CONVERSION OF RESEARCH AND TEST REACTORS TO LOW ENRICHED URANIUM FUEL: TECHNICAL OVERVIEW AND PROGRAM STATUS*

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Abstract

Many of the nuclear research and test reactors worldwide operate with high enriched uranium fuel. In response to worries over the potential use of HEU from research reactors in 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 by converting research reactors to low enriched uranium (LEU) fuel. The Reactor Conversion program is currently under the DOE's National Nuclear Security Administration's Global Threat Reduction Initiative (GTRI). 55 of the 129 reactors included in the scope have been already converted to LEU fuel or have shutdown prior to conversion. The major technical activities of the Conversion Program include: (1) the development of advanced LEU fuels; (2) conversion analysis and conversion support; and (3) technology development for the production of Molybdenum-99 (Mo^{99}) with LEU targets. The paper provides an overview of the status of the program, the technical challenges and accomplishments, and the role of international collaborations in the accomplishment of the Conversion Program objectives

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 and began to collaborate with Russian institutes with the objective of converting Russian-supplied reactors to the use of LEU fuel.

Increased security concerns in recent years have 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 include securing radiological and fissile materials. A follow up conference for the International GTRI partnership held at the IAEA in September 2004 [1] 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. A total of 129 reactors are included in the scope of the Program (see Figure 1 – updated from [2]).

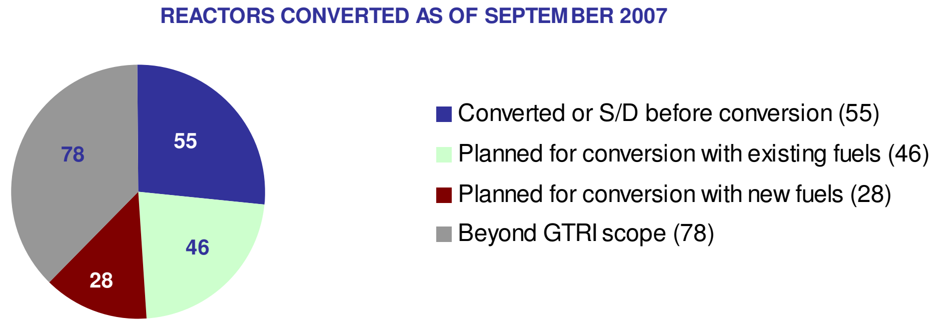

Figure 1. Status of Research and Test Reactor Conversions to LEU Fuels.

Under GTRI, DOE has established targets for the conversion of 129 HEU-fueled research reactors. The current goal is to convert the remaining 74 reactors in the list of candidates by the year 2018. Of the 74 remaining research reactors within the scope of the Conversion Program, 46 can be converted with existing LEU fuels, while the remaining 28 require the development of advanced high density fuels to allow their conversion. A new very high density U-Mo fuel is under development that will allow the conversion of at least 19 of these reactors, while further analysis is needed to determine the appropriate fuel for the remaining 9 reactors. The goal is the completion of the development of the advanced fuels by 2010. Table 1 (updated from [2]) shows the reactors that have currently converted to LEU or shutdown before conversion.

It must also be noted that, with one exception, all new research reactors over 1 MW designed by Western countries since the inception of the Conversion Program have been fueled with LEU.

2. CONVERSION PROGRAM TECHNICAL SCOPE

The major technical activities of the Conversion Program include: (1) the development of advanced LEU fuels; (2) conversion analysis and conversion support; and (3) technology development for the production of Molybdenum-99 (Mo^{99}) with LEU targets.

2.1. Fuel Development

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 [3] 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.

Table 1. Research reactors that have converted to LEU fuel, with conversion initiated, or that were shutdown before conversion (as of September 2007).

	Country	City	Reactor		Country	City	Reactor
1	Argentina	Ezeiza	RA-3	29	Netherlands	Delft	HOR
2	Australia	Lucas Heights	HIFAR	30	Netherlands	Petten	HFR
3	Austria	Vienna	TRIGA II	31	Pakistan	Rawalpindi	PARR-1
4	Austria	Niederosterreich	ASTRA	32	Philippines	Quezon City	PRR-1
5	Brazil	Sao Paulo	IEA-R1	33	Portugal	Sacavem	RPI
6	Canada	Chalk River	NRU	34	Romania	Pitesti	TRIGA II
7	Canada	Montreal	SLOWPOKE Montreal	35	Slovenia	Ljubljana	TRIGA MARK II
8	Canada	Hamilton	MNR McMaster	36	Sweden	Studsvik	R2-0
9	Chile	Santiago	La Reina	37	Sweden	Studsvik	R2
10	China	Chengdu	HFETR-CA	38	Switzerland	Wuerenlingen	SAPHIR
11	China	Chengdu	HFETR	39	Taiwan	Hsinchu	THOR
12	China	Shanghai	MNSR-SZ	40	Turkey	Istanbul	TR-2
13	Colombia	Bogota	IAN-R1	41	USA	Ames IA	UTR-10
14	Czech Republic	Prague	Sparrow	42	USA	Atlanta GA	GTRR
15	Denmark	Roskilde	DR-3	43	USA	Charlottesville VA	UVAR
16	France	Saclay	OSIRIS	44	USA	East Lansing MI	Ford
17	France	Saclay	Ulysses	45	USA	Manhattan NY	MCZPR
18	Germany	Berlin	BER- I I	46	USA	College Station TX	NSCR
19	Germany	Geesthacht	FRG-1	47	USA	Columbus OH	OSURR
20	Germany	Juelich	FRJ-2	48	USA	Gainesville FL	UFTR
21	Germany	Zittau	ZLFR	49	USA	Lowell MA	UMLRR
22	Greece	Athens	GRR-1	50	USA	Narragansett RI	RINSC
23	Iran	Tehran	TRR	51	USA	Rolla MO	UMRR
24	Japan	Ibaraki-Ken	JRR-4	52	USA	Schenectady NY	RPI
25	Japan	Ibaraki-Ken	JMTR	53	USA	Worcester MA	WPI
26	Libya	Tajoura	Critical Facility	54	USA	West Lafayette, IN	PURR-1
27	Libya	Tajoura	IRT-1	55	Vietnam	Dalat	DRR
28	Mexico	Ocoyoacac	TRIGA Mark III				

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 different fuel development programs occurred in recent years. The failures observed in the dispersion fuels 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 had suggested that the addition of Si to the Al matrix could stabilize the interaction product. Irraditation tests have recently shown that small amounts of Si additions to the Al matrix eliminate the formation of porosity [4].

Recent focus is on the development of the monolithic U-Mo fuel, which could reach the uranium density necessary for the conversion of the U.S. high performance research reactors. The first monolithic samples were irradiated to ~80% burnup in the RERTR-4 test with no apparent performance problems. The primary issues for monolithic U-Mo fuels have been identified as the fabrication methods and the performance of full-scale plates. Friction Bonding and Hot Isostapic Pressing (HIP) are the current reference methods for fabrication of U-Mo monolithic fuel plates [5]. Irradiation campaigns in the ATR reactor at INL have been prepared to continue the performance analysis for monolithic fuels as well as to continue the investigation of the performance and prevention of swelling in dispersion fuels. In order to meet the schedules targeted by the GTRI, the main activities leading to the qualification of high density LEU fuel need to be completed by 2009/2010.

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, Canada, France, Republic of Korea, Russia, and the U.S.), to jointly investigate the causes of the dispersion fuel falures, U-Mo fuel behavior in general, and to share information for the development of high density LEU fuels for research reactors. Progress in the solution for the swelling of U-Mo fule have been extensively diuscussed in the group, as well as progressin the fabrication of the monolithic U-Mo fuel. The group typically meets twice a year.

Fuel development activities under the Russian – GTRI-Conversion collaboration are particularly important to enable the conversion of a significant number of high performance reactors of Russian design. Current agreements with Russian organizations cover the conversion of Russian-designed reactors in third countries, as agreed in the summit between the U.S. and Russian presidents in Bratislava in 2005. The main activities in the current scope include qualification of LEU UO_2 tube-type dispersion fuel with densities between 2.5 and 3 g/cm^3 and development and qualification of tube-type and pin-type U-Mo dispersion and pin-type monolithic fuel with densities up to 5.4 g/cm^3.

2.2. Conversion Analysis and Support

The conversion analysis and support activity provides the required analytical and design evaluations to support the program. Since the inception of the RERTR program, analysis methods and codes have been developed specifically for 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. Computer codes include MCNP and REBUS for neutron physics analysis, RELAP5, PLTEMP, NATCON, and on specific cases computational fluid dynamic codes for thermohydraulics analyses, and RELAP5 and PARET for transient analysis.

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 unduly burden the operators or negatively impact the facility. 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. This element requires close coordination of the conversion studies with the fuel development activities;
- Ensure that the ability of the reactor to perform its scientific 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 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; and
- Coordinate with the fuel repatriation programs to establish the preferred time for conversion to LEU fuel. For more rapid or immediate conversions, the owner/operator may be compensated for the unused service lifetime of the repatriated HEU fuel.

As implied in this list of principles, the initial step in the study of a reactor conversion is ensuring that an LEU fuel assembly can be satisfactorily used in the conversion. To accomplish this, the Conversion program generated a set of definitions, as follows [6]:

- Qualified Fuel Assembly: a fuel assembly that has been successfully irradiation-tested and is licensable from the point of view of fuel irradiation behavior.
- Available Fuel Assembly: a fuel assembly that is available from a commercial manufacturer;
- Suitable Fuel Assembly: a fuel assembly that satisfies criteria for LEU conversion of a specific reactor (number of assemblies used per year is the same as or less than with HEU fuel; performance of experiments is not significantly lower than with HEU fuel; and safety criteria are satisfied.

If an LEU fuel assembly is qualified, commercially available, suitable for use in a specific reactor, and is acceptable to the reactor operator, the fuel assembly is considered acceptable for the conversion of that reactor to LEU.

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. The acceptability of possible changes needs to be determined by the facility operator. Once a fuel assembly design and core configuration has been selected, key safety parameters are calculated.
- *Operational and safety analysis*, necessary 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. The process for U.S. universities, for example, licensed by the NRC, requires a review of the safety analysis report for the facility to determine if and how the safety analysis for the different transients with LEU fuel would differ from the behavior with HEU fuel. It must be demonstrated that all safety requirements are met.

Analyses related to the core conversion, as agreed between the facility operator and the GTRI Conversion program, can be the responsibility of the operator, the Conversion program, or can be done jointly. The safety analysis and submittal of the LEU conversion request to the regulatory authorities is the responsibility of the operator and safety analysis performed by the Conversion program can be used for verification purposes. In any case the Conversion program is available to provide support to the facility operator.

2.3. Mo-99 Production with LEU

The programmatic objective of the technology development for Mo^{99} program element is to eliminate the use of HEU targets in the production of Mo^{99}. The program intends to accomplish this objective through the development of LEU targets and chemical processing methods that do not significantly impact the isotope production yields, costs and waste treatment and disposal with respect to current production with HEU targets.

The technology development for using LEU targets is performed on the bases of the following technical constraints with respect to current production with HEU targets:

- Production of equivalent (or greater) Mo^{99} yields;
- Use of same irradiation positions, handling and transportation methods;
- Development of recovery processes that imply no decrease in yield or purity; and
- Development of waste treatment and disposal options to minimize impacts of conversion.

To maintain an equivalent yield of Mo^{99}, about five times more LEU (<20% U^{235}) is required than HEU (~95% U^{235}), and the targets must contain about 5 times more uranium. Mo^{99} recovery and purification, as well as the solid waste generated, will need to deal with an increased amount of uranium that could result in larger liquid volumes for the dissolution process and the generation of more liquid waste. The proposed solution under the GTRI Conversion program is the use of LEU foil targets instead of dispersion targets. The decrease in the amount of aluminum in the target decreases the amount of liquid needed for digestion. A fission-recoil barrier is wrapped around the foil to prevent bonding of the foil to the target walls. Because the uranium foil is removed from the target before processing, only the uranium and fission barrier foils must be dissolved [7].

If foil production is made economical, target fabrication is expected to be of a lower cost than current HEU target fabrication. With regards to the Mo^{99} recovery processes, the alkaline digestion of LEU foil targets uses significantly less solution than for an HEU foil and the acidic dissolution will use the same or less solution than for an HEU target. Development of the LEU foil target technology continues in the context of international collaborations with very promising results. Argentina and Australia, for example, are currently using LEU-based production methods, and demonstrations of the foil target process have taken place or are underway in Argentina, Indonesia and the U.S. (University of Missouri). Demonstration of LEU technologies are being facilitated thorugh a Coordinated Research Project organized by the International Atomic Energy Agency (IAEA).

3. SPECIFIC EXAMPLES OF CURRENT CONVERSION ACTIVITIES

Two specific cases are described that highlight the technical challenges in the conversion of reseacrh reactors. These cases illustrate (1) activities of the GTRI Conversion program to ensure that an acceptable LEU fuel assembly is available for the conversion of a reactor; and (2) the close relationship between the conversion analyses and the fuel development and qualification activities.

3.1. Conversion of Reactors Requiring Test Assemblies

The GTRI Conversion program is currently collaborating on projects for the conversion of the MARIA research reactor in Poland and the WWR-K research reactor in Kazakhstan. These two reactors are examples of a situation in which a qualified LEU fuel assembly does not yet exist. Therefore the projects for the conversion of these research reactors have been initiated with the design and qualification (irradiation testing) of an LEU assembly.

The program provides flexibility to adapt to the specific needs of each project, within the bounds of the general principles, so that the approach for the qualification of the fuel assembly for the two reactors follows a different organization path: the MARIA fuel assembly qualification project has been organized through a Purchase and Supply Agreement (PSA) at the IAEA, while the supply of test assemblies for the WWR-K reactor is planned to be carried out through NNSA.

Feasibility studies have been performed for the use of LEU silicide fuel assemblies for the MARIA reactor. A fuel supplier for two LEU silicide test assemblies was selected by the IAEA under the PSA process and a specific assembly design has been developed. The MARIA reactor operator (the Institute of Atomic Energy – IAE) is performing the safety analysis, with support from the GTRI Conversion program, to obtain regulatory approval for the irradiation-testing of the two test assemblies. As part of the preparations for the irradiation testing, there will be thermohydraulic tests carried out for mockup assemblies of the new design. The project plans are for conducting the irradiation that will lead to the acceptance of the LEU assembly. Operational and safety analysis will then be performed for applicaton to the regulatory authorities to proceed with the conversion of the reactor to LEU fuel. The overall project is a multi-year effort, with the fuel assembly qualification only (assembly design, mockup testing, and test assembly irradiation) taking approximately 2 years.

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 [8], the Institute of Nuclear Physics (INP) selected a preferred assembly design. On the basis of that design, plans for the irradiation testing of three test assemblies have been developed. In order to reach the desired irradiation conditions and burnup in a shorter time, INP is planning to place the test assemblies in the center of the core, with a beryllium reflector structure surrounding the assemblies [9]. The process for the final design and procurement of the test assemblies is currently being initiated.

3.2. U.S. High Performance Reactor Conversion

Table 2 shows the list of the high performance reactors currently operating in the U.S. with HEU fuel. These are reactors with a very high neutronic flux that require an LEU fuel of very high density in order to convert with no significant decrease in the fuel cycle and experiment performance. Because of the common needs for the conversion of these facilities, a working group has been formed in order to coordinate the feasibility studies and the fuel development efforts.

Table 2. U.S. High Performance reactors.

Reactor	Location	Power (MW)
MITR	Massachusetts Institute of Technology, Cambridge, MA	5
MURR	University of Missouri, Columbia, MO	10
NBSR	National Institute of Standards and Technology, Gaithersburg, MD	20
HFIR	Oak Ridge National Laboratory, Oak Ridge, TN	100
ATR	Idaho National Laboratory, Idaho falls, ID	250
ATRC	Idaho National Laboratory, Idaho Falls, ID	0.005

The group was formed in late 2005 and has been meeting about 3 times per year. All reactor operators are currently performing feasibility studies and providing valuable input to the Conversion program fuel development effort. The current outcome from the partial feasibility studies indicates that all facilities will require LEU fuel with uranium densities that can be achieved with the monolithic U-Mo fuel, but probably not with the dispersion fuel.

These reactors as a group are those that offer the highest technical challenges for their conversion within the contraints of the principles of the Conversion program, but the formation of the working group has been very beneficial in identifying the needs of each particular reactor. Although all reactors appear to require the monolithic U-Mo fuel under development, each facility has special needs, ranging from variable U-Mo foil thickness, to foil thickness grading in two dimensions, to the use of burnable poisons. The fuel development program element is adapting to provide answers to the reactor operators on the possibilities for meeting their special needs in the fuel fabrication and performance. On the other hand, the feasibility studies are being tailored and fine-tuned to adapt to the findings of the fuel development team with respect to the ranges of diffferent paramaters of interest.

An additional challenge that conversion of the high performance reactors presents is in terms of schedules to meet the goals of the GTRI Conversion program. There will be a need to coordinate the regulatory review of the monolithic U-Mo fuel, the possible need for test assembly irradiation, the availability of a commercial source of U-Mo monolithic fuel, and the conclusion of the safety analsysis and regulatory submittal and review to complete the conversion to LEU fuels. In order to address these challenges, interactions with the regulatory authoritiers has been initiated. The conversion of the group of high performance reactors, including all aspects of the process as mentioned, is a multi-year task that requires the coordination of mutiple organizations.

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 and Mo^{99} targets and process technology) to enable the conversion of research and test reactors that use HEU fuel, and to enable the production of Mo^{99} without the use of HEU.

Since the inception in 1978 of the RERTR program, 55 research and test reactors have converted to LEU fuel or have shutdown before conversion. The basic technology for the production of Mo^{99} with LEU targets has also been developed and demonstrated. With the incorporation fo the Conversion program into GTRI, accelerated schedules for the conversion of the remaining reactors have been established. The goal is to convert all remaining reactors by 2018. 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 as well as in the collaboration for the conversion of Russian-supplied reactors in third contries.

The program is focusing its efforts on the development of advanced high density fuels, particularly U-Mo fuels that will make feasible the conversion of between 19 and 28 additional research reactors. The goal is the completion of the development of the advanced fuels by 2009/2010. In the Mo^{99} production with LEU, the Conversion program is optimizing the technology to reduce the volumes in the target dissolution process and the minimization of waste streams.

The paper has provided a summary of the technical challenges that are faced by the reactor conversions, with the description of two specific and particularly challenging cases that are currently under way. Thorughout 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. 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 can purchase 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.

A key element of the Conversion Program is the coordination with multiple organizations, ranging from facility operators to regulatory bodies, and significantly, the International Atomic Energy Agency (IAEA). The IAEA supports the objectives of the Conversion Program and is currently leading coordinated research projects for conversion analysis of Miniature Neutron Source Reactors and technology development for Mo^{99} production without HEU. In addition the IAEA is instrumental in facilitating country-specific conversion support projects under the Technical Cooperation Department.

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