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USING LOW-ENRICHED URANIUM IN RESEARCH REACTORS: THE RERTR PROGRAM*

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ABSTRACT

The goal of the RERTR program is to minimize and eventually eliminate use of highly enriched uranium (HEU) in research and test reactors. The program has been very successful, and has developed low-enriched uranium (LEU) fuel materials and designs which can be used effectively in approximately 90 percent of the research and test reactors which used HEU when the program began. This progress would not have been possible without active international cooperation among fuel developers, commercial vendors, and reactor operators.

The new tasks which the RERTR program is undertaking at this time include development of new and better fuels that will allow use of LEU fuels in all research and test reactors; cooperation with Russian laboratories, which will make it possible to minimize and eventually eliminate use of HEU in research reactors throughout the world, irrespective of its origin; and development of an LEU-based process for the production of ^{99}Mo.

Continuation and intensification of international cooperation are essential to the achievement of the ultimate goals of the RERTR program.

INTRODUCTION

Approximately 313 research reactors are in operation today in 67 countries[1], performing useful experiments, producing isotopes, and extending human knowledge in a variety of fields. Nearly half of these reactors use highly-enriched uranium (HEU) in their fuels or in the samples which they irradiate, and the presence of this material at the reactor sites and elsewhere during fabrication, shipment, and storage, raises serious proliferation concerns, especially when the material has not yet been irradiated.

Safeguarding special nuclear materials, or reducing their amounts, plays a crucial role in nonproliferation activities. This is especially true for HEU, which is considered comparatively easier to use in the manufacture of a nuclear explosive device. It is for this reason that President Clinton, in formulating U.S. nonproliferation policy in his Presidential Decision Directive 13, announced that the U.S. will "*seek to minimize use of highly-enriched uranium in civilian nuclear programs.*" Research and test reactors utilize most of the HEU used in civilian nuclear programs.

To address this problem, Argonne National Laboratory was named by the U.S. Department of Energy in 1978 to be the lead laboratory in the Reduced Enrichment Research and Test Reactor (RERTR) Program. DOE continues to fund and manage the program in coordination with the Department of State (DOS), the Arms Control and Disarmament Agency (ACDA), and the Nuclear Regulatory Commission (NRC). The primary objective of the program is to develop the technology needed to minimize and eventually eliminate use of HEU in research and test reactors. It aims to do so by developing low-enrichment uranium (LEU) fuels which can replace HEU fuels without significant penalties in the experiment performance, economic, or safety aspects of the reactors.

Under Argonne leadership, the RERTR program has developed, tested, and qualified several types of low-enriched fuel that can be used to replace highly-enriched fuel in about 90 percent of the world's research reactors. The program is now preparing to initiate development of more advanced fuels that would make it possible to convert all existing research reactors to low-enriched fuels.

Development of the new fuels has been accomplished in close cooperation with all the major fuel fabricators to ensure compatibility with current fuel fabrication techniques and to maintain existing competitive relationships in the nuclear fuel industry. Accurate computational methods and computer codes were also developed to optimize use of low-enrichment fuels and to predict with confidence the behavior of the research reactors after conversion.

The Argentinean CNEA was one of the first fuel developers with which the RERTR program established a cooperation agreement. Beginning in 1979 with joint activities in the development of oxide dispersion fuel, the cooperation continued through the years with many exchanges also in other fields such as safety and thermal hydraulics, and with several visits by CNEA and Argonne personnel to each other's sites. Miniplates of advanced fuels were produced by the CNEA, irradiated in the Oak Ridge Research Reactor (ORR), and examined at Argonne yielding interesting and promising data. Full-size oxide demonstration elements produced at the CNEA were also irradiated in the ORR with excellent results. The cooperation progressed with the establishment of a full-fledged LEU fuel fabrication line at the CNEA and with the holding of the X International RERTR Meeting in Buenos Aires in 1987[2], Our cooperation culminated in 1990 with the successful conversion of the RA-3 reactor to low-enriched fuel.

It gives me special pleasure to be here today, in this beautiful country, to describe the progress achieved by the RERTR program. I am looking forward to visiting the CNEA facilities, to meeting with old friends, and to continue and renew the productive cooperation which served us so well in the past.

FUEL DEVELOPMENT

The amount of ^{235}U in the core of a research reactor controls the ability of the reactor to become critical and to work for a certain period of time without need for new fuel. In addition to ^{235}U, reactor fuel also contains ^{238}U, which does not contribute significantly to the sustenance of the neutron chain reaction. Since the amount of ^{235}U must be maintained nearly constant, the only way to decrease the enrichment of the fuel is to increase the amount of ^{238}U and, therefore, the total amount of uranium contained in the core. This means that the key to converting a reactor to low-enriched uranium is to pack uranium more densely in the same volume.

Most research reactor fuels contain thin metallic plates, 1 to 2 mm thick, separated by water channels of similar thickness. Each plate comprises three layers: two outer layers of nearly pure aluminum (the clad) enclosing an inner layer containing the uranium (the meat). Frequently, about twenty plates are used to form an element and about 30 elements to form a core.

One way to increase the amount of uranium in the core of a research reactor is to change the dimensions of the fuel element so that the volume fraction of the meat is greater. The usefulness of this approach is limited by the need to extract large amounts of heat from the fuel during operation, and by the very stringent safety constraints of research reactors.

Another way to increase the uranium content of the core is to change the structure of the meat. The meat in dispersion-type fuels is normally a compressed mixture of two powders: pure aluminum (the matrix) and a uranium compound (the dispersed phase). The RERTR program has successfully pursued the approach of using dispersed phases which occupy a greater fraction of the meat volume and consist of compounds with greater uranium density. Similar considerations and approaches apply also to TRIGA reactors, which use rods instead of plates for fuel.

Most plate-type fuels used in highly-enriched reactors contain uranium aluminide or uranium oxide as the dispersed phase. Highly-enriched TRIGA fuels use uranium dissolved in zirconium hydride.

The main results achieved by the RERTR program in its efforts to develop new fuel materials to replace those used with HEU in research reactor fuels are summarized below.

(a) The qualified uranium densities of the three main fuels which were in operation with HEU in research reactors when the program began (UAl_x-Al with up to 1.7 g U/cm^3; U_3O_8-Al with up to 1.3 g U/cm^3; and $UZrH_x$ with 0.5 g U/cm3) have been increased significantly. The new uranium densities extend up to 2.3 g U/cm^3 for UAl_x-Al, 3.2 g U/cm^3 for U_3O_8-Al, and 3.7 g U/cm^3 for $UZrH_x$. The new $UZrH_x$ fuel was developed by General Atomics and tested by the RERTR program. Each fuel has been tested extensively up to these densities and, in some cases, beyond them. All the data needed to qualify these fuel types with LEU and with the higher uranium densities have been collected.

(b) For U_3Si_2-Al, after reviewing the data collected by the program, the U.S. Nuclear Regulatory Commission (NRC) issued a formal approval[3] of the use of U_3Si_2-Al fuel in research and test reactors, with uranium densities up to 4.8 g/cm^3. A whole-core demonstration using this fuel was successfully completed in the ORR using a mixed-core approach.

(c) For U_3Si-Al, miniplates with up to 6.1 g U/cm^3 were fabricated by ANL and the CNEA, and irradiated to 84-96% in the ORR. Postirradiation examinations (PIE) of these miniplates gave good results, but showed that some burnup limits might need to be imposed for the higher densities. Four full-size plates fabricated by CERCA with up to 6.0 g U/cm^3 were successfully irradiated to 53-54% burnup in SILOE, and a full-size U_3Si-Al (6.0 g U/cm^3) element, also fabricated by CERCA, was successfully irradiated in SILOE to 55% burnup. However, conclusive evidence indicating that U_3Si became amorphous under irradiation has convinced the RERTR Program that this material as currently developed could not be used safely in plates beyond the limits established by the SILOE irradiations.

(d) Two concepts based on hot-isostatic pressing (HIP) procedures have been developed for LEU silicide fuels with the potential of holding effective uranium densities much greater than 4.8 g U/cm^3. One of the concepts is based on a composite structure of U_3Si wires and aluminum (up to 12.9 g U/cm^3), while the other is based on a U_3Si_2-Al dispersion structure (up to 10.2 g U/cm^3). Sample miniplates have been produced for both concepts.

The newly qualified fuels are currently fabricated and marketed by a number of international fuel fabricators, including companies in Argentina, Canada, Denmark, France, and the United States. Other fuel fabricators are developing the capability to produce and market these fuels in Brazil, Chile, Indonesia, South Korea, and the United Kingdom. These new fuels make it technically feasible to convert to LEU approximately 90 percent of the research reactors which used HEU of U.S. or other Western origin when the RERTR program began.

The fuel development effort was interrupted by budget constraints at the end of 1989, but the program is now preparing to resume development of LEU fuels with uranium density greater than the 4.8 g/cm^3 which is currently qualified, with the intent of ensuring successful LEU operation in all existing and future research reactors.

REACTOR ANALYSIS

Research and test reactors present many analytical challenges not encountered with current power reactors or advanced reactors. The reactors have a varied geometry with usually no simplifying symmetry. The fuel element designs include flat or curved plates type fuel with varying number of plates, concentric tubes of fuel, and pin type fuel. Reflector materials may include graphite, beryllium, and heavy water. The coolant and moderator can be either light or heavy water or some combination of the two. The energy spectrum changes spatially over these small leaky cores, and requires a significant amount of spatial detail in the calculations. Average fuel burnups af 50-60 atom percent in 235U are not uncommon, and require burnup-dependent cross-section data. For thermal hydraulic considerations these reactors operate at very low temperatures and pressures compared to power reactors.

The RERTR program has adapted and modified a number of methods and computer codes to resolve these difficulties and to analyze the performance and safety characteristics of research reactors utilizing LEU fuels. The results have been compared, with excellent results, with the measurements obtained from the full-core demonstration achieved by the program in the FNR and in the ORR.

Extensive studies had been conducted, with favorable results, on the performance, safety, and economic characteristics of a variety of LEU conversions. These studies included many joint study programs, which have been in progress for about 28 reactors from 17 different countries.

REACTOR CONVERSIONS

The process of converting a research reactor from HEU to LEU fuels requires many consecutive steps and may be lengthy in some special cases. After determining the feasibility of the conversion, frequently through a joint study with Argonne, the reactor organization must develop a systematic plan defining how the conversion will be implemented. A revision of the safety documents and of the technical specifications must be prepared and approved by the regulatory authorities. Irradiation of prototype elements is occasionally required. The LEU needed to manufacture the new core must be purchased, and the manufacturing order must be placed with a fuel fabricator. Finally, the actual conversion must take place, but even this apparently simple final operation may require several years to complete, depending on the burnup desired from the original fuel.

To date, twenty-four research reactors in sixteen countries have been converted from HEU to LEU in agreement with the goals of the RERTR program. Table I lists all the converted reactors, their powers, and the dates when their conversions was begun and completed. Many other reactors are at an advanced stage in their efforts to convert, but have not yet reached the special threshold when the first LEU fuel element is used to replace an HEU element to begin the core conversion. It is estimated that, as a whole, approximately 60 percent of the work needed to convert all the reactors that used to require HEU of Western origin when the RERTR program began has been accomplished[4].

All U.S. research reactors licensed by the NRC are required to convert to LEU if adequate fuels are available[5].

All the eight research reactors which have been built in the world since 1980, or whose construction has been started, use LEU fuels. The list of these reactors is provided in Table II.

PRODUCTION OF FISSION ^{99}Mo FROM LEU TARGETS

^{99}Mo, through its daughter product ^{99m}Tc, is the most commonly used medical radioisotope throughout the world. Over 34,000 treatments involving ^{99}Mo are performed daily in the United States alone, and it is estimated that ^{99}Mo is responsible for approximately 90 percent of the value of all the radioisotopes used world-wide for medical applications.

Nearly all the ^{99}Mo is currently produced by irradiating HEU targets in research reactors, dissolving the targets after irradiation, and separating the ^{99}Mo from the other fission products. This operation is very efficient but requires significant amounts of HEU, which in some cases rival the amounts of HEU required to fuel the reactors in which the targets are irradiated.

The RERTR program has initiated an analytical/experimental program to determine the feasibility of using LEU instead of HEU in fission targets dedicated to the production of ^{99}Mo for medical applications. A procedure for basic dissolution and processing of LEU silicide targets had been developed and is ready for demonstration on full-size targets with prototypic burnup[6]. Cooperative arrangements with several potential international developers and producers are planned in a manner similar to what was done to develop new fuels, with the goal of developing at least one viable process during the next few years.

RUSSIAN COOPERATION WITH THE RERTR PROGRAM

The disappearance of the Soviet Union and the emergence of the New Independent States offer a historic opportunity to address nuclear nonproliferation goals on a global basis. For the RERTR program, this means the opportunity to minimize civilian use of HEU world-wide, irrespective of its origin.

In March 1993, RERTR and DOE personnel visited Moscow to exchange information and discuss possible cooperation on a Russian RERTR Program with representatives of the Research and Development Institute of Power Engineering (RDIPE), the Russian Federation Ministry of Atomic Energy (MINATOM), and other organizations. This cooperative undertaking would expand the goals of the RERTR effort to include research reactors supplied with HEU fuel by the Russian Federation. The results of the visit were very encouraging. Unknown to us, RDIPE had already been involved since 1978 in a very active program motivated by Soviet concerns about exporting research reactor fuel containing HEU. The program had completed the development and demonstration of fuel with 36% enrichment, but work on fuels with less than 20% enrichment was interrupted in 1988.

An agreement of cooperation between the U.S. RERTR Program and RDIPE was signed in July 1993 with the goal of developing and demonstrating within the next five years the technical means needed to convert Russian-supplied research reactors to LEU fuels. A joint program plan is at advanced stage of development, and joint activities are expected to begin soon. We are very excited at the prospect of working with our Russian colleagues, and we hope that with their help the RERTR program will be in condition to reduce and eventually eliminate the use of HEU in civilian nuclear programs nearly everywhere in the world.

RETURN OF SPENT RESEARCH REACTOR FUELS OF U.S. ORIGIN

The end of the Cold War and the resulting closure of the reprocessing plant at Savannah River have made permanent the interruption of the reprocessing services which the U.S. Department of Energy used to offer to foreign research reactor operators until late 1988. This has left many research reactor operators without a well established process to dispose of their spent fuel, and may cause undesirable stockpiles of irradiated HEU fuel in many parts of the world. The RERTR program is seriously concerned about this problem because most of the reactors with which it cooperates are affected, and because the spent fuel stockpiles run counter to its mandate.

In response to proliferation concerns and to the needs of foreign research reactor operators, DOE has drafted an off-site spent nuclear fuel policy that would allow spent research reactor fuel containing HEU and LEU of U.S. origin to be returned to the U.S. for disposal. An Environmental Assessment addressing the return of approximately 400 urgent-relief elements is due to be completed in April 1994. A draft Environmental

Impact Statement addressing the return of all U.S. origin spent research reactor fuel is planned to be completed by the end of December 1994, with a goal of completing the entire National Environmental Policy Act (NEPA) review process by June 1995.

SUMMARY AND CONCLUSION

The goal of the RERTR program is to minimize and eventually eliminate use of HEU in research reactors. The program has been very successful, and has developed LEU fuel materials and designs which can be used effectively in approximately 90 percent of the research and test reactors which used HEU when the program began. This progress would not have been possible without active international cooperation among fuel developers, commercial vendors, and reactor operators.

The new tasks which the RERTR program is undertaking at this time include development of new and better fuels that will allow use of LEU fuels in all research and test reactors; cooperation with Russian laboratories, which will make it possible to minimize and eventually eliminate use of HEU in research reactors throughout the world, irrespective of its origin; and development of an LEU-based process for the production of ^{99}Mo.

Once more, I ask for international friendship and cooperation. I firmly believe that by continuing to work together, as we have for the past sixteen years, we can overcome the inevitable obstacles and achieve our common goals.

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Table I. LIST OF CONVERTED REACTORS

No.	COUNTRY	REACTOR	POWER	BEGIN	END
1	Argentina	RA-3	2.8 MW	1990	1990
2	Austria	ASTRA	8 MW	1983	1990
3 *	Brazil	IEA-R1	2 MW	1981	≥1995
4	Canada	NRU	125 MW	1992	1993
5	Denmark	DR-3	10 MW	1988	1990
6	France	OSIRIS	70 MW	1979	1979
7	Germany	FRG-1	5 MW	1991	1991
8	Iran	NCRR	5 MW	1991	1991
9	Japan	JMTR	50 MW	1993	1994
10	Pakistan	PARR	5 MW	1991	1991
11	Philippines	PRR-1	1 MW	1987	1987
12 *	Romania	SSR	14 MW	1992	≥1995
13	Sweden	R-2	50 MW	1990	1993
14 *	Switzerland	SAPHIR	10 MW	1986	≥1996
15	Taiwan	THOR	1 MW	1978	1987
16	United States	FNR	2 MW	1981	1983
17	United States	RPIR	100 W	1987	1987
18	United States	OSURR	10 kW	1988	1988
19	United States	WPIR	10 kW	1988	1988
20	United States	ISUR	10 kW	1991	1991
21	United States	MCZPR	0.1 W	1992	1992
22	United States	UMRR	200 kW	1992	1992
23	United States	RINSC	2 MW	1993	1993
24	United States	UVAR	2 MW	1993	1993

* Conversion in progress.

Table II

RESEARCH AND TEST REACTORS BUILT SINCE 1980
ALL LEU

OPERATIONAL

No.	COUNTRY	REACTOR	POWER
1	Algeria	NAMUR	1 MW
2	Bangladesh	TRIGA	3MW
3	Canada	Slowpoke	2 kW
4	Indonesia	RSG-GAS	30 MW
5	Japan	JRR-3	20 MW
6	Peru	RP-10	10MW

UNDER CONSTRUCTION

No.	COUNTRY	REACTOR	POWER
1	Canada	MAPLE-X	10 MW
2	Korea	KMRR	20 MW

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END