RESEARCH AND TEST REACTOR CONVERSION TO LOW ENRICHED URANIUM FUEL: TECHNICAL AND PROGRAMMATIC PROGRESS

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Abstract

The U.S Department of Energy (DOE) initiated a program — the Reduced Enrichment for Research and Test Reactors (RERTR) — in 1978 to develop the technology necessary to reduce the use of High Enriched Uranium (HEU) fuel in research reactors by converting them to low enriched uranium (LEU) fuel. In 2004, the reactor conversion program became the driving pilar of the Global Threat Reduction Initiative (GTRI), a program established by the U.S. DOE's National Nuclear Security Administration. The overall GTRI objectives are the conversion, removal or protection of vunerable civilian radiological and nuclear material. As part of the GTRI, the Conversion Program has accelerated the schedules and plans for conversion of additional research reactors operating with HEU. This paper provides an update on the progress made since 2007 and describes current technical challenges that the program faces.

1. INTRODUCTION

Nuclear research and test reactors worldwide have been in operation for over 60 years. Many of these facilities operate with high enriched uranium (HEU – U^{235} enrichment ≥ 20%) fuel. In response to increased worries over the potential use of HEU from research reactors in the manufacturing of nuclear weapons, the U.S Department of Energy (DOE) initiated a program – the Reduced Enrichment for Research and Test Reactors (RERTR) - in 1978 to develop the technology necessary to reduce the use of HEU fuel in research reactors by converting them to low enriched uranium (LEU) fuel. The reactor conversion program was initially focused on U.S.-supplied reactors, but in the early 1990s it expanded with the objective of converting Russian-supplied reactors to the use of LEU fuel.

Increased security concerns in recent years led to the establishment of the Global Threat Reduction Initiative (GTRI) by the U.S. DOE's National Nuclear Security Administration. The overall GTRI objectives are the conversion, removal or protection of vulnerable radiological and fissile material. A follow up conference for the International GTRI partnership held at the IAEA in September 2004 established the framework for international collaborations in meeting the goals of the program. As an integral part of the GTRI, the Conversion Program has accelerated the schedules and plans for conversion of additional research reactors operating with HEU.

Since the inception of the Conversion Program, 76 research reactors have been converted to LEU fuel or have shutdown prior to conversion. The program has had and continues to have a strong U.S. domestic effort with 20 of the reactors converted (or shutdown before conversion) being located in the U.S. and 56 abroad. HEU reactors that have permanently shutdown before conversion, did so for reasons unrelated to the conversion program. In 2005, the U.S. committed to the conversion by 2011 of all the domestic reactors that could be converted with existing LEU fuel. The milestone was reached in 2009, with the conversion of the last two reactors in this category.

The major technical activities of the Conversion Program include: the development and qualification of advanced LEU fuels, conversion analysis and conversion support. It must be noted that the development of technologies in support of the conversion of Mo-99 isotope production from the use of HEU to LEU targets is also a part of the GTRI conversion program. This paper, however, focuses on reactor fuel conversion and will not describe the medical isotope production conversion activities.

The key factor in enabling the conversion of a research reactor lies in the availability of a fuel with much greater uranium content, to compensate for the reduction in the content of U^{235} in the LEU material. The reactor conversion program has supported the development of high density LEU fuels to enable the conversion of research reactors. While LEU fuels developed in recent years reached uranium densities as high as 4.8 g/cc, many remaining reactors have designs and higher neutron flux that require higher uranium densities in order to make conversion feasibible without a significant loss in performance. The remaining research and test reactors in the U.S. fueled with HEU are mostly high flux (high performance - HP) reactors and require higher density fuels not currently available. High density fuels based on U-Mo alloys have been under development to supply these reactors with an LEU fuel option. The GTRI program has been developing a monolithic version of the UMo fuel for the conversion of the U.S. HP reactors. In addition, GTRI has been engaged in a cooperation with Russian organizations to develop UMo dispersion fuel for use in Russian designed reactors, and has been recently supporting the European effort LEONIDAS for the development of UMo dispersion fuel for the conversion of the RHF and BR-2 reactors. The most significant technical challenges for the conversion of these research reactors reside in the qualification of these high density fuels and the establishment of a fabrication capability that can reliably supply LEU fuel after conversion.

2. TECHNICAL ACTIVITES IN THE CONVERSION PROGRAM

The major technical activities of the Conversion Program include the development of advanced LEU fuels, and the conversion analysis and conversion support. Close coordination between analytical efforts and fuel development is essential in properly establishing the fuel requirements and verifying that no significant negative impact in reactor performance would result from conversion to LEU.

The initial feasibility analyses for speciifc research reactors provide the basic uranium loading requirements in a fuel assembly and thus identify the possibility of using exisitng LEU fuels. Additional, more refined analysis will then lead to the specifications for the LEU fuel assembly. Initial feasibility studies for high flux reactors indicated that higher densities that those in existing LEU fuels were required for their conversion, and fuel development programs were started. The fuel development programs become part of an iterative process with the conversion analysis activities. As the initial fuel requirements are developed, the fuel development and fabrication activities ensure that the required specifications and geometry (such as fuel plate compositions, thickness and cladding minium thickness) can be met. The process can result in a set of iteratons in which the fuel assembly geometry changes to adapt to fuel fabrication possiblities until a design that meets fuel performance requirements, reactor conversion requirements and fuel fabrication constraints is found.

2.1. Conversion analysis

The conversion analysis activities provide the required analytical and design evaluations to support the reactor conversion and licensing. Since the inception of the program, analysis methods and codes have been developed specifically for the analysis of research reactors. Different countries have also adapted computer codes to the analysis of research reactors. The methods and codes are continuously evolving to incorporate the latest tools and data and have been validated with experimental data.

The overall approach to the conversion of a research reactor to LEU fuel is based on a set of princicples designed to ensure that the conversion does not significantly impact in a negative manner the performance and operation of the facility after conversion. The following major principles are followed when studying the conversion of a research reactor to LEU:

- Ensure that an LEU fuel alternative is provided that maintains a similar service lifetime for the fuel assembly;
- Ensure that the ability of the reactor to perform its mission is not significantly diminished;
- Ensure that conversion to a suitable fuel can be achieved without requiring major changes in reactor structures or equipment;
- Demonstrate that the conversion and subsequent operation can be accomplished safely and that the proposed LEU fuel meets safety requirements;
- Determine, as possible, that the overall costs associated for conversion to LEU fuel does not increase the annual operating expenditure for the owner/operator, closely linked to the use of LEU fuel that maintains a similar service lifetime to that of the HEU fuel, so that the fuel assembly consumption is not significantly impacted.

There are three major components of the conversion analysis and studies, as follows:

- Feasibility studies to determine suitable LEU fuel assembly designs for each reactor. The fuel assemblies must be designed using qualified LEU fuels or fuels that are currently under development. The design of the fuel assembly may be an iterative process with the fuel development activities. Once a fuel assembly design has been selected, the reactor performance with the LEU fuel must be compared with the performance with the HEU fuel before conversion.
- Operational and safety analysis, to demonstrate that the transition from HEU to LEU fuel can be done safely and without interrupting normal operations. It must also be demonstrated to the satisfaction of the facility that operations will not be significantly affected by the conversion to LEU fuel, and it must be shown that the LEU-fueled reactor, as well as mixed HEU-LEU cores during the transition to a full LEU core, when applicable, satisfy all safety requirements.
- Support for the Regulatory Process, to obtain regulatory approval for the conversion to LEU fuel**.** The request for conversion must be submitted to the competent regulatory authority for approval.

2.2 Fuel development, qualification, and fabrication capability

The key factor in enabling the conversion of a research reactor lies in the availability of a fuel with much greater uranium content, to compensate for the reduction in the content of U^{235} in the LEU material. HEU fuels in plate-type fuel are usually dispersion fuels with densities ranging from 1.3 to 1.7 g/cm^3. Hydride HEU TRIGA fuel has a density of 0.5 g/cm^3. LEU fuels require a much larger uranium density in order to reach similar densities of U^{235} that allows the LEU-fueled reactor to have similar neutron flux characteristics. Several high density LEU fuels were developed by RERTR, in particular the uranium disilicide dispersion fuel with uranium densities up to 4.8 g/cm^3. General Atomics developed LEU fuel for TRIGA reactors with densities of 3.7 g/cm^3. Oxide tube-type LEU fuels for the conversion of Russian-supplied reactors with uranium densities of 2.5 g/cm^3 have also been qualified for use in several reactors. An accelerated fuel development and qualification program was initiated [1] with the objective of qualifying very high density LEU fuels that enable the conversion of the remaining reactors that are not convertible with existing qualified fuels.

Initial irradiation samples of a variety of fuel forms indicated that U-Mo alloys in an Al matrix were very promising, and these fuels are the focus of the current fuel development efforts. Both monolithic and dispersion fuels are being developed. The development program for U-Mo fuels targets Molybdenum contents between 6 and 10% and uranium densities of 6-8 g/cm^3 for dispersion fuels and up to 16 g/cm^3 for monolithic fuels. Several failures of dispersion samples in fuel development programs occurred in recent years. The failures were of a similar nature: formation of large bubbles in the fuel meat at the interface between the U-Mo/Al interaction product and the Al matrix. Swelling occurs when the bubbles interconnect. Run-away swelling can lead to failure of the fuel element. Analysis suggested that addition of Si to the Al matrix could stabilize the interaction product. Irraditation tests showed that small amounts of Si added to the Al matrix eliminate or reduce the formation of porosity [2], as could a coating that avoids the interaction between fuel particles and the Aluminum matrix (or Aluminum cladding in the case of monolithic fuel).

Basic initial development of UMo fuel in the U.S. concentrated on dispersion fuels, fabricated using a similar technology to that used in fabricating aluminide, oxide, and silicide dispersion fuels. With additional feasibility analyses for some of the high flux or high performance reactors, the need for uranium densities in the range exceeding the dispersion fuel fabrication capabilities, the priority for the development of fuels in the U.S. shifted to monolithic UMo fuel [3]. Development of LEU UMo fuel in other countries continued to emphasize the dispersion fuel option, estimated suitable for the conversion of high flux reactors in Western Europe, such as BR-2 and RHF. In the last few years, very significant efforts have been ongoing in the U.S., Russia, and Western Europe to develop UMo fuels and the capability to fabricate them. In addition, significant efforts are also underway in other countries that want to use UMo dispersion fuels in existing reactors or in research reactors under design, such as in Argentina, South Korea and Canada.

The Conversion program has led to the formation of an International Fuel Development Working Group (IFDWG), with participation of countries actively developing advanced fuels for research reactors (Argentina, Belgium, Canada, France, Republic of Korea, Russia, and the U.S.), initially to jointly investigate the causes of the dispersion fuel failures and more recently to share information on UMo fuel behavior for different compositions and types. Progress in the solution for the swelling of UMo fuels have been extensively discussed in the group. The IAEA is also an observer in the UMo fuels development and is leading the preparation of a UMo handbook with all these contributions.

The three major international initiatives will be described in the following section, under the respective efforts to convert sets of high performance or high flux research reactors. These efforts include the U.S. GTRI monolithic fuel development, the LEONIDAS [4] initiative in Western Europe, and the Russia-GTRI long-term collaboration for Russian-supplied research reactors.

3. MAIN CONVERSION ACTIVITIES

Since 2004, when the RERTR program became part of GTRI, the conversion program has accelerated both in the U.S. and internationally. NNSA has pursued agreements with many countries and organizations operating research reactors with the proposal to cooperate in their conversion to LEU. Technical cooperation between GTRI and the research institutes operating the reactors follow the establishment of the policy-level agreements. The technical cooperation can include fuel development and qualification efforts, support for fuel procurement in some cases, and conversion analysis and licensing. Recent and current major conversion projects are described in the following sections.

3.1. U.S. domestic reactors

Since the last IAEA conference on Research Reactor Utilization in Sidney in 2007, the U.S. has completed the conversion of all civilian research reactors that can convert with existing qualified fuel. The milestone was reached in 2009, two years ahead of the initial commitment. The remaining reactors are mostly included under the High Performance group, which require the completion of the qualification of the UMo monolithic fuel and two reactors that may not need any fuel development, but for which the fabrication and availability of the LEU fuel may be a challenge.

3.1.1. U.S. high performance reactors (USHPR)

The high performance reactors currently operating in the U.S. with HEU fuel are reactors with a very high neutron flux that require LEU fuel of very high density in order to convert with no significant decrease in the fuel cycle and experiment performance. The reactors are shown in Table 1. Because of the common needs for the conversion of these facilities, a working group was formed in 2005 in order to coordinate the feasibility studies and the fuel development, qualification, and fabrication efforts.

Recently the completion of the fuel development and conversion for these 5 reactors and critical assembly has been assembled into the single USHPR conversion project. The project consists of three major pillars that are responsible for the major technical areas:

- Fuel Development – responsible for completing the irradiation and material properties testing program for coordination of regulatory qualification of the monolithic fuel;
- Fuel Fabrication Capability – this pillar is responsible for establishing the basic fuel fabrication technology developed under the fuel development effort into a production process that will meet the annual LEU fuel requirements for the 5 reactors and will also be capable of supplying the LEU fuel during the transition from HEU to LEU; and
- Reactor Conversion – responsible for defining the fuel requirements based on the conversion analysis, preparing the updated Safety Analysis Report for the conversion, and supporting the licensing and potential reactor-specific modifications that may be required for conversion.

TABLE 1. U.S. HIGH PERFORMANCE REACTORS.

Reactor	Location	Power (MW)	Licensing Responsibility
MITR	Massachusetts Institute of Technology, Cambridge, MA	6	USNRC
MURR	University of Missouri, Columbia, MO	10	USNRC
NBSR	National Institute of Standards and Technology, Gaithersburg, MD	20	USNRC
HFIR	Oak Ridge National Laboratory, Oak Ridge, TN	100	DOE
ATR	Idaho National Laboratory, Idaho falls, ID	250	DOE
ATRC	Idaho National Laboratory, Idaho Falls, ID	0.005	DOE

The current emphasis of the fuel development activities are the tests of full size assemblies representative of the three USNRC-regulated reactors to be converted using UMo foil with a Zirconium layer between the foil and the Aluminum cladding. A fuel qualification report will be prepared for submittal to the USNRC for review and approval of the UMo monolithic fuel for use in the reactors the Commission regulates. Additional tests for burnable poisons and non-uniform foil cross sections will be further conducted leading to a second qualification report for the USDOE reactors, HFIR and ATR, both of which require these special design characteristics.

Fabrication of the new UMo monolithic fuel is a technical challenge since the dissimilar metals require an alternative to the plate rolling methodologies used in dispersion fuel fabrication. Co-rolling of a Zr layer on top of the UMo foil, as a difussion barrier, followed by Hot Isostatic Pressing (HIP) of multiple plates at the same time is the basic approach [5]. The fuel fabrication capability pillar of the USHPR project is currently working on defining the baseline for the fabrication of the monolithic fuel, establishing the necessary domestic capability based on the baseline technology, and optimizing the production process with repsect to the laboratory-scale process in order to achieve the required production volumes at an acceptable cost.

The reactor conversion pillar has performed feasibility studies that concluded that the conversion will be feasible if the fuel assemblies can be fabricated as designed. The studies are led by the reactor operator organizations and GTRI provides technical support or verification as needed. Safety analyses are ongoing and will be ready for submittal to the NRC after the fuel is qualified. Some of the reactors are planning some system modifications considered necessary to enable the conversion without a significant impact in performance. These potential modifications and their scheduling are being planned under this technical pillar.

3.2. U.S. supplied reactors in other countries

In the last few years, the GTRI program has also started multiple projects for the conversion of US supplied rectors in other countries. Sinced the last IAEA research reactor utilization conference in Sydney, the RPI reactor in Portugal, the KUR reactor in Japan, and the SAFARI-1 reactor in South Africa have converted to LEU fuel.

The program has also engaged additional reactors in Japan (UTR-Kinki at Kinki University and the KUCA critical assemblies at the Kyoto University) to perform feasibility studies for conversion. For the UTR-Kinki reactor, the technical challenge includes the possible facility modifications or upgrades that may be required in applying for a license for the new fuel. No fuel development is expected to be needed for the conversion of the KUCA facilities, but fabrication of fuel of special design characteristics that maintain the performance requirements of the facility will be a challenge.

Progress has been made in the conversion of the SLOWPOKE at ICENS in Jamaica. Conversion of this type of reactors has been performed before and no fuel development or qualification is required. However, the LEU fuel for this type of reactors is not being routinely manufactured and its fabrication is a challenging technical issue that is currently being addressed by the program in cooperation with other organizations that include the IAEA and the Atomic Energy of Canada Limited (AECL).

The largest set of technical activities currently ongoing in support of the conversion of US supplied reactors in other countries is the project to convert two high flux reactors in Europe, BR-2 in Belgium and RHF in France. SCK/CEN, operator of BR-2 and the ILL, operator of RHF, along with CEA of France and Areva-CERCA have formed the LEONIDAS project intended to qualify high density UMo dispersion fuel. GTRI is supporting selective portions of this effort. Feasibility studies performed by both organizations have concluded that conversion will be feasible if the fuel can be qualified. Full size plates of the UMo dispersion fuel are being irradiated in the BR-2 reactor [6].

3.3. Russian supplied reactors

Fuel development activities under the Russian – GTRI collaboration are particularly important to enable the conversion of a significant number of high performance reactors of Russian design. Most reactors outside Russia have already been converted with Uranium dioxide fuel of differnet geometries (square tubes and hexagonal tubes) developed by Russian organizations. Since the last IAEA research reactor conference in 2007, reactors in Uzbekistan (WWR-SM), Ukraine (WWR-M), and and Hungary (BRR) have converted to LEU. The reactor in Vietnam (DRR) will be fully converted to LEU by the end of 2011.

The main activities in the current scope for fuel development include the development of LEU UMo tube-type and pin-type dispersion fuel with densities up to 5.4 g/ cm^3 to meet the requirements of the highest power IRT-type reactor. The fuel development phase is about to be completed and the final report is expected by the end of this year.

3.3.1. Russian supplied reactors in other countries

Activities continue on the conversion of the MARIA reactor in Poland and the WWR-K reactor and its critical assembly in Kazakhstan. These two reactors have required the qualification by irradiation testing of lead test assemblies (LTAs) of LEU fuel for their conversion. The MARIA fuel assembly qualification project has almost concluded; irradiation testing of 2 silicide LEU LTAs fabricated by Areva-CERCA was finished in early 2011 and LEU fuel fabrication in under way to initiate the conversion to LEU in late summer 2012. Replacement of the primary pumps to allow the use of LEU assemblies of a design that has a higher pressure drop is necessary. The Institute of Atomic Energy has developed the project for the replacement of the pumps, which will take place during the planned long shutdown of late 2012. The project is the result of a very successful collaboration of GTRI with the MARIA reactor institute and Areva-CERCA.

The studies for the conversion of the WWR-K reactor in Kazakhstan have included several variations of the assembly design. The conversion is currently planned to be accomplished with uranium oxide fuel with a uranium density of approximetely 2.8 g/cm^3. After significant studies comparing the fuel cycle and experiment performance of the various assembly design variations, the Institute of Nuclear Physics (INP) selected a preferred assembly design. On the basis of that design, LTAs were procured by GTRI in Russia and are currently being irradiated. A BU exceeding 18% had been reached by the end of October. In order to reach the desired irradiation conditions and burnup in a shorter time, INP has placed the test assemblies in the center of the core, with a beryllium reflector structure surrounding the assemblies. The LEU LTAs are fabricated in Russia and use uranium dioxide. LEU fuel is already being ordered and it will be delivered in the summer of 2012, allowing for the critical assembly of the WWR-K reactor may convert to LEU in 2012, as the critical assembly does not need to wait for the qualification of the fuel for high burnup.

Feasibility studies for the conversion of two other Russian supplied reactors in Kazakhstan, IGR and IVG-1M, were initiated last year and will be concluded in late 2011. The potentail fabrication and supply of LEU fuel is being assessed, as the fuel required is not routinely fabricated. Potential modifications that may be required to enable the conversion feasibility are assessed.

3.3.2. Russian domestic reactors

As a result of negotiations between NNSA and Rosatom, Rosatom identified 6 Russian domestic reactor for the performance of feasibility studies for their conversion to LEU. An implemening arrangement that establishes the basis for the collaboration on the feaisbility studies was signed in December 2007 by DOE Undersecretary Poneman and Rosatom

Director General Kiriyenko. The feasibility studies were initated in early 2011 and will be completed between November 2011 and May 2012. The 6 reactors include 3 reactors at the National Research Center Kurchatov Institute (ARGUS, OR, and IR-8), the IRT-MEPHI reator at the Moscow Engineering Physics Institute, the IRT-T reactor at the Tomsk Polytechnic University, and the MIR reactor at the Research Institute of Atomic Reactors. The feasibility analyses are being performed in cooperation with ANL.

In addtion to the technical feasibility studies, reactor-specific economic impact studies are being performed by the institutes operating the 6 reactors. Russia has not made a decision on the conversion of their domestic reactors, and the completion of the feasibility studies and the economic impact assessments are expected to be the key information for the decision on conversion.

ARGUS is a homogeneous solution reactor and does not require fuel development (fuel assembly design and irradiation) for its conversion. OR is studying the possibility of converting with existing IRT-4M LEU oxide fuel. The three IRT-type reactors are assessing the feasibility of converting with the IRT UMo dispersion fuel that has been under development in Russia [7]. MIR is studying its conversion with the same dispersion UMo fuel , but with a cylindrical assembly geometry. Because of the potential use of the fuel of the IRT UMo dispersion type, a project for irradiaton testing of LTAs for final qualification of the fuel is being planned and expected to be initiated in early 2012.

3.4. Conversion of Chinese supplied reactors

A project was established through the IAEA in 2005 to determine the feasibility of converting Chinese-designed MNSR reactors to LEU fuel. Two MNSR reactors remain in operation in China, as well as a reactor each in Ghana, Nigeria, Iran, Pakistan and Syria. The IAEA project successfully completed the feasibility study with the conclusion that the MNSRs were convertible with LEU fuel of about 12.5% enrichment. A generic safety analysis report that can be used as the basis for the reactor specific reports has also been carried out under the IAEA project.

Significant work has been accomplished with the China Institute of Atomic Energy (CIAE) on how to approach the fabrication and preparation for the LEU cores for conversion of the MNSRs. As a result, a Zero Power Test Facility (ZPTF) is being designed and built at CIAE in cooperation with GTRI. The ZPTF will be able to perform the measurements for each specific core and make adjustments before shipping the core to the facilities for conversion. The specifc project approach to schedule the schedule and order for conversion of the MNSRs is currently starting.

4. SUMMARY

The overall objective of the Conversion Program is to reduce and eventually eliminate the use of HEU in civil applications. The Program develops the technical means (conversion analysis and high density LEU fuels) to enable the conversion of research reactors that use HEU fuel to the use of LEU fuels.

Since the inception in 1978 of the RERTR program, 76 research and test reactors have converted to LEU fuel or have shutdown before conversion. With the incorporation of the Conversion program into GTRI, accelerated schedules for the conversion of the remaining reactors have been established. Interaction is occurring with multiple facilities and analysis is being initiated for the conversion of multiple reactors. Progress is being made in the collaboration with Russia in the fuel development, in the collaboration for the conversion of Russian-supplied reactors in third contries, and in the initiation of feasibility studies for 6 Russian domestic reactors.

The program focusses its efforts on the development of advanced high density fuels, particularly U-Mo fuels that make feasible the conversion of high flux and performance reactors in the U.S. and elsewhere. Efforts include development of UMo monolithic fuel for the US reactors, and the development of dispersion UMo fuels for the conversion of reactors in Europe and Russia.

The paper has provided a summary of the technical challenges that are faced by the reactor conversions, with the description of specific and particularly challenging cases that are currently under way. Throughout the years the program has developed a set of constraints for carrying out the reactor conversions in a manner that is acceptable to the operators of the facilities. A systematic approach to the analyses needed for the conversion has been established and applied to numerous conversion projects. This approach is currently being applied in the studies for the conversion of reactors that need an irradiating testing program and to the U.S. and other high performance reactors that need close interaction with the fuel development efforts.

Under GTRI, the program has the possibility of establishing incentives for accelerating the conversion of research reactors. Domestically, NNSA has purchased the LEU fuel for the university reactors, thus facilitating the scheduling of the conversion. Internationally, it is possible to provide an incentive in the form of LEU fuel supply with an equivalent lifetime to that remaining in the HEU fuel it replaces.

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