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STATUS AND PROGRESS OF THE RERTR PROGRAM IN THE YEAR 2000*

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ABSTRACT

This paper describes the progress achieved by the Reduced Enrichment for Research and Test Reactors (RERTR) Program in collaboration with its many international partners during the year 2000 and discusses the main activities planned for the year 2001.

The past year was characterized by important accomplishments and events for the RERTR program.

- Four additional shipments containing 503 spent fuel assemblies from foreign research reactors were accepted by the U.S. Altogether, 3,740 spent fuel assemblies from foreign research reactors have been received by the U.S. under the acceptance policy.
- Postirradiation examinations of three batches of microplates have continued to reveal excellent irradiation behavior of U-Mo dispersion fuels in a variety of compositions and irradiating conditions. Irradiation of two new batches of miniplates of greater sizes is in progress in the ATR to investigate the swelling behavior of these fuels under prototypic conditions. These materials hold the promise of achieving the program goal of developing LEU research reactor fuels with uranium densities in the 8-9 g /cm^3 range.
- Qualification of the U-Mo dispersion fuels is proceeding on schedule. Test fuel elements with 6 gU/cm^3 are being fabricated by BWXT and are scheduled to begin undergoing irradiation in the HFR-Petten in the spring of 2001, with a goal of qualifying this fuel by the end of 2003. U-Mo with 8-9 gU/cm^3 is planned to be qualified by the end of 2005.
- Joint LEU conversion feasibility studies were completed for HFR-Petten and for SAFARI-1.
- Significant improvements were made in the design of LEU metal-foil annular targets that would allow efficient production of fission ^{99}Mo. Irradiations in the RAS-GAS reactor showed that these targets can formed from aluminum tubes, and that the yield and purity of their product from the acidic process were at least as good as those from the HEU Cintichem targets.
- Progress was made on irradiation testing of LEU UO_2 dispersion fuel and on LEU conversion feasibility studies in the Russian RERTR program.
- Conversion of the BER-II reactor in Berlin, Germany, was completed and conversion of the La Reina reactor in Santiago, Chile, began.

These are exciting times for the program. In the fuel development area, the RERTR program is aggressively pursuing qualification of high-density LEU U-Mo dispersion fuels, with the dual goal of enabling further conversions and of developing a substitute for LEU silicide fuels that can be more easily disposed of after expiration of the FRR SNF Acceptance Program. The ^{99}Mo effort has reached the point where it appears feasible for all the ^{99}Mo producers of the world to agree jointly to a common course of action leading to the elimination of HEU use in their processes. As in the past, the success of the RERTR program will depend on the international friendship and cooperation that has always been its trademark.

INTRODUCTION

This is the twenty-third time that scientists from all over the world gather under the aegis of the Reduced Enrichment for Research and Test Reactors (RERTR) Program to exchange information about their activities and to coordinate their efforts.

The RERTR Program was established in 1978 at the Argonne National Laboratory (ANL) by the Department of Energy (DOE), which continues to fund the program and to manage it in coordination with the Department of State (DOS) 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 high-enriched uranium (HEU) for civilian applications worldwide. Since nearly all the HEU used in civil nuclear programs is used in research and test reactors, the RERTR program concentrates on the use of low-enriched uranium (LEU) instead of HEU in research and test reactors, and on making this conversion feasible without significant penalties in experiment performance and in economic or safety aspects of the reactors.

Close cooperation with international organizations has been the cornerstone of the RERTR Program since its beginning. This cooperation and the high quality of the technical contributions that many partners have brought to the overall effort are to be credited for much of the progress that the program has achieved.

This first International RERTR Meeting of the third millennium is being held in Las Vegas, Nevada. There were several very good reasons for selecting this location for the meeting, including the relatively low cost of holding a conference here, easy accessibility, spectacular scenery, and glamorous entertainment. A special reason, however, is the proximity of Yucca Mountain, where work is in progress on the characterization of a site proposed as a permanent repository for spent nuclear fuel. Spent fuel disposal is a major concern for many research reactor operators, and many of the attendees have shown great interest in seeing what needs to be done to establish a permanent repository. The one hundred openings for visiting Yucca Mountain on Wednesday, October 4, were all eagerly spoken for.

I am looking forward to listening to the many interesting papers which have been submitted for presentation at this meeting and to interacting with the other participants, so that we may learn from each other, as we did in the past, how to better achieve our common goals.

OVERVIEW OF THE PROGRAM STATUS

By October 1999, when the last International RERTR Meeting was held[1], many important results had been achieved in the fuel development area:

(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 up to 0.5 g U/ cm^3) had been increased significantly. The new qualified uranium densities extended 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 $UZrH_x$. Each fuel had 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 had been collected.

(b) For U_3Si_2-Al, after reviewing the data collected by the program, the U.S. Nuclear Regulatory Commission (NRC) had issued a formal approval[2] 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 had been successfully completed in the Oak Ridge Research Reactor (ORR) using a mixed-core approach. This type of fuel had become internationally accepted, and was routinely fabricated for twenty reactors by four fuel fabricators in four countries, with five more fuel fabricators in as many countries preparing to do so. Plates with uranium densities of up to 6.0 g/cm^3 and full-size elements with up to 5.8 g/cm^3 had been fabricated by CERCA and had been irradiated to 55% and 74% burnup, respectively, with good results.

(c) For U_3Si-Al, miniplates with up to 6.1 g U/cm^3 had been fabricated by ANL and the CNEA, and irradiated to 84-96% in the ORR. Postirradiation examinations of these miniplates had given good results, but had shown that burnup limits would need to be imposed for the higher densities. Four full-size plates fabricated by CERCA with up to 6.0 g U/cm^3 had been 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, had been successfully irradiated in SILOE to 55% burnup. However, conclusive evidence indicating that U_3Si became amorphous and did not recrystallize under irradiation had convinced the RERTR Program that this material as then developed could not be used safely in plates beyond the limits established by the SILOE irradiations.

(d) The effort to develop new advanced LEU fuels with much higher effective uranium loadings had been restarted in 1996 after a pause of about six years. Two batches of microplates containing a variety of promising fuel materials, including dispersion fuels containing U-Mo and U-Zr-Nb alloys, had been irradiated in the Advanced Test Reactor (ATR) in Idaho. Preliminary postirradiation examinations had indicated very promising behavior of microplates containing U-10Mo alloy particles dispersed in an aluminum matrix.

Important results had been obtained also in other areas. Reprocessing studies at the Savannah River Site (SRS) had concluded in 1983 that the RERTR fuels could be successfully reprocessed there and DOE had defined the terms and conditions under which these fuels would be accepted for reprocessing. These results had been rendered moot, however, by DOE's decision to phase out reprocessing at SRS and by the expiration of the Off-Site Fuel Policy at the end of 1988. An Environmental Impact Statement[3] and a related Record of Decision[4] had been issued in 1996 for a new DOE policy allowing, until May 2009, the return of spent research reactor fuel elements of U.S. origin irradiated before 13 May 2006.

Implementation of this policy through the U.S. Foreign Research Reactor Spent Nuclear Fuel (FRR SNF) Acceptance Program had been very successful, but the closure of the UKAEA Technology reprocessing plant at Dounreay, U.K., had created a potential problem for research reactors using or planning to use silicide fuel. Many research reactors intend to send their fuel to the COGEMA plant in La Hague, France, after expiration of the FRR SNF Acceptance program. COGEMA has indicated that it will accept spent research reactor fuels for the foreseeable future but, unlike Dounreay, cannot accept silicide fuel. Various options for coping with this issue had been discussed.

An analytical/experimental program was in progress to determine the feasibility of using LEU instead of HEU in fission targets dedicated to the production of ^{99}Mo for medical applications. Procedures had been developed for dissolution and processing of both LEU silicide targets and LEU metal foil targets. These procedures were ready for demonstrations on full-size targets with prototypic burnups. Three series of LEU metal foil targets had been irradiated in the RAS-GAS reactor at BATAN, Indonesia. The LEU foil targets from the third series had been successfully separated from their enclosure and the ^{99}Mo had been extracted. However, the irradiated foils were brittle and the process still needed to be optimized.

Extensive studies had been conducted, with positive results, on the performance, safety, and economic characteristics of LEU conversions. These studies included many joint study programs for about 32 reactors from 21 countries. A study to assess the feasibility of using LEU in the fuel of a modified version of the FRM-II reactor, which was being designed with HEU at the Technical University of Munich, had stimulated spirited discussions.

Coordination of the safety calculations and evaluations was continuing for the U.S. university reactors planning to convert to LEU as required by the 1986 NRC rule. Nine of these reactors had been converted, safety evaluations had been completed for four other reactors, and calculations for four more reactors were in progress.

The end of the Cold War, which prompted the DOE decision to phase out reprocessing at SRS, also enabled a new cooperation between the RERTR program and several Russian institutes with the goal of converting to LEU many Russian-designed research reactors still operating with HEU. International attention had become increasingly focused on the dangers of nuclear proliferation and had resulted in increased support for the goals of the RERTR program, especially after it became known that in 1990 Iraq had been on the verge of acquiring and using a nuclear weapon built from research reactor fuels containing HEU.

LEU fuels were planned for the new Ongkharak TRIGA reactor in Thailand, the new MAPLE1 and MAPLE2 reactors in Canada, the new Jules Horowitz Reactor in France, the new China Advanced Research Reactor in China, and the new Replacement Reactor in Australia. However, some reactor designs still considered use of HEU in their fuels. The Advanced Neutron Source Reactor had been discontinued by the U.S. Congress, but the FRM-II reactor in Germany was still being designed with HEU fuel, and so was the PIK reactor in Russia. New and better LEU fuels were needed to convert the most demanding existing reactors and to encourage use of LEU fuels in research reactors yet to be built.

PROGRESS OF THE RERTR PROGRAM IN 2000

The main events, findings, and activities of the RERTR Program during the past twelve months are summarized below.

1. The U.S. FRR SNF Acceptance Program made significant progress since October 1999. Four additional shipments of spent research reactor fuel containing 413 MTR-type elements were received at the SRS, and one additional shipment containing 90 TRIGA elements was received at the Idaho National Engineering and Environmental Laboratory (INEEL). With these additional shipments, 2,905 MTR elements have been received at SRS and 835 TRIGA

elements have been received at INEEL under the FRR SNF Acceptance Program, for a total of 3,740 elements. These shipments, and other similar future shipments which will be conducted in accordance with the Final Environmental Impact Statement and the related Record Of Decision, are expected to greatly reduce the inventories of spent fuel at many research reactor facilities worldwide. The process is consistent with U.S. policy[5] and will resolve operational problems of the reactor sites while eliminating a serious proliferation concern.

2. The effort to develop new LEU research reactor fuels with a uranium density of 8-9 g/cm^3 in the fuel meat has made good progress during the past year. Examinations of the two batches of microplates that were irradiated in the ATR (RERTR-1, removed in November 1997 with 40% burnup, and RERTR-2, removed in July 1998 with 70% burnup) have been complemented by examinations of the third batch (RERTR-3, removed in December 1999 with ~40% burnup)[6,7]. Several samples of dispersion fuels containing U-Mo alloys of various compositions and temperatures were tested in RERTR-3 with densities of up to 8 gU/cm^3 and found to behave very well under irradiation.

3. A new irradiation experiment has been assembled and is now under irradiation in the ATR[8]. This experiment consists of two nearly identical batches of plates, RERTR-4 and RERTR-5, containing 34 positions each and planned to reach 50% and 80% burnup, respectively. The plates have larger dimensions than those used in prior experiments, have densities of either 6 gU/cm^3 or 8 gU/cm^3, and are intended to investigate the swelling behavior of U-Mo dispersion fuels under a variety of realistic operating conditions. Some of the plates to be irradiated have solid U-Mo[9] meat, to investigate the feasibility of using this concept in research reactor plates.

4. The effort to qualify U-Mo dispersion fuel with a uranium density of 6 g/cm^3 by the end of 2003, and with a uranium density of 8-9 g/cm^3 by the end of 2005, is proceeding on schedule. The main features of the qualification program were defined at a workshop that was held at ANL on January 17-18, 2000, and that was attended by 31 participants from 11 countries, representing 13 reactors, 7 fuel developers, and one fuel reprocessor[10]. Qualification of LEU U-Mo fuel with the intermediate density of 6 gU/cm^3 will provide useful data for qualification of the 8-9 gU/cm^3 fuel and will enable research reactors currently using LEU silicide fuel, or new research reactors, to begin using, before expiration of the FRR SNF Acceptance Program, a fuel that COGEMA can accept. The first test elements with 6 gU/cm^3 are being fabricated at BWXT using atomized powder produced by KAERI, and their irradiation in the HFR-Petten is scheduled to begin in the spring of 2001. The good behavior of the U-Mo fuels during irradiation[6,7] and the excellent full-sized plate fabrication results[9] demonstrated by ANL tests give every indication that U-Mo fuels with 6 gU/cm^{3}can be successfully qualified.

5. The analytical model developed to predict the behavior of stabilized uranium alloys under irradiation in dispersion fuels has been modified to take into account the results of the ATR microplate irradiations and of the postirradiation examinations performed to date[11].

6. Cooperation with various components of the Russian RERTR program has continued[12]. The purpose of the activity is to conduct the conversion studies, safety analyses, fuel development, and fuel tests needed to establish the technical and economic feasibility of converting Russian-supplied research and test reactors to the use of LEU fuels. Significant results obtained during the past year include the continued irradiation of LEU UO_2-Al elements in the WWR-M reactor at the Petersburg Nuclear Physics Institute in Russia. In

addition, analytical studies were conducted to investigate the feasibility of converting to the use of LEU U-Mo fuels the WWR-M[13] reactor in Gatchina, Russia, and several other Russian-designed research reactors[14] currently operating with HEU fuels. These reactors include the IR-8 reactor in Moscow, Russia, the WWR-SM research reactor in Tashkent, Uzbekistan, and the MARIA reactor in Swierk, Poland.

7. Significant progress was achieved during the past year on several aspects of producing ^{99}Mo from fission targets utilizing LEU instead of HEU. The goal is to develop and demonstrate during the next few years one or more viable technologies compatible with the processes currently in use with HEU at various production sites throughout the world. This activity is conducted in cooperation with several other laboratories including the Indonesian National Nuclear Energy Agency (BATAN), the Australian Nuclear Science and Technology Organization (ANSTO), and the Argentina Comisión Nacional de Energía Atómica (CNEA). Cooperation in this area is also beginning with MDS Nordion and AECL (Canada), Mallinckrodt Medical (The Netherlands), IRE (Belgium), NECSA (South Africa), and KAERI (Republic of Korea). During the past year, four targets of the new annular design reported last year were irradiated at BATAN, showing that (1) aluminum can be used for the target tubes and (2) uranium foils with nickel, zinc, or aluminum fission-recoil barriers can be removed from the target. The acidic chemical process to be used in combination with this target was demonstrated[15], and the feasibility of using LEU metal foil targets in combination with the basic process was assessed[16].

8. In the area of Reactor Analysis, improvements were made to the methods and codes available to study the design, performance and safety characteristics of research reactors. These improvements included upgrades of the WIMS-ANL code and of the REBUS Fuel Management Software[17].

9. Several joint studies were conducted to facilitate reactor conversions or to improve utilization of LEU fuel in converted reactors. Among the most important, conversion studies were conducted for the HFR-Petten[18] in the Netherlands and for SAFARI-1 in South Africa[19]. Core modifications of the RINSC, in Rhode Island[20,21], were studied to increase its neutron flux and improve BNCT applications.

10. The BER-II, in Germany, completed successfully its conversion to LEU during the past year and the first LEU elements were inserted in the La Reina reactor in Chile. With these developments, 19 research reactors have been fully converted to LEU fuels outside the United States, including ASTRA, BER-II, DR-3, FRG-1, IAN-R1, IEA-R1, JMTR, JRR-4, NRCRR, NRU, OSIRIS, PARR, PRR-1, RA-3, R-2, SAPHIR, SL-M, THOR, and TRIGA II Ljubljana. Ten research reactors have been fully converted in the U.S., including FNR, GTRR, ISUR, MCZPR, OSUR, RINSC, RPI, UMR-R, UVAR, and WPIR. Seven foreign reactors, GRR-1, HOR, La Reina, MNR, SSR, TR-2, and TRIGA II Vienna, have been partially converted. (GTRR, ISUR, MCZPR, SAPHIR, and UVAR were shut down after conversion).

PLANNED ACTIVITIES

Most of the fuel of U.S. origin irradiated in research reactors through 12 May 2006 is expected to be returned to the United States under the auspices of the U.S. FRR SNF Acceptance Program, and to be safely disposed of here. There is still significant uncertainty, however, about what will be done with the research reactor fuel of U.S. origin that will be irradiated after May 2006, when the U.S. FRR SNF Acceptance Program expires, and with spent research reactor fuels from other sources. The U.S. Government has repeatedly stated that the U.S. FRR SNF Acceptance Program will not be extended.

The French company COGEMA has indicated that it will continue to accept spent research reactor fuel for the foreseeable future, and that it will dispose of it subject to conditions acceptable to many reactors. COGEMA does not accept silicide fuel, but currently accepts U-Al alloy and aluminide fuels and has indicated that it will accept fuels based on U-Mo alloys.

To assist in the resolution of this very pressing problem, and to achieve its goal of developing fuels adequate for LEU conversion of most research reactors currently in operation, the RERTR program intends to concentrate its fuel development effort on fuels based on U-Mo alloys with two major thrusts:

(1) To develop, demonstrate, and qualify U-Mo fuels with uranium densities of 6 gU/cm^3 that can replace silicide fuels in current use. Qualification of these fuels is scheduled for late 2003. If successful, this effort will provide an opportunity for research reactors that have converted to LEU silicide fuels to change to U-Mo fuels before the end of the FRR SNF Acceptance period.

(2) To develop, demonstrate, and qualify U-Mo fuels with uranium densities in the 8-9 gU/cm^3 range, to enable conversion of reactors that cannot be converted today. Qualification of these fuels is scheduled for late 2005.

The major activities that the RERTR Program plans to undertake during the coming year are listed below.

1. Complete postirradiation examination of the first three batches of microplates irradiated in the ATR.

2. Complete irradiation in ATR of two more batches of miniplates (RERTR-4 and RERTR-5), including samples of several materials that have been selected on the basis of the results from the first three batches. Perform the irradiation tests under conditions close to prototypical for high-performance reactors, and begin the postirradiation examinations.

3. Continue out-of-pile characterization tests on the main fuel materials of interest, to assess their properties and likely performance.

4. In cooperation with fuel manufacturers, complete fabrication of full-size LEU elements containing U-Mo alloy dispersion fuels with 6 gU/cm^3 for irradiation testing in the HFR-Petten.

5. Begin irradiation of full-size LEU elements containing U-Mo alloy dispersion fuels with 6 gU/cm^3 in the HFR-Petten under prototypic conditions.

6. Continue LEU conversion feasibility studies for U.S. and foreign research reactors. Continue calculations and evaluations about the technical and economic feasibility of utilizing reduced-enrichment fuels in reactors that require such assistance, and in reactors of special interest.

7. In collaboration with the Russian RERTR program, continue to implement the studies, analyses, fuel development, and fuel tests needed to establish the technical and economic feasibility of converting Russian-supplied research and test reactors to the use of LEU fuels.

8. Continue development of viable processes based on LEU for the production of fission ^{99}Mo in research reactors, in cooperation with several current and future ^{99}Mo producers.

SUMMARY AND CONCLUSION

The year 2000 has been a productive year for the RERTR program. The main events are summarized below.

a) In the area of **U.S. acceptance of spent fuel** from foreign research reactors, four additional shipments have taken place, including 503 fuel assemblies. This brings to 3,740 the total number of spent fuel assemblies that have been accepted by the U.S. under the FRR SNF Acceptance Program.

b) In the area of advanced **fuel development**, postirradiation examinations of the first three batches of microplates irradiated in the ATR has revealed excellent irradiation behavior of the U-Mo dispersion fuel in a variety of compositions and irradiating conditions. This fuel material holds the promise of meeting the program goal of developing an LEU fuel with uranium density of 8-9 g/cm^3 in its core. Irradiation of two new batches of miniplates of greater size is now in progress in the ATR to investigate the swelling behavior of these fuels under prototypic conditions.

c) **Qualification** of the U-Mo dispersion fuels is proceeding on schedule. U-Mo fuel with 6 gU/cm^3 is to be qualified by the end of 2003, and U-Mo with 8-9 gU/cm^3 is to be qualified by the end of 2005. Test fuel elements with 6 gU/cm^3 are being fabricated by BWXT. Their irradiation in the HFR-Petten is to begin in the spring of 2001.

d) **The Russian RERTR program**, which aims to develop and demonstrate the technical means needed to convert Russian-supplied research reactors to LEU fuels, has made good progress. The characteristics of U-Mo fuel assemblies that might be used in the conversion of various reactor types have been assessed.

e) Joint **conversion feasibility studies** were completed for HFR-Petten and for SAFARI-1.

f) The new annular target that would allow efficient production of fission **molybdenum-99** was successfully tested in the RSG-GAS reactor in Indonesia, showing that uranium foils with nickel, zinc, or aluminum fission-recoil barriers can be used in conjunction with aluminum target tubes. Two targets were processed using the modified Cintichem (acidic) process, showing that yield and purity was at least as good as that for HEU Cintichem targets.

g) **Conversion** of the BER-II reactor in Berlin, Germany, was completed and conversion of the La Reina reactor in Santiago, Chile, began.

All major program areas have made solid progress during the past year. In particular, the results in ^{99}Mo production from LEU achieved by the RERTR program and by its international partners have been so successful that it appears feasible, at this time, for all the ^{99}Mo producers of the world to agree jointly to a common course of action that would eliminate, at some future time, the need to use HEU in their processes.

The most exciting developments, and the greatest challenges, continue to be in the fuel development area. Further tests have been performed in the ATR on U-Mo alloys with positive results, and it appears now very probable that these fuels will make it possible to reach the program goal of qualifying a fuel meat density of 8-9 gU/cm^3 by the end of 2005. The effort to qualify these fuels with a meat density of 6 gU/cm^3 by the end of 2003, so that they can be used to replace LEU silicide fuels when the FRR SNF Acceptance Program expires, is proceeding on schedule. This schedule is very tight, however, and close cooperation of the parties involved in the qualification program – including powder producers, commercial fuel fabricators, fuel shippers, and fuel testers - will be required.

The RERTR program plans to reach this objective on time, but the research reactor operators affected must do their part by beginning immediately the extraordinary effort required to implement the new fuels. This includes preparing for the licensing process and, whenever necessary, for the design, procurement, and irradiation of prototypic elements. We have seen little evidence that this process is actually taking place. The U.S. Government has repeatedly stated that the U.S. FRR SNF Acceptance Program will not be extended.

As usual, success of the RERTR program depends on free exchange of ideas and information, on mutual trust, and on our willingness to help each other. It is in this spirit of international friendship and cooperation that we can look forward to the day when our common goal of eliminating the international traffic of highly enriched uranium for civilian purposes shall be finally attained.

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