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**LEONIDAS U(MO) DISPERSION FUEL QUALIFICATION PROGRAM:  
PROGRESS AND PROSPECTS**

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**ABSTRACT**

The LEONIDAS Group (AREVA-CERCA, CEA, SCK•CEN, ILL) was formed in 2009 to carry out experiments required to qualify U(Mo) dispersion LEU fuel for use in the BR2 and RHF high flux European reactors and later in the RJH high flux reactor. The LEONIDAS initiative supported by the US GTRI through a collaboration with INL and ANL has planned to perform two experiments in the BR2 reactor.

The first experiment on dispersed U(Mo) in an Al(Si) Matrix (E-FUTURE) has started in June 2010 with irradiation of 4 full size fuel plates at maximum heat fluxes of 470 W/cm<sup>2</sup>. For this purpose SCK•CEN designed, licensed and manufactured a specific irradiation basket and AREVA-CERCA fabricated 16 fuel plates with various Si content and heat treatments. The 4 fuel plates to be irradiated were carefully chosen in close collaboration with the US partners and were further characterized by CEA and SCK•CEN. At the end of irradiation, PIE will be carried out on the irradiated plates to help select the U(Mo) fuel plate characteristics to be used in the BR2 mixed fuel element for the second experiment.

In this paper, the progress in the LEONIDAS program is described as well as the connections to subsequent conversion programs.

## 1. Introduction

LEONIDAS is a European initiative for the qualification of dispersed U(Mo) fuel at high power densities. The objective is to perform a common program for qualification of the high density U(Mo) dispersion fuel system for the European high performance research reactors. The concerned reactors are BR2 operated by SCK•CEN and RHF operated by the ILL to begin with, and afterwards the future JHR operated by the CEA.

The LEONIDAS members are those who adhere to the common objective: they share their know-how, knowledge and capabilities to meet the ambitious goal in a well defined timeframe.

The founding members are SCK•CEN, ILL, CEA and AREVA-CERCA.

## 2. Partnership and work-plan

The parties have agreed to share a European position in the worldwide collaborations on U(Mo) dispersion fuel and execute a common technical program for the qualification of this fuel for the high performance European research reactors [1].

The LEONIDAS initiative has materialized in a Memorandum Of Understanding, signed in April 2009 and a Collaboration Agreement signed in May 2010. It is managed by two committees: a strategic committee and a technical program committee.

The LEONIDAS initiative is supported by the US GTRI Reactor Conversion program, through contracts with Idaho National Laboratory and Argonne National Laboratory [2]. This support is intended to facilitate the common US-DOE and EU-LEONIDAS objective on high density LEU for the high performance research reactors.

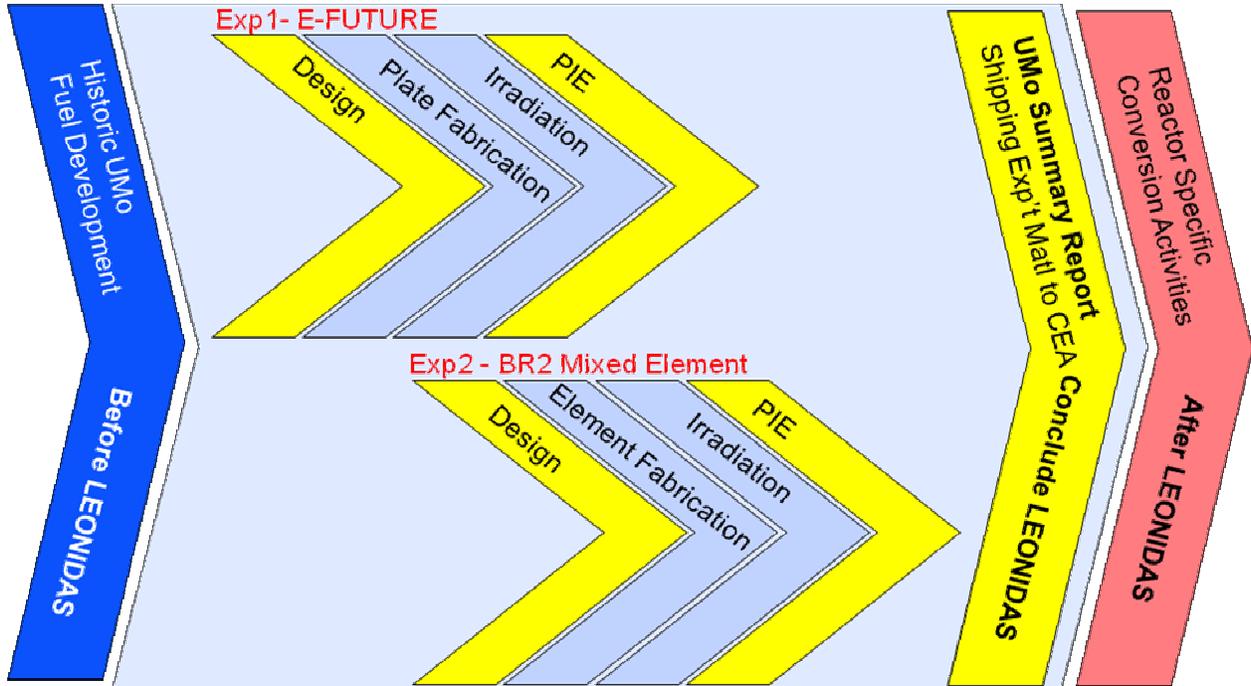
The LEONIDAS technical program committee meets every time technical choices or decisions are required: it has been meeting five times since September 2009, including three meetings with GTRI Reactor Conversion Program representatives.

The LEONIDAS experimental program is based on the international results showing that the addition of Si to the matrix stabilizes the growth and improves the properties of the interaction layer between U(Mo) and the Al matrix. However these experimental programs, such as IRIS 3 and IRIS-TUM [3], were carried out at low heat flux.

Thus the LEONIDAS experimental program intends to confirm these results under high power operating conditions, representative of the European high performance research reactors BR2, RHF and JHR. It is composed of two different irradiation tests:

- The LEU fuel parameters, such as Si content in Al matrix and final thermal treatment, have to be carefully chosen in close correlation with the high power operating conditions, and then validated under irradiation; this is the purpose of the first LEONIDAS « E-FUTURE » irradiation test.
- Subsequently, there is an absolute necessity to test the best combination of these parameters under representative conditions for the high performance research reactors (470 W/cm<sup>2</sup>, 11 m/s for BR2; 500 W/cm<sup>2</sup>, 17 m/s for RHF); this is the objective of the second LEONIDAS BR2 « Mixed Element » irradiation test.

After the end of the LEONIDAS experimental program, each reactor will have to pursue its own conversion program as illustrated in Figure 1.



**Figure 1:** The LEONIDAS roadmap

### 3. The E-FUTURE irradiation test

The E-FUTURE irradiation test intended to choose the best combination parameters for the LEU-U(Mo) in terms of Si content and thermal treatment, is already well advanced. It consists in irradiating four full size flat fuel plates in BR2 at high heat fluxes, reaching a burn-up above 50 % and then in assessing their performance parameters through non-destructive and destructive post-irradiation examinations.

The main steps of E-FUTURE are as follows:

- specification and fabrication of the U(Mo) fuel plates,
- fuel plates selection for irradiation and fresh fuel characterization,
- irradiation in BR2,
- post-irradiation examination.

### 3.1. Specification and fabrication of the U(Mo) fuel plates

The E-FUTURE plates are full size, high density, flat fuel plates made of dispersed U7Mo in Al-Si matrix (8 gU/cm<sup>3</sup>, 19.7 % <sup>235</sup>U enrichment) with two different claddings (AG3NE as used in BR2 and AlFeNi as used in RHF and JHR).

One important parameter to be specified for the E-FUTURE fuel plate is the Si content in Al matrix. Some hypotheses had to be made to assess the required Si content to stabilize the interaction layer formed between the U(Mo) and the Al matrix. In the absence of a clear threshold, it was considered on the basis of the ternary phase diagram, that a Si content of 5 at% would avoid formation of UAl<sub>4</sub> type compounds, which are known to be unstable under irradiation [4]. This criterion was subsequently applied to determine the needed matrix Si content by assuming that all Si in the recoil zone around each fuel particle would end up in the interaction layer. Using the approach developed by Kim et al. [5], an expected interaction layer thickness of 5.5 μm was assumed for the assessment [4].

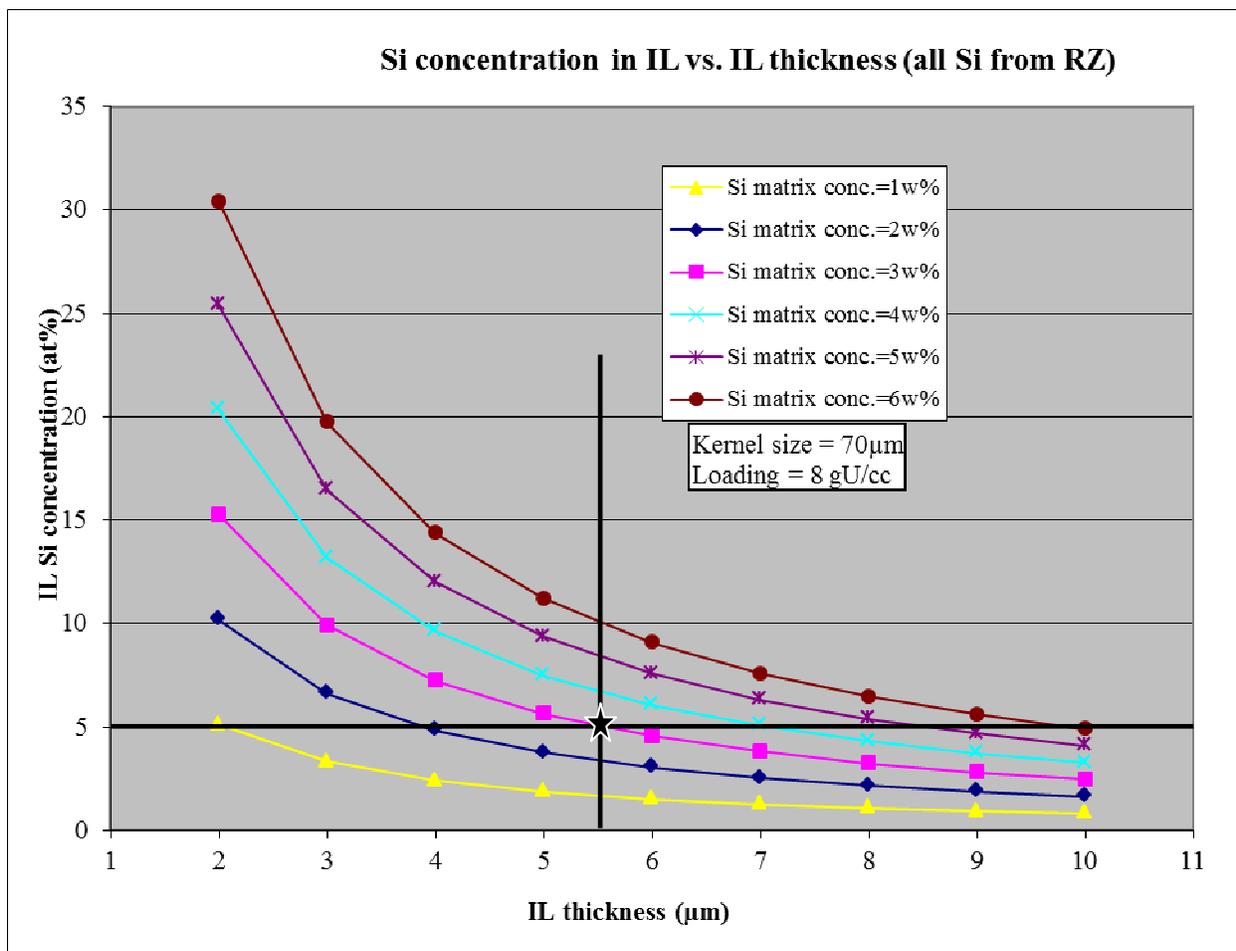


Figure 2: Si content in stable interaction layer

The calculations made by ANL [4] indicated that 5 wt% Si in the Al matrix would keep the Si content of the interaction layer above 5 at%. Subsequent calculations by the LEONIDAS group (Figure 2) have shown that a 4 wt% Si content in the E-FUTURE fuel plate would be sufficient and that a 6 wt% Si content should provide margin.

Besides a compromise should be reached between a value of Si content sufficient to stabilize the interaction layer and back-end concerns, which is why both Si contents (4 and 6 wt%) were chosen for the E-FUTURE test plates.

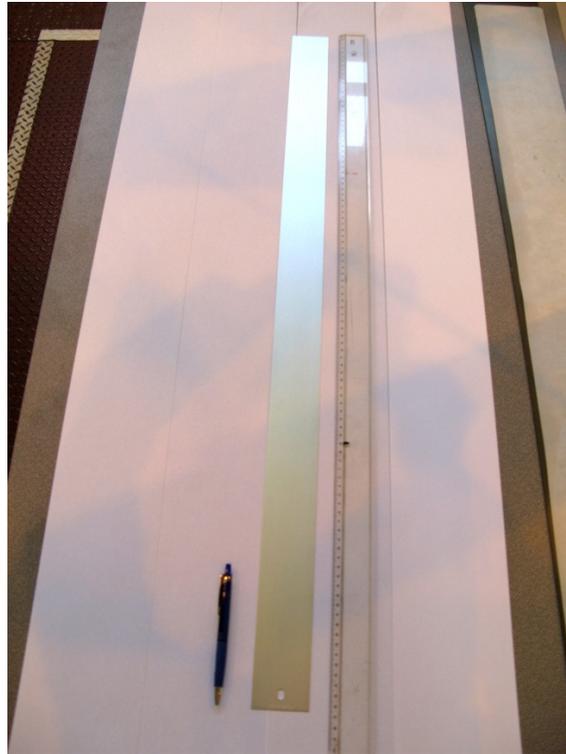
In the same way, two different final thermal treatments were chosen, taking into account US GTRI, CEA and AREVA-CERCA feedback on previous U(Mo) test programs. These had indicated a beneficial, perhaps required, influence of Si rich layers around the fuel particles formed during fabrication [6]. To develop these layers, diffusion of the Si in the matrix to the fuel particle surfaces is required, which is enhanced by higher temperatures. Therefore, specific thermal treatments were applied on fuel plates to develop the desired properties for the pre-formed Si rich layers around the U(Mo) kernels.

The fuel parameters chosen for the E-FUTURE fuel plates to be irradiated in BR2 were approved in September 2009 by LEONIDAS members and US GTRI Reactor Conversion program representatives. They are summarized in Table 1.

Si content	Final Thermal Treatment
4%	2 hours at 425 °C
	2 hours at 475 °C
6%	2 hours at 425 °C
	4 hours at 475 °C

**Table 1:** E-FUTURE test matrix

Beginning of 2010, 16 plates were fabricated by AREVA-CERCA as previously specified, within a very short period of time (Figure 3).



**Figure 3:** Fabricated E-FUTURE plate

### *3.2. Fuel plates selection for irradiation and fresh fuel characterization*

In April 2010, during the fabrication acceptance, four plates were selected to be irradiated and four “twin” plates were selected to be cut and used for fresh fuel characterization (Table 2).

Si content	Final Thermal treatment	Cladding	Current state of plate
4%	425 °C x 2h	AlFeNi	Irradiated in BR2
		AlFeNi	Used for characterization
		AG3Ne	Stored
	475 °C x 2h	AlFeNi	Stored
		AG3Ne	Irradiated in BR2
		AG3Ne	Used for characterization
	No final TT	AG3Ne	Stored
AlFeNi		Stored	
6%	425 °C x 2h	AlFeNi	Irradiated in BR2
		AG3Ne	Used for characterization
		AG3Ne	Stored
	475 °C x 4h	AlFeNi	Rejected (blister) - Used for characterization
		AlFeNi	Rejected (blister)
		AG3Ne	Irradiated in BR2
		AG3Ne	Stored
	No final TT	AlFeNi	Stored

**Table 2:** E-FUTURE fuel plates selection

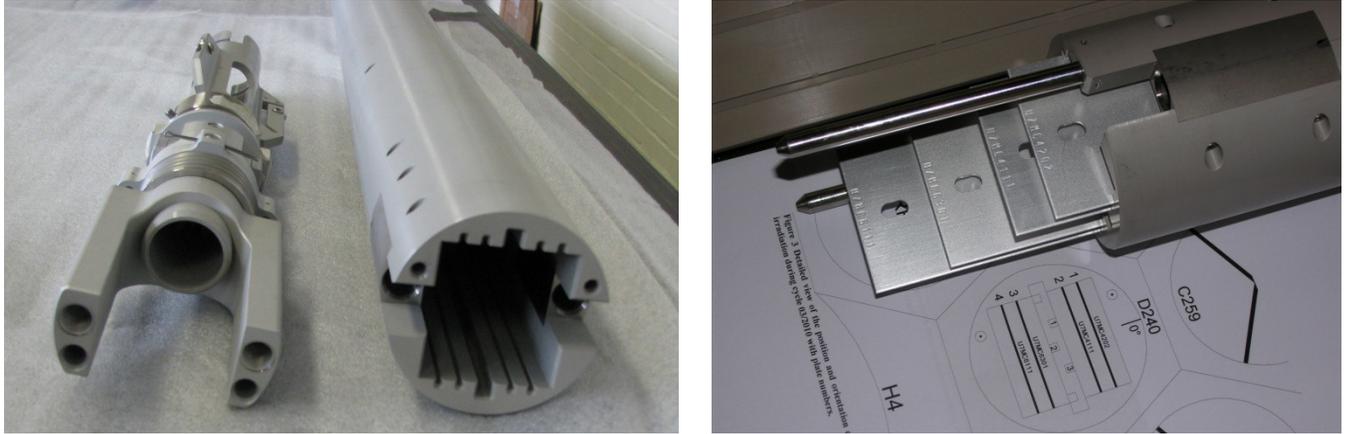
CEA and SCK•CEN have already carefully characterized the fresh fuel in order to analyze and compare the microstructure of the different types of fuel plates. The results of these characterizations are the subject of a specific paper in this conference [7].

### 3.3. Irradiation in BR2

The irradiation of the four selected E-FUTURE plates has started in BR2 on June 1, 2010.

Prior to the irradiation, SCK•CEN had to carry out neutronic and thermal-hydraulic calculations in order to estimate the fuel plates maximum temperatures and ensure the safety of the E-FUTURE irradiation test.

SCK•CEN had also to design, license and manufacture a specific irradiation basket to hold the fuel plates in the BR2 core (Figure 4).



**Figure 4:** E-FUTURE irradiation basket and fuel plates

The irradiation objective was to attain a heat flux  $\geq 450\text{W/cm}^2$  during at least 10 % of the irradiation time and a mean burn-up of the four fuel plates of at least 55 %.

From June to August 2010, the E-FUTURE fuel plates were irradiated in BR2 for two cycles (BR2 cycles 03/10A and 04/10). During both cycles, the basket was positioned so that the four plates would receive similar irradiation conditions as much as possible. As a result there was a flux gradient across the width of the plates. No fission product release was detected up to now, which means that there was no clad failure.

The main characteristics of the first two cycles are given in column 1 and 2 of Table 3.

Cycle	1 (03/10A)	2 (04/10)	3 (05/10) estimate
Dates (2010)	June 1 – June 29	July 20 – August 17	Sept. 28 – Oct. 19
Length	28 days	28 days	21 days
EOC Mean Burn-up	19 %	36 %	~ 50 %
EOC Max Burn-up	32 %	55 %	
BOC max heat flux	470 W/cm <sup>2</sup>	350 W/cm <sup>2</sup>	330 W/cm <sup>2</sup>
EOC max heat flux	340 W/cm <sup>2</sup>	270 W/cm <sup>2</sup>	

**Table 3:** Characteristics of E-FUTURE irradiation

At the end of BR2 cycle 04/10, the visual inspection of the four E-FUTURE fuel plates showed a typical color distribution of oxide on both faces of the plates, more pronounced on the hot side (towards reactor center) and on the level of the hot plane. The inspection revealed no visible blisters or actual differences between the plates (no difference between AG3NE or AlFeNi claddings).

The sole exception concerned the plate U7MC6111 (6 % Si and low thermal treatment conditions) that showed a black elongated spot on both faces, hot side (towards reactor center), around the level of the hot plane, but no visible swelling or blistering.

Based on these observations, the basket was reloaded for the third cycle (cycle 05/10) in the same channel as during the first two irradiation cycles but the plate U7MC6111 was turned 180° around the vertical axis in order not to expose the spotted side to the highest flux.

The third cycle (05/10) started up on September 28, 2010 and is expected to last 21 EFPD. The BOC maximum heat flux for the four E-FUTURE plates is estimated between 295 W/cm<sup>2</sup> and 330 W/cm<sup>2</sup> and the EOC mean burn-up of the four plates should come close to 50 % (see third column of Table 3).

After the end of the E-FUTURE irradiation and when all data are available, a detailed report will be the subject of a paper in the next RRFM meeting.

### *3.4. Post-irradiation examination*

After the end of the irradiation in BR2 and allowing for cooling time, post-irradiation examinations (PIE) will be carried out by SCK•CEN on the E-FUTURE fuel plates. Both non-destructive examinations (visual inspection, plate swelling, oxide thickness measurements and gamma scanning) and destructive examinations (microscopy and spectroscopy) are planned on the irradiated fuel plates. The objective is to analyze the irradiated fuel microstructure especially the interaction between U(Mo) particles and the Al(Si) matrix and characterize the fission gas behavior.

These examinations will lead, if possible, to the choice of the best parameter combination in terms of Si content and final thermal treatment that will be used for the second LEONIDAS irradiation test.

## **4. The BR2 mixed element irradiation test**

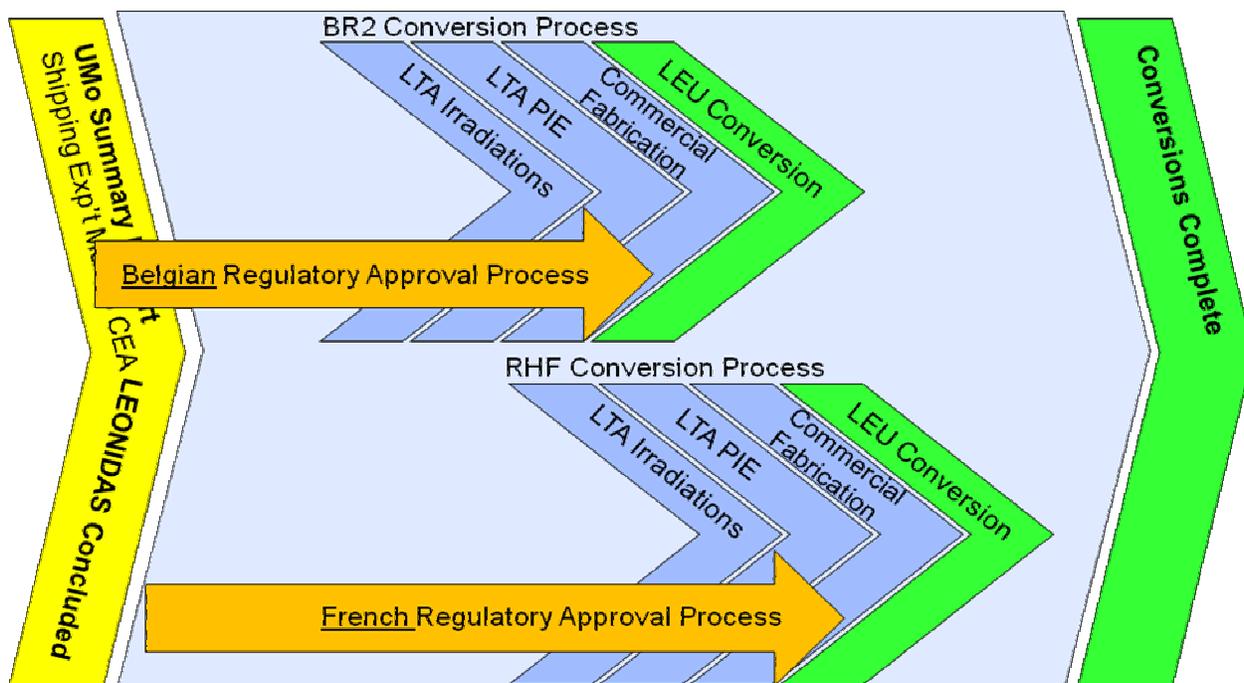
The objective of this second LEONIDAS irradiation test is to irradiate the U(Mo) dispersion fuel selected at the end of the E-FUTURE irradiation test in representative BR2 conditions (not far from RHF conditions).

It will consist in irradiating a standard BR2 fuel element in which the outer shell of the six standard HEU shells is replaced by a LEU-U(Mo) dispersion fuel shell (3 curved fuel plates). After irradiation, PIE will be carried out on the outer ring plates of the mixed element.

The detailed program of this test is still to be decided depending on the results of the E-FUTURE irradiation test.

## **5. Post-LEONIDAS conversion programs**

After the LEONIDAS experimental program is complete, the European high performance research reactors will still have a significant amount of work towards conversion (Figure 5).



**Figure 5:** Conversion road map after LEONIDAS

BR2 and RHF will need to irradiate some lead test assemblies (LTA's) in their specific geometry with the qualified burnable absorbers and carry out all necessary calculations and/or tests, part of their respective country regulatory approval process [8, 9].

The actual conversion process will start by loading the first batch of fresh LEU fuel elements which means that no more HEU will be needed from this point on. This requires first, that the fuel manufacturer makes the necessary overall adaptations to produce U(Mo) LEU fuel on an industrial scale and second, that the reactor operators get approval from the Safety Authorities.

Besides SCK•CEN, ILL and CEA currently send their spent fuel to the reprocessing plant of La Hague and have very little spent fuel storage capacity; therefore the back-end of the fuel cycle must be preserved.

## 6. Conclusions

Within the frame of the LEONIDAS European initiative contractually supported by the US GTRI program, the E-FUTURE irradiation test is at an advanced stage and will help define the future LEU fuel for the conversion of European high performance research reactors.

LEONIDAS is a focused fuel qualification program that will not encompass conversions; but assuming the success of the experimental program, BR2 and RHF operators are each working simultaneously to pursue subsequent conversion, a shared goal of all the partners.

## 7. Acknowledgements

The LEONIDAS European group wishes to thank particularly the Argonne National Laboratory, the Idaho National Laboratory and the US-DOE/NNSA for their support in the LEONIDAS experimental program.

## 8. References

- [1] E. Koonen, H. Guyon, P. Lemoine, C. Jarousse, D.M. Wachs, J. Roglans-Ribas, "Dispersed U(Mo) fuel qualification road map for the BR2 and RHF Reactors", Proceedings of RRFM 2009, Vienna, Austria, March 22-25, 2009.
- [2] E. Koonen, H. Guyon, P. Lemoine, C. Jarousse, D.M. Wachs, J.G. Stevens, "The LEONIDAS and US Partnership for UMo dispersion fuel qualification", Proceedings of RERTR 2009, Beijing, China, November 1-5, 2009.
- [3] M. Ripert, S. Dubois, J. Noirod, P. Boulcourt, P. Lemoine, S. Van den Berghe, A. Leenaers, A. Röhrmoser, W. Petry, C. Jarousse, "Overview on high density U(Mo) fuel in-pile experiments in OSIRIS", Proceedings of RRFM 2008, Hamburg, Germany, March 2-5, 2008.
- [4] G.L. Hofman, Y.S. Kim, "Utilising the stabilising effect of silicon in U-Mo/Al dispersion and minimum Si addition for the BR-2 test", Intra-laboratory Memo, Aug 11, 2009.
- [5] Y.S. Kim et al., "Post-irradiation analysis and performance modeling of dispersion and monolithic U-Mo fuels", Proceedings of Reduced Enrichment for Research and Test Reactors, Prague, Czech Republic, September 23-27, 2007.
- [6] D.D. Keiser, A.B. Robinson, D.E. Janney and J.F. Jue, "Results of recent microstructural characterization of irradiated U-Mo dispersion fuels with Al alloy matrices that contain Si", Proceedings of RRFM-2008, Hamburg, Germany, March 2-5 2008
- [7] X. Iltis, F. Charollais, M.-C. Anselmet, P. Lemoine, A. Leenaers, S. Van den Berghe, E. Koonen, C. Jarousse, D. Geslin, F. Fréry, H. Guyon, "Microstructural characterization of the E-FUTURE fresh fuel plates", Proceedings of Reduced Enrichment for Research and Test Reactors, Lisbon, Portugal, October 10-14, 2010.
- [8] Y. Calzavara, F. Frery, F. Thomas, H. Guyon, J. Stevens, A. Bergeron, A. Tentner, "ILL Conversion Program", Proceedings of Reduced Enrichment for Research and Test Reactors, Lisbon, Portugal, October 10-14, 2010.
- [9] S. Kalcheva, "Neutronics Codes and Methodologies Applied for the 3-D Whole Core Evaluations of the Fuel Cycle at the BR2 Reactor", Proceedings of Reduced Enrichment for Research and Test Reactors, Lisbon, Portugal, October 10-14, 2010.