# Measuring Progress in Reactor Conversion and HEU Minimization Towards 2020 – the Case of HEU-fuelled Research Facilities

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**Abstract.** *This paper analyzes how to measure progress in the minimization of HEU-fueled research reactors with respect to the International Fuel Cycle Evaluation (INFCE) completed in 1978, and the establishment of new objectives towards 2020. All HEU-fueled research facilities converted, commissioned or decommissioned after 1978, in total more than 310 facilities, are included. More than 130 HEU-fuelled facilities still remain in operation today. The most important measure has been facility shut-down, accounting for 62% of the reduction in U-235 consumption from 1978 to 2007. Presently, only three regions worldwide use significant amounts of HEU; North-America, Russia with the Newly Independent States, and Europe. Projected HEU consumption in 2020 will drop to less 50 kg as the current HEU-fueled steady-state reactors are shut-down or converted. However. if the current lack of concern for HEU in life-time cores is not changed, in particular in Russia, 50-100 such facilities may continue to be in operation in 2020.*

## INTRODUCTION

In 1980, representatives from 59 states agreed in the paper of the International Fuel Cycle Evaluation (INFCE) study that: *"The trade in and widespread use of highly enriched uranium and the production of fissile materials constitute proliferation risks with which INFCE is concerned. Proliferation resistance can be increased by: 1. Enrichment reduction preferably to 20% or less which is internationally recognized to be a fully adequate isotopic barrier to weapons usability of $^{235}U$; 2. Reduction of stockpiles of highly enriched uranium."* [1]. However, as we approach the 30-year anniversary of INFCE, the number of HEU-fueled research reactors in operation worldwide is still more than 130. However, there is ongoing confusion with regard to the scope as well as the progress of on-going activities: Which materials and facilities are actually targeted, at what pace, with what progress for HEU elimination? The aim of this paper is to provide the technical basis for answering these questions. The paper provides baseline information on the number and different types of HEU-fueled facilities, focusing on the key parameters, power, core inventory and annual HEU/ U-235 requirements. Projections of HEU usage through 2020 as a medium-term milestone are provided as well.

## MEASURING PROGRESS 1978 – 2007

The amount of HEU consumed in civilian steady-state reactors in operation in 1978 is estimated in this paper as 1225 kg U-235, or 1351 kg HEU, in 154 research reactors in 42 countries with total nominal power of 1919 MW. When comparing these values with INFCE *"over 140 research and test reactors of significant power (between 10 kW and 250 MW) are in operation (…) in more than 35 countries, with total power in excess of 1,700 MW"*, our baseline measurement should provide the needed accuracy for evaluating the progress after 1978.

The estimated annual requirement of HEU for research reactor fuel has been reduced by 42% from 1978 as described in Figure 1; from 1351 kg in 1978 to 787 kg in 2007. However, both the HEU consumption and the number of HEU-fueled facilities increased the first years after 1978 as the Chilean RECH-1, the Czech Sparrow, the Russian RBT-6 and the large Chinese HFETR-reactor went critical in 1974, 1975, 1979 and 1982, respectively. The Chinese, Chilean and the Czech facilities has subsequently been converted to LEU. China began to export HEU-fueled Miniature Neutron Source Reactors (MNSR) in the end of the 1980's adding China to the list of countries exporting HEU-fueled reactors. Although these facilities did not contribute significantly to annual HEU consumption containing only about 1 kg of HEU each, this gave reason for additional proliferation concern at that time. While facility shut-down accounts for the major part of the reduction in annual HEU consumption – 450 kg as seen in FIG 2 – conversion had moderate influence up until 2006 except for the period around 1993 when a new moderate-density silicide fuel was qualified. However, in the period 2006-2007 we have found a reduction in HEU consumption of over 100 kg, for the whole period 1978 – 2007 the reduction has been estimated to 278 kg as seen in FIG 3. The introduction of Germany's HEU-fueled FRM-II in 2004 has offset a large part of the savings achieved.

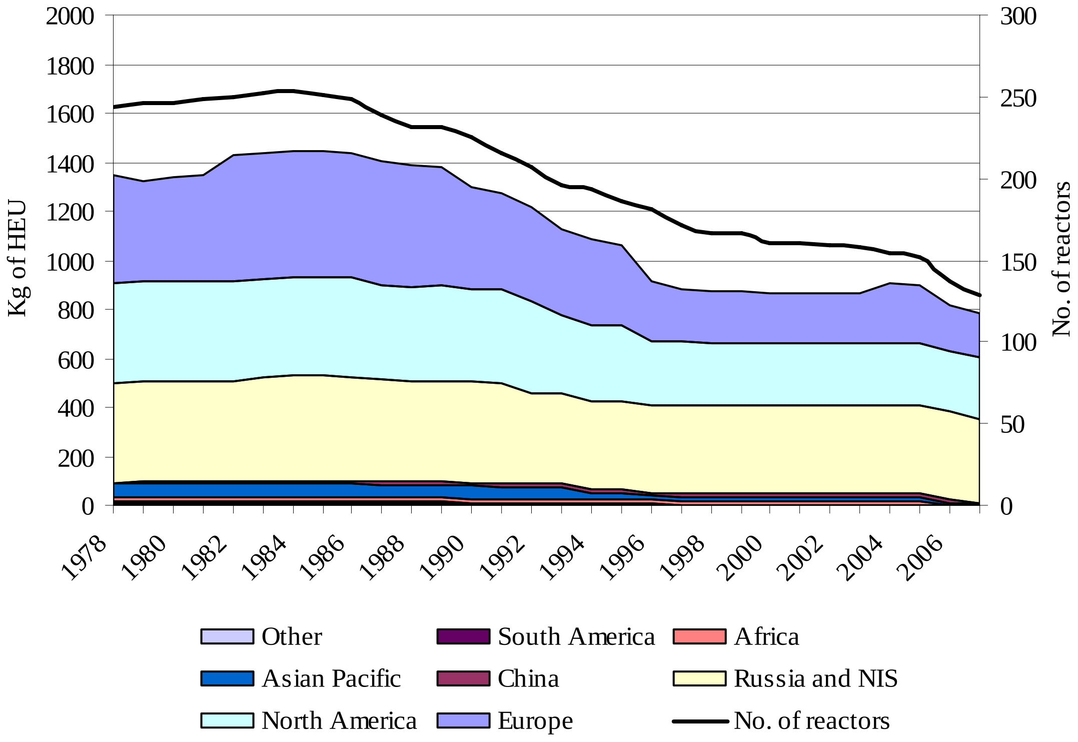


FIG. 1. Operational HEU-fueled research reactors and associated HEU consumption (kg) 1978 – 2007

In total, 53 HEU-fueled facilities has been converted since 1978, 49 as part of the US-led initiative on reduced enrichment in test and research reactors (RERTR). Of these, three reactors were shutdown immediately after conversion was completed, and another 5 within five years after conversion. The RB assembly in Slovenia was converted to LEU without the participation of the this program, this is also valid for the conversion of Chinese facilities HFETR, its critical assembly and the MJTR reactor. Including the reactors converted to 36-percent HEU as part of the Russian conversion effort in the 1980's, the overall figure for converted facilities is 65. Very few pulsed reactors or critical assemblies have been converted since 1978. The exceptions are the critical assemblies associated with China's HFETR and Libya's IRT facility, which was converted in 2006, and at Renselaer Polytech Institute in the US converted in 1987. With respect to shut-down, the US decommissioned a large number of military critical assemblies and pulsed reactors (20) at the end of the 1980s and beginning of the

1990s. Also other countries decommissioned critical assemblies, such as Germany (3), Spain, Belgium, Poland, and few critical assemblies in Russia.

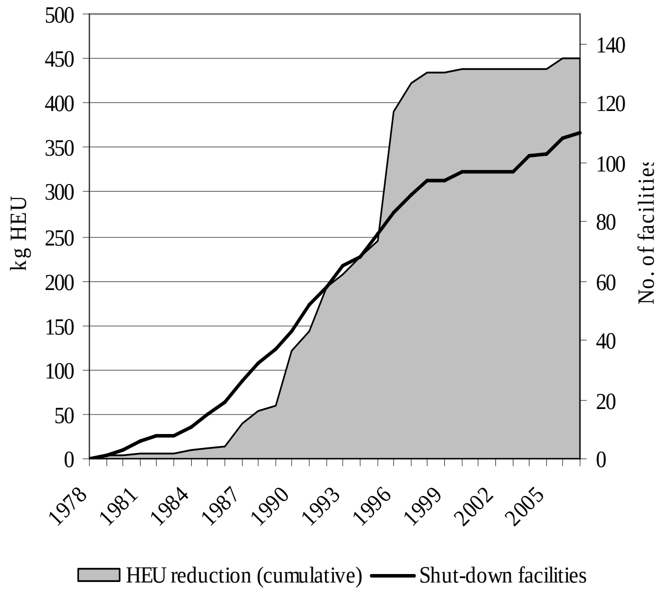


FIG. 2. Shutdown HEU-fueled research reactors and associated HEU consumption (kg) (cumulative) 1978–2007

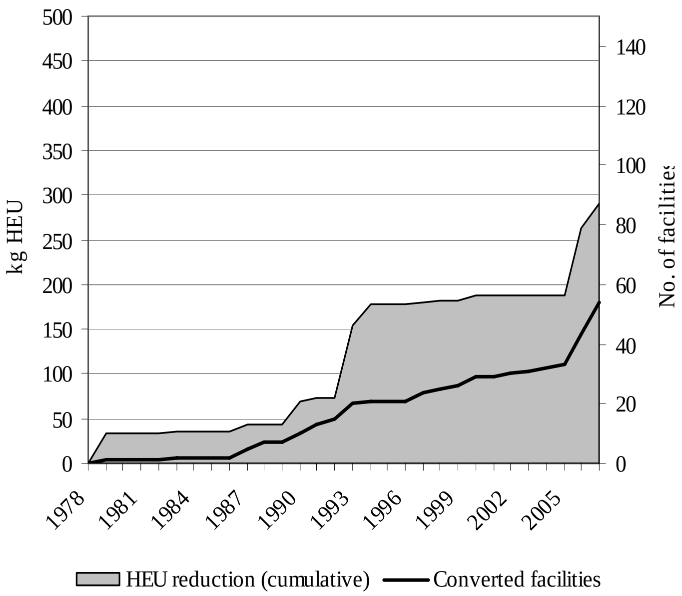


FIG. 3. Converted HEU-fueled research reactors and associated HEU consumption (kg) (cumulative) 1978–2007

## STATUS 2007

The largest HEU consumers in the civilian steady-state reactor sector for 2007 and their estimated annual consumption, primarily based on the IAEA's Research Reactor Database (RRDB) figures for availability and burn-up, are presented in FIG 4. For reactors with large annual HEU consumption, such as the U.S ATR and HFIR reactors, figures presented of operators have been applied as the calculated values using the RRDB obviously are out of range. For the other reactors, as information on the relevant facilities has been removed from the public domain, the RRDB's information on nominal power, average burn-up and availability has been used to calculate the annual consumption of U-235 in HEU, adjusting for for example enrichment and capture when using burn-up [3]. The error bars indicate the range of consumption estimates for each reactor given in various other sources, including the RRDB [4]. These 20 facilities altogether use between 500 and 1000 kg HEU per year, with 655 kg as a representative value for 2007. This represents 62% of the total consumption of HEU for research reactors in 2007.

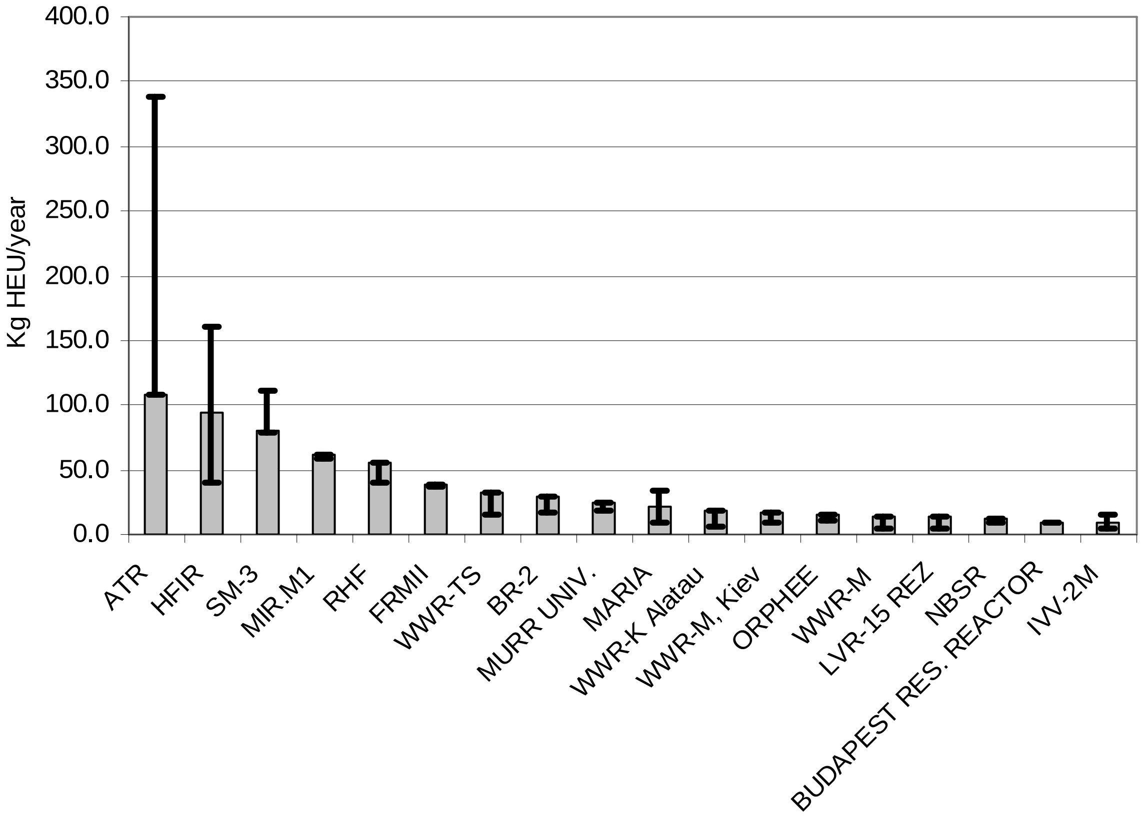


FIG. 4. HEU consumption in civilian steady-state research reactors (Top 20) – 2007

As seen in Table 1, more than 50% of the HEU-fueled research reactors in operation are non-steady-state reactors. Many contain large quantities of barely irradiated HEU as most critical test facilities does not exceed 100W in power. An example is the Russian BIGR pulsed reactor at the Institute of Experimental Physics at Sarov (VNIIEF) whose core contains 833 kg of 90% HEU [5]. The pulsed reactors with the biggest HEU inventories, however, are used by the nuclear-weapon states for simulating the effects of the neutrons from nearby nuclear explosions on missile warheads and satellites. VNIIEF has requested United States funding to do study on the feasibility of converting BIGR to using LEU [6].

## PROJECTED PROGRESS 2020

When establishing a 2020 projection, one has to consider that the HEU consumption in all other regions than North-America, Russian together with the Newly Independent States, and Europe after 2007 is about 10 kg or less as seen in FIG 6. As the Mexican facility has virtually completed its conversion process, the Chiliean facility Rech-1 will not restart with HEU fuel, the Indian APSARA will probably convert in 2008 as will the Japanese KUR facility. The remaining facilities are primarily MNSR’s and Slowpoke facilities with insignificant annual material consumption.

Table 1. Operational HEU-fueled research reactors 2007

| | | Russia & NIS | China | Europe | US | Other | **Total** |
|---|---|---|---|---|---|---|---|
| Critical assemblies | | 39 | 1 | 5 | 5 | 2 | 52 |
| Pulsed reactors | | 14 | 0 | 1 | 3 | 0 | 18 |
| Steady-state research reactors (MW) | < 0,25 | 1 | 3 | 5 | 1 | 12 | 22 |
| | 0,25 – 1 | 1 | 0 | 0 | 1 | 2 | 4 |
| | 1 – 2 | 0 | 0 | 0 | 3 | 0 | 3 |
| | 2 – 10 | 7 | 0 | 1 | 2 | 2 | 12 |
| | 10 – 250 | 8 | 0 | 7 | 4 | 0 | 19 |
| **Total** | | **70** | **4** | **19** | **19** | **18** | **130** |

A symposium held in Oslo in the summer of 2006 considered in detail the technical experiences of conversion of various kinds of civilian reactors, and concluded, inter alia, that: “*(…) conversion of research reactors to the use of LEU fuel can be accomplished without significant loss of capability. Fuel change to LEU without further modifications may result in 5–10% decrease in neutron flux and corresponding experiment performance.*” [7]. With respect to the possible decrease in neutron flux, it has been demonstrated how instruments upgrades and improved neutron guides may increase performance far beyond potential losses due to conversion [8]. However, still 25 reactors in North-America, Russian together with the Newly Independent States, and Europe require development of new fuel in order to be able to convert to LEU without profoundly changing their properties. The candidate fuel types are U-Mo dispersion fuel and monolithic fuel. Regarding the former, full size dispersion prototype fuel plates are now to be fabricated for testing and will be ready within 2011. While dispersion fuel originally was considered a viable option for some reactors, now all U.S. high-performance research reactors are waiting for the completion of a qualified monolithic fuel type. However, there are considerable difficulties in identifying suitable fabrication methods [9]. As the present schedule for having the monolithic fuel qualified in 2011 requires no unforeseen problems in the experimental scale-up to full size plates, one should not expect this effort to be completed before after 2012. Subsequently, the conversion of the relevant high-performance reactors will probably not take place before 2015/16.

Thus, a realistic schedule for eliminating the remaining HEU-fueled facilities thus have to assume that the U.S. commitment to complete conversion of its high-performance research reactors in 2014 is not realistic. A revised assumption may suggest 2016 for the large reactors ATR – including ATRC – and HFIR, and 2015 for MITR, MURR, NBSR. The U.S. has not committed to convert other types of facilities, and in 2007 4 HEU-fueled critical facilities was re-commissioned and put into operation.

Russia has the largest number of high-powered HEU-fueled reactors, with 9 high-flux facilities requiring fuel development for conversion. The IR-8, IRT-Mephi and IRT-T remain in operation and conversion of these facilities has not been suggested by Russia nor others. The US has offered to support conversion feasibility studies for the IVV-2M, MIR and WWER M Gatchina, all three in the Top 20 HEU research reactors shown in FIG 4. However, WWER M Gatchina was commissioned in 1959 and should be considered for decommissioning together with the mothballed Soviet-designed facilities EVG-1 and IGR in Kazakhstan. RBT-6 are being planned shut-down 2009, the RBT 10 in 2012, and MIR and SM-3 in 2017 [10]. The WWR-TS may be converted with existing fuels, however, as large parts of the Russian research reactor complex are underutilized, this has been assumed decommissioned in 2010 in FIG 6. Similar assumptions has been given for BOR-60 (2015), BR-10 (2013) and WWR-M (2014). However, as seen in FIG 6, several HEU-fueled research reactors will still remain in operation in Russia. The U.S has offered assistance for considering conversion of the smaller steady-state Russian research reactor OR in addition to other research reactors of various types, but no response has yet been given [6]. The lack of plans for the decommissioning or conversion of Russian facilities are striking, in particular when considering the low utilization factors for Russian research reactors as described in FIG 5 [11]. The large majority of Russian facilities various types of life-time core facilities in the Russian military-industrial complex. The continued existance of these facilities undermine the objectives and the results for minimizing the use of HEU in research reactors.

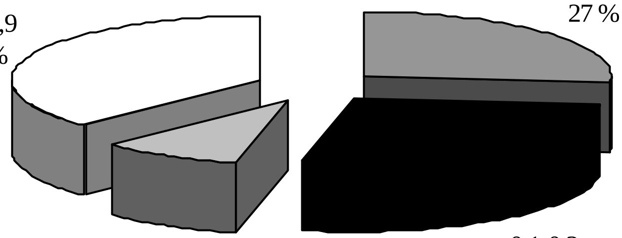


*FIG. 5. Utilization factors for Russian research reactors 2001-05*

Europe has 6 high-flux facilities in operation that require the development of new fuel for their conversion. The BR-2 and LVR 15 Rez have committed to convert when adequate fuel has been developed, but were commissioned in the 1950's and should be considered for decommissioning. In Figure 6, these have been scheduled for decommissioning after 55 years of operation, 2016 and 2012 respectively. The Budapest research reactor, close to 50 years of operation, may be converted with existing fuels, however, with no conversion date given it is considered scheduled for decommissioning in 2014, also after having reached 55 years of operation. The Netherlands and Poland (2009) has already committed themselves to converting their national research reactors, in the former case this will reach 55 years of operation in 2015 and should be considered for decommissioning. France, probably will launch its new Jules Horowitz reactor with HEU fuel enriched slightly above 20% - 27% - but the reactor has been designed to use high-density LEU fuel as soon as it has been licensed. The RHF and Orphee reactors are relatively new, the former has also committed to convert when adequate fuel has been developed, in line with earlier estimates we have assumed 2016. Germany's FRM-II is an exception and was designed to use higher density HEU fuel so that its conversion to LEU will be difficult – although perhaps not impossible – in FIG 6 this is the last European high power facility being converted in 2018.

## DISCUSSION

The issue of decommissioning is a sensitive one, since it touches upon a whole set of other issues such as national strategies for nuclear research, perceptions of progress and national pride, as well as local and regional issues. The US-led conversion initiative may not be the appropriate framework for addressing these issues. The IAEA conducts a series of smaller activities related to HEU minimization and would seem an obvious candidate for coordinated and qualified HEU-reduction efforts. So far, however, the IAEA too has not addressed frontally the need to decommission a large fraction of the world's research reactor. The organization has been capable of offering only limited assistance and facilitation upon the request of member states. An international assistance program for decommissioning HEU-fueled facilities might be bundled assistance in addressing a number of security-related issues in the back end of the fuel cycle as spent fuel inventories increase.

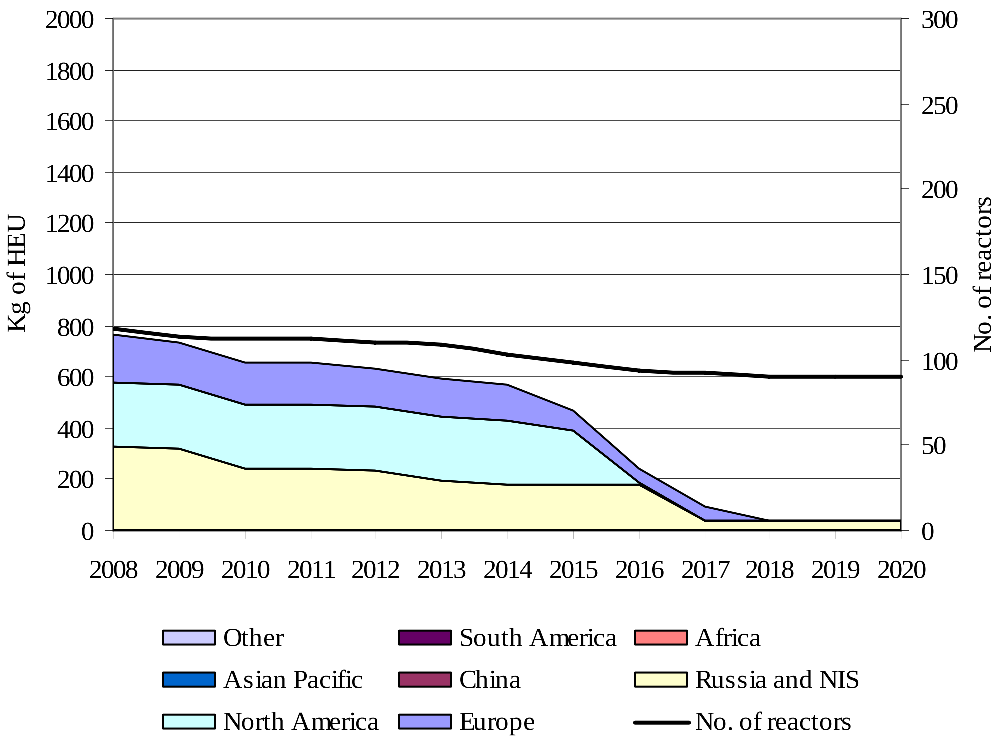


FIG. 6. Operational HEU-fueled research reactors and associated HEU consumption (kg) – Projected 2020

As a prerequisite for both facility conversion as well as decommissioning, there is a need to consider more closely the justification for continued operation of each HEU-fueled facility. In order to facilitate multilateral cooperation, such considerations ideally should be from regional rather than national perspectives. Costly new research reactors projects, beyond the possible resources of single states, could contribute to the de-nationalizing and hence reduction of overlapping HEU-activities. The most promising measure is to advance the creation of centers of excellence or reactor coalitions as is presently being tried in Australia/ Asia and Africa. For regions like the European Union and Russia, geographically close, but with a large number of high-performance reactors, this may be the concept accentuating the gain – and the lack of relevance – for a large number of operating HEU fueled facilities today.

The obvious candidate is the IAEA being the one promoting coalitions today. However, in order to be able to address conversion, the obvious advantages related to coalitions or centers of excellence in other contexts, such as nuclear science and technology, has to be promoted. The IAEA has issued guidance documents advising the operators of research reactors to establish a strategic plan which *"provides the rationale for the future for the facility"* [12]. The IAEA has also specified that it will only *"support requests for new facilities or equipment for research reactor utilization if they are accompanied by a strategic implementation plan clearly demonstrating that the items requested are necessary to achieve the plan."* Similar statements have been issued by representatives for the GTRI program, but the US-led programs should prioritize its resources on conversion of facilities with the best long-term prospects for future operation while other efforts encourage underused facilities to shutdown and decommission.

## CONCLUSION AND RECOMMANDATIONS

From the beginning of the international conversion assistance programs in 1978 till 2007, 107 HEU-fueled reactors with a combined HEU consumption of 450 kg/year have been shutdown. This includes 70 civilian steady–state research reactors. For older facilities, the possibility of facility shutdown and cleanout should be considered before conversion. In fact, many operational HEU-fueled facilities are fast approaching retirement age. Only a small number of the existing 130 HEU-fueled research reactors still in operation should be converted, the large number should be decommissioned and provisions for assisting the operator and the country in question with fuel handling, facility dismantlement and access to similar research facilities elsewhere should be established. The obvious candidate for accelerating shut-down activities is the IAEA with its broad and general mandate.

Forty nine research reactors have completed the conversion to LEU as a result over continued international assistance over three decades. This has resulted in a decrease in HEU consumption of 278 kg – or 38% compared to the amount of HEU consumed in 1978 in this class of facilities. All the HEU-fueled reactors outside US, Russia and France – 22 – are presently part of the international minimization programs. Among the three major nuclear states, however, only the US has committed to convert all its existing civilian research reactors as alternative fuels are developed. Russia and the EU -- most notably France – have not made similar commitments.A revised, realistic schedule for the overall conversion activities and goals should be developed as soon as possible as a point of departure for renewed international HEU-elimination efforts.

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