thickness: 10 cm, uranium density: 19 g/cc). Data obtained in MCNP 4B calculations with ENDF B-VI cross-sections at 300 K.

Furthermore, for an assessment of proliferation risks, not only the material at the reactor sites has to be considered, but also its entire "history" and the maintenance of the associated infrastructure including off-site storage of fresh and irradiated HEU, fuel fabrication, and transport links between sites, during which the material can be especially vulnerable.

In the past, reprocessing was the standard back-end option for irradiated HEU fuel. Given the availability of HEU from excess weapons, this strategy is no longer supported

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[4] See [Albright et al., 1997], Appendix D.

in the U.S. Various promising technologies have been studied to prepare spent HEU fuel for (direct) final disposal, notably the "Melt and Dilute" technology identified in [DOE, 2000]. In the meantime, the HEU is stored "as is."[5] For this reason, even an optimum disposition option from a nonproliferation perspective cannot avoid proliferation risks, which are perpetuated during the time until the dilution to LEU takes place.

Attractiveness of research reactors as potential targets for terrorist attack

Unfortunately, many research reactors have to be considered attractive targets for theft of highly enriched uranium that is contained in the fresh fuel with the intention to use this material in a crude nuclear explosive device. In comparison to military facilities, research reactors are typically located in relatively low security environments and, in comparison to spent light-water power-reactor fuel, their fuel elements are relatively easy to handle and transport.

Irradiated HEU fuel might also qualify as a potential target, in particular, if it has been stored for significant time periods on-site and the radiation barrier is sufficiently low to handle the fuel without sophisticated equipment. For most research reactor fuels, the radiation barrier falls below 1–1.5 Sv per hour (unshielded in air at 1 meter from fuel element centerline) during the interim storage period.[6] A dedicated attacker might be willing to accept significant and ultimately lethal radiation doses of up to 5 Sv. For this dose level, the first symptoms of the acute radiation syndrome occur after 1–2 hours, but are still considered mild or moderate.[7] These facts suggest that an attack scenario, targeting a number of irradiated fuel elements, is credible and could be carried out in principle.

HEU use in reactors interferes with the elimination of the large stocks recovered from excess weapons

As long as HEU is used as a reactor fuel, large stocks of the material will be reserved in the military sector for future use in naval reactors or to be offered for use in civilian research reactors. Indeed, most U.S. excess weapon-grade HEU is being placed in

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[5] Germany, for instance, plans to store the irradiated HEU fuel of FRM-II for several decades in a centralized interim storage facility.

[6] Activity and estimated photon dose rates strongly depend upon the burnup of the fuel. For an MTR-type fuel element of 40% burnup, using a simple line source model proposed in [Pond and Matos, 1996], a photon dose rate of 1.5 Sv/h after 9 years and 1.0 Sv/h after 23 years at an unshielded distance of 1 meter in air can be estimated. Assumptions for irradiation history: 200 kW per fuel element, 390 kW per kilogram of uranium-235.

[7] In this case, the ultimate recovery of the exposed individual is uncertain, but survival still possible. See [UNSCEAR, 1988], Annex G, *Early effects in man of high doses of radiation,* in particular, Table 13.

reserve for use in naval reactors. This stockpile is large enough to fuel the entire U.S. nuclear-powered fleet for "many decades."[8] Conversely, the existence of these excess stocks and the possibility of new supply agreements, can encourage reactors operators to delay conversion to low-enriched fuel.[9] Thus, the ongoing use of HEU in reactors and the postponement of conversion of specific facilities delay irreversible nuclear disarmament, which would require blend-down of all excess HEU stocks.

At the same time, the nonproliferation regime may be in its most fragile and uncertain situation since its inception three decades ago. The Comprehensive Test Ban Treaty has not come into force and negotiations of a Fissile Material Cut-Off Treaty (FMCT) are deadlocked, while the cornerstone of the regime, the Nuclear Nonproliferation Treaty (NPT), has been seriously weakened by the recent appearance of new overt nuclear-weapon states and by violations of parties to the treaty.[10]

There are various ways to strengthen the nonproliferation regime, including improved export-control and safeguards systems. However, to preserve the legitimacy of the regime, it is also necessary to minimize its inherent asymmetries. It is therefore important that the nuclear weapon states of the NPT, as well as other states with privileged access to HEU to fuel reactors, do not prolong this use unnecessarily — while denying the access to the same material to other parties to the treaty. The survivability of the NPT regime ultimately depends upon minimizing such discriminatory approaches.

For all the above reasons, conversion of reactors to low-enriched fuel should be pursued globally — not just in specific countries where the near-term proliferation risk is considered especially high.[11]

Conversion of marine propulsion reactors

In contrast to civilian research reactors, the conversion of marine propulsion reactors to low-enriched fuel has thus far attracted relatively little attention. The total annual

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[8] DOE official cited in [Albright et al., 1997], pp. 93–94, and [ONNP, 1995], p. 28.

[9] There have been several recent supply agreements, according to which some Western-European reactors receive additional HEU for fuel fabrication. These incidences could postpone conversion to LEU of the corresponding facilities and encourage reconsideration on the part of other reactor operators who plan to convert or have already converted.

[10] India and Pakistan, which are not parties to the NPT, held nuclear weapons tests in 1998. A third non-party, Israel has not tested but is widely believed to have a substantial nuclear-weapons program. North Korea, which is party to the NPT, admitted in October 2002 that it is illegally pursuing a covert nuclear weapons program.

[11] There are various encouraging developments in this respect. In particular, China and France are designing their newest research reactors for LEU fuel. The Russian PIK reactor, which is already under construction, might also be re-designed for LEU use.

demand of HEU for naval reactors has dropped to less than 4 metric tonnes (Table 1) due to a sharp decline of the world's operational nuclear fleet after the end of the Cold War. But this is still more material than currently required by research reactors. HEU fuel continues to be used in about 150 nuclear-powered submarines and military surface vessels, as well as in some Russian icebreakers.

There have been some confirmed thefts of Russian HEU naval fuel — although the danger has been somewhat reduced as a result of a consolidation of storage sites and upgrades of security at the remaining sites carried out by the U.S.-Russian cooperative materials protection, control, and accounting (MPC&A) program.

Conversion of the world's nuclear navies to LEU is important to nuclear disarmament as well as to the effort to reduce the opportunities for terrorists to acquire HEU. As already indicated, conversion would make it unnecessary for countries to retain large stockpiles of HEU for future naval use. Conversion would also greatly strengthen the verifiability of the proposed Fissile Material Cutoff Treaty (FMCT). This is because both the NPT and the FMCT would allow countries to take HEU out from under IAEA safeguards for use in naval reactors. It would be impossible to verify in a timely manner that none of this HEU was going to weapons use.

Submarines

While Chinese and some French submarines reportedly use LEU fuel enriched to less than 20%, operational Russian and U.S./U.K. submarine reactors are designed for uranium enriched to 21–45% and 93–97%, respectively [Ma and von Hippel, 2001].

Officially, in the case of the U.S., the issue of conversion has been hardly addressed so far, with the only official review coming to the conclusion that "the use of LEU for cores in the U.S. nuclear powered warships offers no technical advantage to the Navy" [ONPP, 1995]. The U.S. Navy has used very high enriched fuels to develop life-time cores for its submarines and ships while, for instance, France has developed a hatch system for its submarines that allows for refueling every five years or so in a period of a few weeks.

An independent discussion and analysis of the impact of propulsion reactor conversion to LEU on submarine performance is hampered by the fact that virtually all fuel and reactor design information is classified. Nevertheless, results of one unclassified study suggested that an LEU core might be accommodated in current hulls if an "integral design" is used that combines the reactor core and the steam generator into one steam generating unit [Ippolito, 1990]. Avoiding the typical component separation leads to a very compact propulsion system. According to the study, the life-time of such an LEU core would be limited to approximately 20 years (approximately 1,200 full power days) and require 1–2 refuelings during the life of the vessel.

Russian icebreakers

Russia's Murmansk Shipping Company currently operates seven nuclear-powered icebreakers and cargo ships. These vessels use fuel enriched to 90%, require refueling every 3–5 years, and are all powered by the same reactor type: a PWR with designation KLT-40 and a thermal power of 135 MW. Preliminary calculations indicate that it would be possible to convert the Russian icebreakers to LEU fuel with a fuel with a density of 4.5 g(U)/cc [Kang and von Hippel, 2001].

A Russian consortium has sought funding from the International Science and Technology Center (ISTC) to support the development of a high-density LEU fuel for a "different purpose water reactor" [Vatulin et al, 1997]. This fuel might be used for a floating nuclear power plant (FNPP), which would also be based on the KLT-40 reactor.

If suitable LEU fuels for the KLT-40 reactor could be developed and qualified, the conversion of the Russian icebreaker fleet would become technically feasible. The benefits of their conversion is significant since the civilian HEU demand would be reduced by another 350–500 kg per year and the danger of theft would have been eliminated for the associated nuclear fuel storage facilities and their transport links.

Conversion of research reactors

The progress of the RERTR program since its beginnings in the late 1970s has been remarkable. As of the end of 2001, 20 foreign and 11 U.S. reactors had been converted and 7 foreign reactors were in the process of conversion [Travelli, 2002]. As a consequence, and as discussed above, the civilian commerce and use of HEU has dropped significantly and stronger international cooperative RERTR activities are likely to emphasize this trend in the future.[12]

With the dramatic exception of the German FRM-II,[13] no HEU-fueled research reactors have been designed in more than a decade.[14] The German case is particularly serious because, for the first time, a reactor will use high-density uranium-silicide HEU-fuel originally developed to allow for conversion of previously existing HEU-fueled reactors.

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[12] See, for instance, [Bukharin et al., 2002] for a discussion of the U.S.-Russian joint efforts.

[13] For a discussion of this case, see for instance, [Glaser, 2002b].

[14] In fact, only Libya, Russia, China, and Germany have started construction of HEU-fueled research reactors since 1980 and some of these reactors may be redesigned to be LEU fueled. The U.S. cancelled an HEU-project in 1995 during the planning stage.

Progress in fuel development has been one essential key to the success of the RERTR program. Uranium densities available today (4.8 g(U)/cc) exceed significantly the expectations at the time of the INFCE conference.[15] and there is only a very limited number of HEU-fueled reactors today that cannot use currently qualified LEU fuel without performance loss.[16]

The development and availability of uranium-molybdenum dispersion fuels with an uranium density of 7–9 g(U)/cc will essentially overcome the problem of accommodating sufficient LEU in a given geometry to reproduce the core life-time of the original HEU design. Qualification of these fuels is therefore a major milestone of international conversion activities.

Possible penalties could be further reduced — or performance even increased — if monolithic fuels (uranium-molybdenum-alloys) became available. MTR-type reactors would probably benefit most from these fuels since a reconfiguration of the core (i.e. reduction of core size) is often feasible. Single element reactors are less flexible in this respect, but the results for a simplified generic reactor discussed in the appendix illustrate the potential important impact.

Ending the use of HEU in research reactors

The annual HEU demand of research reactors in operation is largely determined by relatively few reactors. Table 3 shows the HEU-fueled reactors in operation with a thermal power greater than 10 MW and an uranium enrichment higher than 60%.[17] The conversion of these facilities is therefore of particular importance, even though the majority of the reactors in Table 3 are located in nuclear-weapon-states; otherwise, annual HEU demand for research reactors will "asymptotically" approach a level that is not significantly different from today's value.

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[15] In 1980, the long-term estimated fuel fabrication potential was believed to have been reached at approximately 3 g(U)/cc. Cf. [IAEA, 1980], in particular, Vol. VIII, p. 142.

[16] Most of these facilities appear in Table 3 below.

[17] Data from [Albright et al., 1997] and [IAEA, 2000]. Additional information for U.S.-supplied (foreign) reactors and Russian or Russian-supplied reactors from [Matos, 1998] and [Civiak, 2002], respectively.

Country	**Code**	**Name**	**Power [MW]**	**Enrichment [%]**	**Supplier**	**HEU [kg/y]**	**Comment**
USA	US-0137	HFIR	85	93	USA	150	FCNA, 9 gU/cc
USA	US-0070	ATR	250	93	USA	130–175	FCNA, 9 gU/cc
China	CN-0004	HFETR	125	90	China	75	
Russia	RU-0013	MIR-M1	100	90	Russia	60	
France	FR-0017	HFR	58.3	93	USA	54.8	CP (FCNA)
Russia	RU-0024	SM-3	100	90	Russia	43	
Germany	DE-0051	FRM-II	20	93	USA, RUS	40.5	
Netherlands	NL-0004	HFR	45	20–93	USA	38.3	CP (FCNA)
Belgium	BE-0002	BR-2	100	74–93	USA	29	CP (FCNA)
Germany	DE-0006	FRJ-2	23	80–93	USA	19.2	CP
USA	US-0204	MURR	10	93	USA	19	FCNA, 9 gU/cc
France	FR-0022	ORPHEE	14	93	USA, RUS	15.8	FCNA
South Africa	ZA-0001	SAFARI	20	87–93	S. Africa	12.6	FS
USA	US-0120	MITR-2	5–10	93	USA	12	FCNA, 9 gU/cc
USA	US-0126	NBSR	20	93	USA	8.7	FCNA, 6 gU/cc
Australia	AU-0001	HIFAR	10	60	USA, UK	8.1	SP (?)
Russia	RU-0008	WWR-M	18	90	Russia	3.7	FS
Russia	RU-0010	IVV-2M	15	90	Russia	3.5	
Kazakhstan	KZ-0003	EWG-1	60	90	Russia	“0”	
Russia	RU-0020	RBT-10/2	10	63	Russia		
Libya	LY-0001	IRT-1	10	80	Russia	“0”	

Table 3: Research reactors with the highest annual HEU demand.

Abbreviations: Fuel currently not available (FCNA), conversion planned (CP), feasibility study exists or underway (FS), and shutdown planned (SP). See Footnote 17 for references.

Summary and conclusion

Recently, a new and heightened awareness of the threat of nuclear terrorism to global security has emerged. In this context, HEU is of particular concern because it is relatively easy to use in a nuclear weapon and therefore an obvious candidate for diversion or theft by state or non-state actors. The threat is so severe because there is too much HEU in too many locations — while a possible loss, theft or diversion anywhere represents a security threat everywhere.

Elimination of HEU to the largest extent possible, which depends upon reactor conversion to low-enriched fuel, is the only nonproliferation strategy that will prevent the possibility of nuclear terrorism in the long-term and would also strengthen the nonproliferation regime in various other ways.

At the same time, the potential benefits of conversion to reactor operators are manifold. In some cases, political and public opposition to reactor operation is likely to decrease considerably. The fact that the use of low-enriched fuel significantly reduces the risk of being the target of a terrorist attack launched with the intention to acquire fresh or irradiated HEU is a serious consideration and should be another strong incentive for reactor operators to convert to low-enriched fuel at the earliest time possible. It is therefore crucial not to narrow the decision to technical or economic criteria alone when balancing the pros and cons of conversion to low-enriched fuel.

Ending HEU use has proven difficult due to a lack of urgency communicated by the responsible governments and the complex interdependence of national and international fuel cycle policies. Also, non-cooperative behavior has arisen in a few circumstances, including the highly controversial case of the German FRM-II. It is crucial to the success of the RERTR program that no new HEU-fueled reactors are built and existing ones are converted as soon as possible. The technical means are now at hand to abandon the use of HEU in research and probably also in most marine propulsion reactors. Both are important.

The contributions of the RERTR program to global security are highly significant. The program clearly requires much higher political attention and needs solid and appropriate funding. Possible disincentives to reactor conversion, often non-technical in nature, have to be removed. To this end, it is also essential that the goals of RERTR are acknowledged and broadly supported on an international level.

APPENDIX
The example of single element reactor conversion

Research reactors that use one compact fuel element (with involute-shaped MTR-type fuel plates) are particularly difficult to convert to LEU fuel. They were originally designed for rather high HEU densities and their core geometry is "inflexible" when compared to standard MTR-type reactors where core re-configuration and optimization is possible. Table 4 summarizes the main results of previous conversion calculations performed for exististing single element reactors, namely RHF (Grenoble, France), FRM-II (Germany), and HFIR (USA).[18] These studies indicate that the uranium densities to be expected with UMo-dispersion fuel will allow for use of low-enriched fuel with modest losses in reactor performance.

	RHF Grenoble	FRM-II	HFIR
Original HEU density	max 1.17 g/cc	max. 3.00 g/cc	max. 1.15 g/cc
Assumed LEU density	6–8 g/cc	7–9 g/cc	9–10 g/cc
Performance loss	7%	15%	10%
Technical challenge		Geometry change	Power peaking

Table 4: Conversion requirements for single element reactors. (References in footnote 18).

In order to estimate the potential of advanced high-density fuels in some more detail, a "generic single element reactor" has been defined and various conversion options studied. Table 5 summarizes the key characteristics of this simplified model and compares them with those of existing reactors. The fuel element geometry is depicted in Figure 1. The core has been modeled and analyzed in Monte Carlo simulations using MCNP 4B [Briesmeister, 1997].

Table 6 summarizes the main results for various fuel and conversion options of this generic reactor. The data illustrate the typical small to moderate performance loss to be expected when converting existing HEU single element reactors of similar design to LEU fuel with a uranium density of 7–9 g(U)/cc (LEU core 1).

The potential of a fuel with ultra-high uranium density is also shown. These results suggest that the availability of a fuel of up to 16 g(U)/cc does not necessarily lead to better reactor performance if the geometry remains unchanged (LEU core 2). However, if not precluded by operating constraints, the core size could be slightly reduced. This has been done for LEU core 3 while the cooling channel widths were increased in order to maintain a comparable coolant volume in the core. In this case, the loss of thermal neutron flux in the heavy water surrounding the core is less than 1%.

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[18] Data are based on the following references: [Mo and Matos, 1989] for RHF Grenoble; [Hanan et al., 1999] and [Glaser, 2002a] for FRM-II; and [Mo and Matos, 1997] for HFIR.

	RHF (ILL)	FRM-II	HFIR		Generic SER
Fuel type	UAl_x in Al	U_3Si_2 in Al	U_3O_8 in Al		UAl_x in Al
Enrichment	93 wt%	93 wt%	93 wt%		93 wt%
Thermal power	57 MW	20 MW	85 MW		30 MW
Uranium density [g(U)/cc]	1.17	1.5 and 3.0	0.78	1.15	1.50
Inner diameter	274 mm	130 mm	128 mm	286 mm	200 mm
Outer diameter	398 mm	229 mm	269 mm	435 mm	300 mm
Number of fuel plates	280	113	171	369	185
Active height of fuel plate	903 mm	700 mm	508 mm		700 mm
Thickness of fuel meat	0.51 mm	0.60 mm	0.77 mm		0.60 mm
Thickness of cladding	0.38 mm	0.38 mm	0.25 mm		0.38 mm
Thickness of cooling channel	1.80 mm	2.20 mm	1.27 mm		2.00 mm
Total uranium inventory	9,200 g	8,108 g	9,430 g		6,627 g
Average power density in core	1,170 kW/cc	1,040 kW/cc	1,670 kW/cc		1,090 kW/cc
Coolant	D_2O	H_2O	H_2O		$\star$
Fuel element: center	$\star$	$\star$	H_2O Trap		$\star$
Fuel element: surrounding	D_2O	D_2O	Be-Reflector		$\star$

Table 5: Key characteristics of single element reactors.
Asterisks ($\star$) represent different reflector, absorber, or coolant materials.

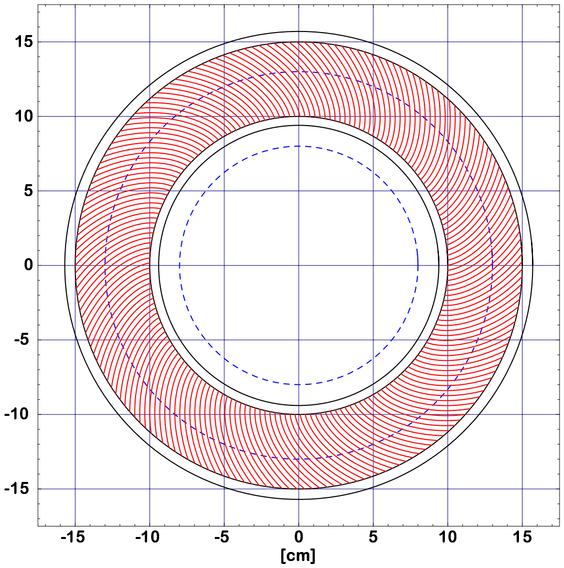

Figure 1: Fuel element for the generic single element reactor. Dashed circles indicate active volume of fuel element with reduced size for LEU core 3. See Table 6 for details.

	HEU Design	LEU Core 1	LEU Core 2	LEU Core 3
Fuel type	UAlx Dispersion	UMo Dispersion	UMo Monolithic	UMo Monolithic
Enrichment	93 wt%	19.75 wt%	19.75 wt%	19.75 wt%
Thermal power	30 MW	30 MW	30 MW	30 MW
Uranium density	1.5 g/cc	8.0 g/cc	16.0 g/cc	16.0 g/cc
Inner diameter	200 mm	200 mm	200 mm	160 mm
Outer diameter	300 mm	300 mm	300 mm	260 mm
Active height of fuel plate	700 mm	700 mm	700 mm	700 mm
Thickness of fuel meat	0.60 mm	0.60 mm	0.50 mm	0.50 mm
Thickness of cladding	0.38 mm	0.38 mm	0.38 mm	0.25 mm
Thickness of cooling channel	2.00 mm	2.00 mm	3.00 mm	2.20 mm
Number of fuel plates	185	185	146	157
Fuel volume	4,418 cc	4,418 cc	2,904 cc	3,247 cc
Uranium-235 inventory	6,163 g	6,980 g	9,176 g	10,261 g
Coolant volume in core	16,363 cc	16,363 cc	17,423 cc	15,875 cc
Coolant	Light water			
Fuel element: center	Beryllium reflector			
Fuel element: surrounding	Heavy water			
k(eff) at BOL	1.241	1.167	1.224	1.186
Maximum thermal neutron flux	9.75E14 n/cm2s (100%)	9.21E14 n/cm2s (94.5%)	8.49E14 n/cm2s (87.1%)	9.66E14 n/cm2s (99.1%)
Capture events in U-235, U-238, and Mo per 100 fissions in U-235	21.0 : 0.8 : —	21.0 : 11.9 : 1.7	21.1 : 11.8 : 1.9	22.4 : 14.1 : 2.3

Table 6: Results for the generic single element reactor.

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