UNDER IRRADIATION QUALIFICATION OF A CHILEAN TEST FUEL

(1) J. Marin, J. Lisboa, L. Olivares
Department of Nuclear Materials
(1) J.C. Chavez
Technical Cooperation and International Relations
(2) M.A.C. van Kranenburg, F. J. Wijtsma
(1) Comisión Chilena de Energía Nuclear, CCHEN, Amunategui 95, Santiago – Chile
(2) Nuclear Research and consultancy Group – NRG – Petten, The Netherlands

ABSTRACT

This paper presents the irradiation and PIE results for a test fuel element irradiated at the High Flux Reactor (HFR) in Petten Site – The Netherlands. The fuel element (LCC 01) was manufactured by CCHEN, and consisted of 16 flat fuel plates of U_3Si_2 – Al with a density of 3.4 g/cm^3. The objective of this irradiation test was to qualify the manufacturer of these LEU fuel elements for research reactors.

The irradiation, which started in May 2003 was successfully ended on November 2004, and no irregularities were observed during all 16 irradiation cycles. The final calculated burnup was approximately 65%. After cooling, the LCC-01 had been dismantled and submitted to PIE at the hot cell facility in Petten. PIE has involved visual inspections and gamma scanning for the fuel element and visual inspection, gamma spectrometry - and plate and oxide layer thickness measurements in one removed plate.

1. Introduction

The Chilean Commission for Nuclear Energy – CCHEN, has two research reactors: RECH-1 designed and operated to 5MW and RECH-2 designed to operate at 10 MW. [1]
The operation of RECH-1 started in 1974 with HEU fuels, with 80% of ^{235}U. During the eighties, fuel with 45% of ^{235}U were provided by UKAEA. According to a contract signed with DOE, after May 2006, this open pool research reactor will be fully converted to LEU fuel [2]. The current loaded core configuration consists of 14 HEU (45% of ^{235}U) fuel assemblies made by the UKAEA Dounreay, Scotland, and 20 LEU (19,75% ^{235}U) fuel assemblies made by the Chilean Fuel Fabrication Plant – PEC.

Since the mid-80´s CCHEN has been involved in the R&D of LEU fuel for research reactors. In the framework of the RERTR Program, considerable efforts have been made in Chile to implement the RERTR policy using equipment and experts provided by IAEA As a result, CCHEN currently has a licensed and ISO 9001 certified Fuel Fabrication Plant. This facility is devoted to research, development and fabrication of MTR fuels.

At the end of 2004, PEC has finished a fabrication program to supply 46 LEU fuel elements for the RECH-1 reactor. These LEU fuel elements were fabricated with a U_3Si_2 – Al meat with an uranium density of 3.4 gU/cm^3. The first four fuel elements, called leaders, were fabricated and loaded into the RECH-1 core by the end of 1998. They are being monitored in order to follow up their behavior under irradiation. However, according to the present

reactor's operating schedule, the foreseen 50% discharge burn up will be attained only in 2007 [3]. Besides, CCHEN does not have a facility for post irradiation examinations (PIE) to evaluate the irradiation behavior of these fuels.

1.1 Under Irradiation Qualification

As the time required for local qualification was longer than the fabrication stage, and in order to advance the RECH-1 LEU fuels conversion, an external qualification was required. Several international nuclear facilities were inquired by CCHEN, and in 2001 a contractual agreement between IAEA, CCHEN and Nuclear Research and consultancy Group (NRG) was established and signed in order to qualify the manufacturing of these LEU fuel elements in a world reference facility as the High Flux Reactor (HFR) in Petten – The Netherlands. The HFR is operated by NRG under contract with the Joint Research Centre (JRC) of the European Community [4]. In this contract, supported by IAEA under TCP CHI/4/021, an irradiation program was established. The general objective of the irradiation program and subsequent PIE, was to provide sound experimental evidence needed to qualify CCHEN as a manufacturer of LEU fuel for research reactors. This qualification has been achieved and it has been demonstrated that, throughout their entire irradiation period at nominal nuclear and thermal HFR operation conditions [5], the test fuel element:

- Has had sufficient rigidity to withstand the mechanical and hydraulically forces associated with normal handling and irradiation;
- Has been sufficiently resistant to local or general deterioration by normal corrosion (scaling, pitting and cracking) of the fuel plate cladding;
- Has not released either fuels or fission products to the reactor coolant;
- Has not deformed due to swelling, blistering or other irradiation or temperature induced mechanisms to such an extent that the minimum cooling channel dimensions required for safe heat removal could not be maintained;
- Has not deformed (twisting, bowing, etc.) due to swelling, differential thermal expansion, hydraulic forces, etc. to such an extent that the proper fitting of the elements in the core grid structure could not be maintained;
- Has not reached fuel or cladding temperature levels, such that the mechanical properties required for proper fuel plate strength and rigidity could not be maintained;
- Could be handled, stored, and after a reasonable decay period, transported to hot cell laboratories (HCL) without deformation, fission product release or other defects.

The test program was addressed to all qualification requirements listed above and all required measurements and analyses were performed to determine the conditions at which the test irradiation was carried out.

2. Experimental Set-up and Results

2.1. Fuel Fabrication

The RECH-1 test fuel was fabricated at PEC based on drawings supplied by NRG together with an agreed Technical Specification [6]. This fuel assembly was designed and manufactured according to the basic specifications of the current HFR LEU fuels. Details

of the fuel core compositions, dimensional and comparisons with the standard HFR HEU fuels are given in Table 1. During the qualification of the LCC-01 element the HFR fuel was HEU fuel, while currently a conversion to LEU is ongoing in the HFR.

Table 1.- Main features of RECH-1 (LEU) compared to the Standard HFR (HEU) fuel assemblies.

Type	***RECH-1/ LEU***	***Standard HFR /HEU***
Number of fuel plates	16 flat plates	23 curved plates
^{235}U mass [g]	229.1	450
^{Tot}U mass [g]	1159.7	483.87
Enrichment [%]	19.75	93
Burnable poison [g]	Not applicable	1.0 (^{10}B)
Upper inlet section	Open, square area	Cylindrical piece
Fuel matrix	U_3Si_2-Al	UAl_x-Al
Uranium Density [$g.cc^{-1}$]	3.4	1.2
Fuel volume fraction [%]	32	20
Porosity [%]	3	< 5
Meat thickness [mm]	0.61	0.51
Plate thickness [mm]	1.53	1.27
Coolant gap [mm]	2.46	2.18
Total heat transfer surface [m^2]	1.26	1.74
Total coolant cross [cm^2]	27.18	33.5

Other features of RECH-1 test fuel element as compared to a standard HFR HEU element are the following:

- The orientation of the RECH-1 test fuel plates is perpendicular to the orientation of the standard HFR fuel plates
- Extra side plates are provided containing no fuel. These extra side plates are thicker than the fuel plates located inside.

Before, during, and after test fuel fabrication, each structural part, fuel plates and final assembly was inspected and approved by a NRG qualified inspector [7], [8], [9]

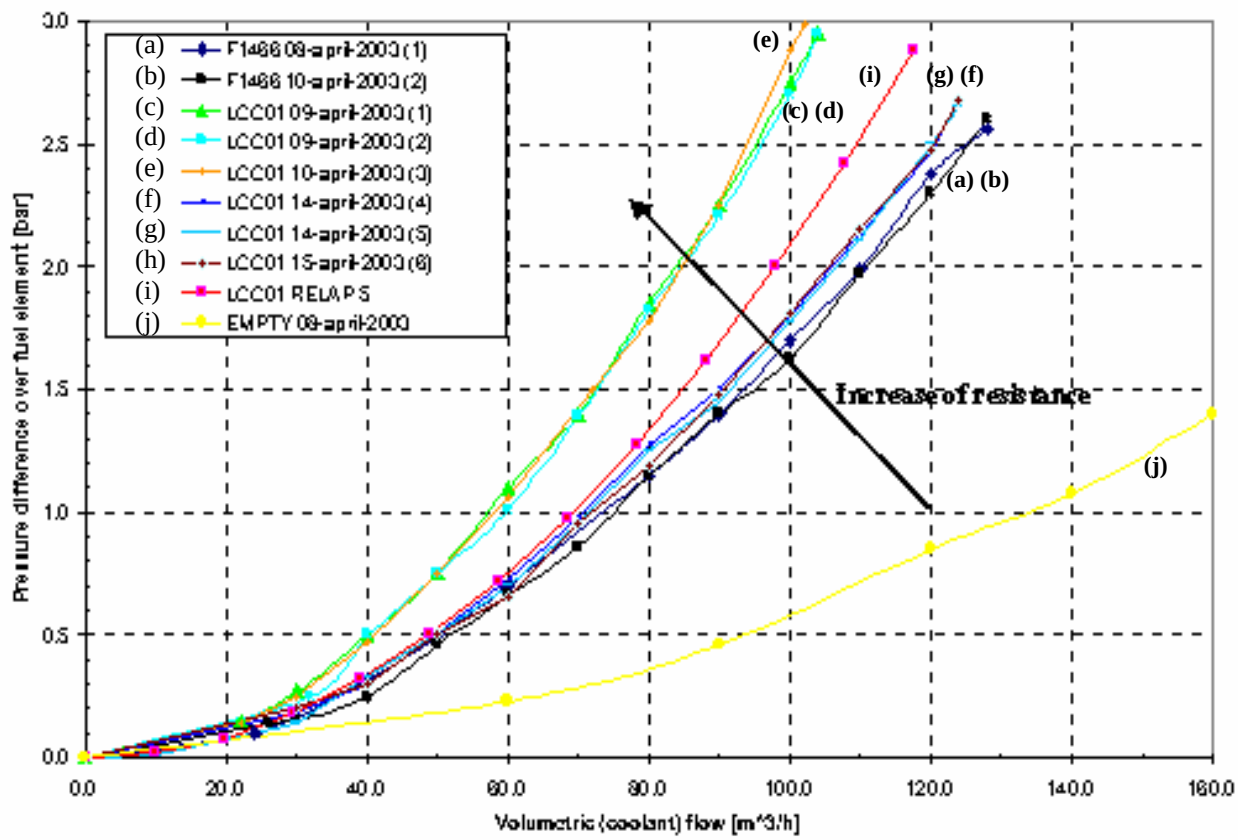
Figure 1. RECH-1 test fuel element ready to be shipped

The RECH-1 test fuel element was shipped and transported to Petten in April, 2003. Prior to start the irradiation, a hydraulic test was carried out to verify, qualify and compare the hydraulic behavior of the mechanical assembly with reference measurements of standard HFR fuel elements [10].

2.2. Hydraulic Test

During the initial phase of the hydraulic test, a remarkable difference between the theoretical RELAP results [11] and the actual measurements was observed. The RECH-1 test fuel element had an increased hydraulic resistance compared to the RELAP calculations as indicated in Figure 2. Visual inspection after the test showed that the fuel plates separation comb was bend and partly blocked the fuel element outlet section. This explained the higher measured resistance of the element. After carefully removing the fuel plate separation comb, the hydraulic test was repeated. The results of these second hydraulic measurements, without the comb closely follow the results of the RELAP5 modeling and the standard HFR fuel element number F1466. Figure 2 presents the hydraulic resistance for both series of measurements.

Figure 2.Hydraulic characteristics (resistance) of both series of measurements

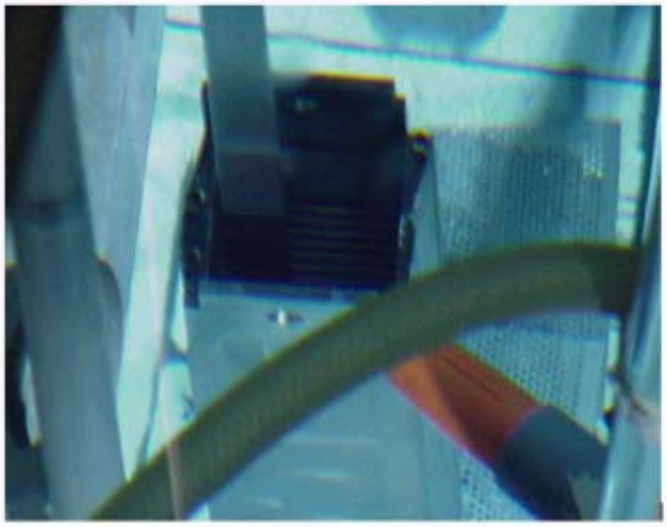


After passing by the hydraulic test, the test fuel element was loaded into the HFR core to irradiate until an initial target burnup of 55%. The initial target burnup was achieved after 13 HFR cycles of approximately 25 full power days for each cycle. To achieve a higher burnup level of 65% ^{235}U the irradiation programme was extended by 3 cycles until 16 HFR cycles.

2.4. Follow Up during irradiation

The RECH-1 test fuel was visually inspected prior to the first start and randomly during the irradiation program. Besides, cooling channel gap measurements with a caliper were carried out at regular intervals throughout the entire irradiation period. Every time this measurement was done, the test fuel was removed from the reactor core to an underwater table in the storage pool and placed back in a storage underwater facility. The caliper, a go-no go type caliper, had an upper limit of 2.15 mm and was made of stainless steel. The coolant gap measurements of the RECH-1 test fuel showed no deviations from the initial values. In table 2 [12] an overview of the coolant gap measurements is given.

Figure 3. Coolant gap measurements and visual inspection of RECH-1 fuel



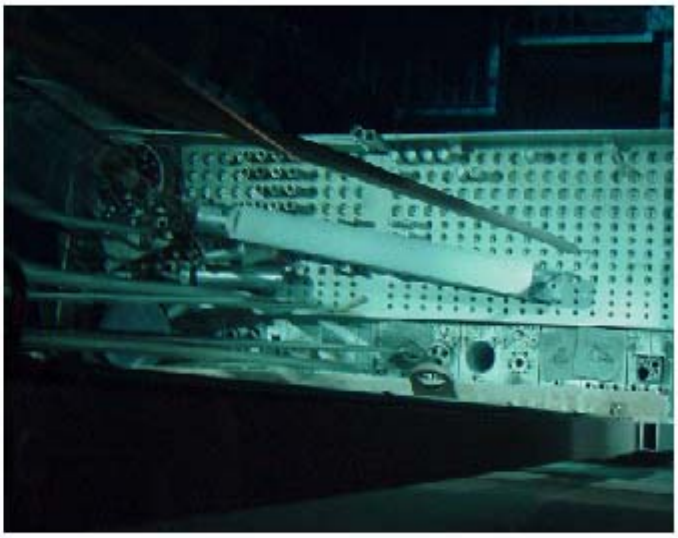


Table 2. Overview of gap measurements of RECH-1 fuel

			Gap numbers														
Cycle Nº	**Measurement**	**Date**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Prior 220-05	1	15 /04/03	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
2003-05 (1)	2	10/06/03		■			■		■			■			■		
2003-06 (2)	-	-															
2003-07 (3)	3	19/08/03	■			■			■				■			■	X
2003-08 (4)	-	-															
2003-09 (5)	4	21/10/03			■		■			■		■		■			
2003-10 (6)	-	-															
2003-11 (7)	5	16/12/03		■			■	■			■		X				■
2003-12 (8)	-	-															
2004-01 (9)	6	10/02/04		■		■				■				■			■
2004-02 (10)	-	-															
2004-03 (11)	7	27/04/04			■		■		X		■			■		■	
2004-04 (12)	-	-															
2004-05 (13)	8	28/06/04			■		■		■			■					■
2004-06 (-)	** See Note																
2004-07 (14)	9	7/09/04	■			■			■			■		■			X
2004-08 (15)	10	5/10/04	■			■		X				■		X	■		
2004-09 (16)	11	14/12/04	■	■	■	■	■		■	■	■	■	■	■	■	■	■
Total number of measurements per gap			5	5	5	6	7	4	7	4	4	7	4	7	4	4	7

■	= Gap measured
X	= Extra gap measurement (>5)

***Note**: In HFR cycle 2004-06 the RECH-1 test fuel was removed from irradiation in order to achieve a new regulatory approval to continue the irradiation to a higher burnup level of 65% ^{235}U

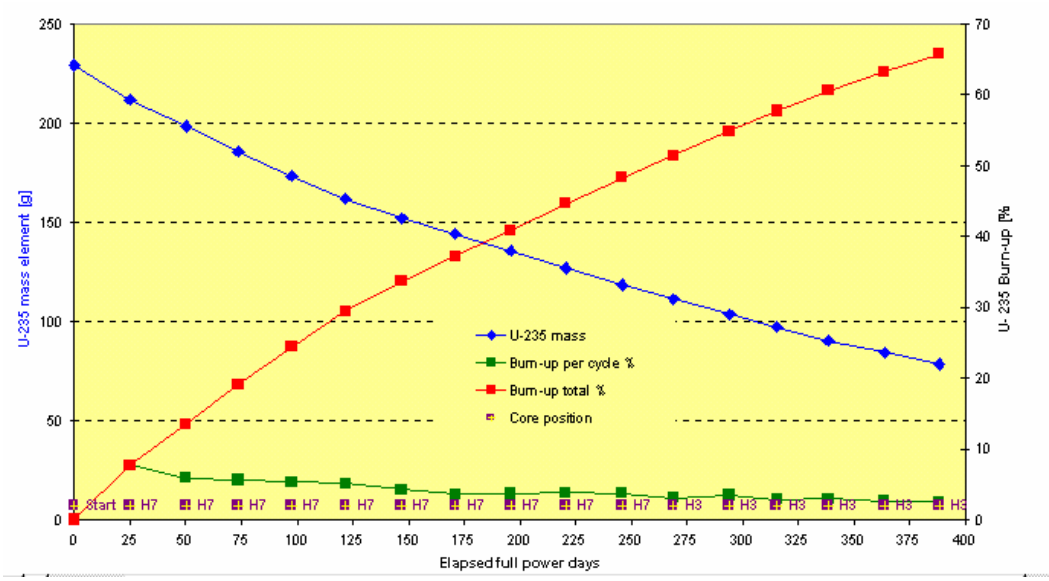
2.5. Irradiation and burnup calculations

Using the HFR core management code, HFR-TEDDI, an overview of the calculated burnup history and the irradiation locations in the core are presented in Table 3 [12]. From this table it can be concluded that after 16 cycles the total calculated burnup is approximately 65% ^{235}U [13]. It should be noted that HFR-TEDDI tends to overestimate the burnup by a maximum of 10 % [14]. This uncertainty was considered the main reason to extend the irradiation to an increased calculated HFR-TEDDI burnup level of 65 % ^{235}U. As indicated in table 3 [12], the RECH-1 test fuel element was moved in irradiation cycle 2004-03 from H7 position and irradiated in core position H3 until the end of the irradiation test. H7 and H3 core positions are symmetrical and flux levels are identical in both locations, with respect to the center of the core. Moving the RECH-1 test fuel element to position H3 resulted in a more homogeneous burnup of ^{235}U in the entire element. When located at position H7 the element was irradiated slightly more from the North, and when located at its final irradiation position H3 slightly more from the South. According to HFR staff, the HFR-TEDDI results were in very good agreement with the MCNP results.

Table 3. Overview of irradiation data of RECH-1 test fuel

Cycle	Location	^{235}U mass (g)	^{235}U burnup per cycle (%)	^{235}U burnup total (%)	Full power (days)	Accum. Full power (days)
2003-05	H7	211.59	7.64	7.64	25.05	25.05
2003-06	H7	198.25	5.82	13.47	25.02	50.07
2003-07	H7	185.43	5.60	19.06	23.55	73.62
2003-08	H7	173.24	5.32	24.38	23.89	97.51
2003-09	H7	161.68	5.05	29.43	24.23	121.74
2003-10	H7	152.05	4.20	33.63	25.11	146.85
2003-11	H7	143.93	3.54	37.18	24.20	171.05
2003-12	H7	135.53	3.67	40.84	24.89	195.94
2004-01	H7	126.84	3.79	44.64	24.71	220.65
2004-02	H7	118.39	3.69	48.32	25.30	245.95
2004-03	H3	111.38	3.06	51.38	23.05	269.00
2004-04	H3	103.52	3.43	54.81	25.07	294.07
2004-05	H3	96.97	2.86	57.67	21.39	315.46
2004-07	H3	90.31	2.91	60.58	23.15	338.61
2004-08	H3	84.19	2.67	63.25	24.97	363.58
2004-09	H3	78.47	2.50	65.75	24.72	388.30

Figure 4. Burnup of ^{235}U of the RECH-1 test fuel after 16 HFR cycles



2.6. Post Irradiation Examination PIE

After seven months of cooling, the irradiated RECH-1 test fuel was transported dry to the Hot Cell Laboratories (HCL) in Petten for Post Irradiation Examinations (PIE). Before the transport, the end pieces of the fuel element were removed by sawing under water in the storage pool of HFR. According to the contract, PIE consisted of: Visual inspection and gamma scanning of complete fuel element, gamma spectrometry, thickness measurement and oxide layer measurement of a removed plate. The PIE results are given in the followings figures [15]:

Figure 5. Visual inspection of RECH-1 test fuel (LCC-01) at HCL

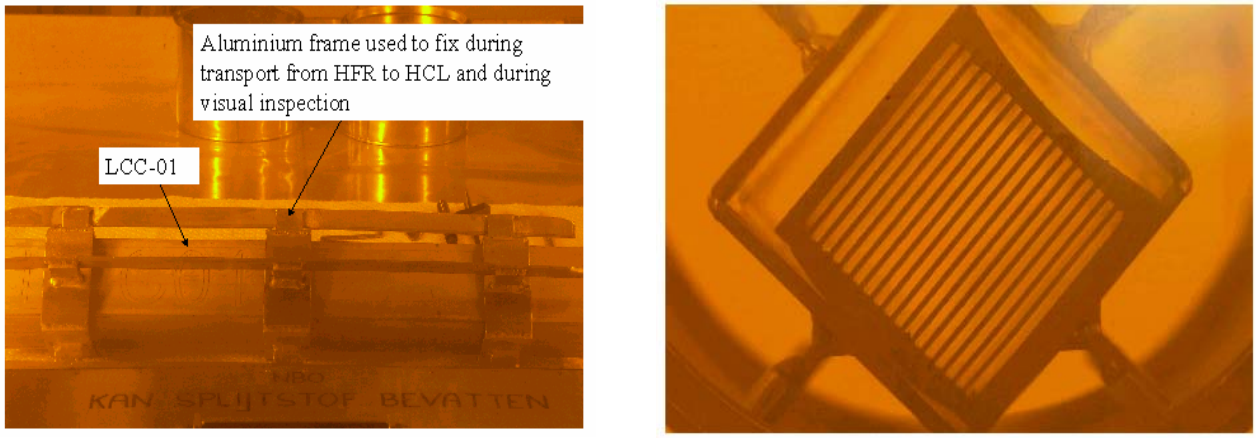
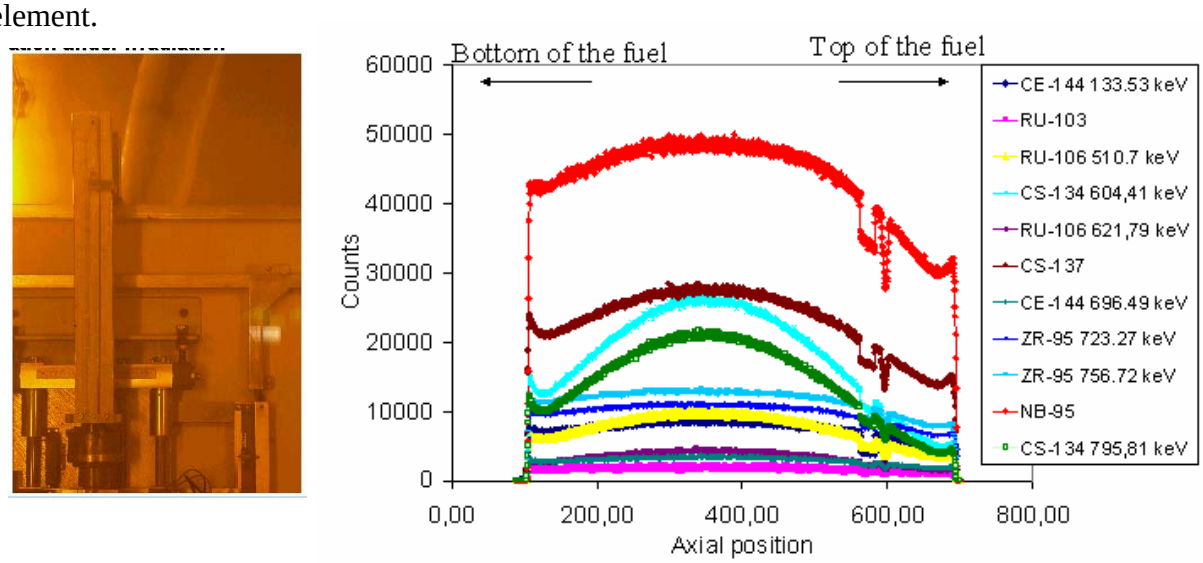


Figure 6. Gamma scanning of RECH-1 test fuel. (a) Fuel assembly in gamma scanning holder in front of gamma spectrometry detector. (b) Gamma scanning profile of fuel element.



One external fuel plate was removed by machining of side structural plates. Currently, this plate has been analyzed by gamma spectrometry, thickness measurement and finally the oxide layer will be measured for completing the PIE.

3. High density fuels developing

In relation to high-density fuel, in the beginning of 2005 an U-Mo developing program was presented and approved at CCHEN. Based on exploratory tests carried out during 2002-2004 and preliminary results that had been achieved in local research and development projects, the planing for next five years is:

Phase	Main activities	Period
U-Mo dispersion fuels	- Developing of techniques for U-Mo powder production - Interaction studies in UMo – Al and Al alloys system - Studies on thermally induced swelling in UMo – Al – Metal systems	2005
U-Mo monolithic fuels	- Developing of U-Mo alloys foils - Assembling of Friction stir welding system for Al 6061 - Bonding by hot rolling of U-Mo foils meat and Al-6061 claddings - Reaction layer studies in monolithic U-Mo and Al-6061	2006-2007
Under irradiation evaluation of U-Mo fuels	- Miniplates fabrication using dispersion and/or monolithic U-Mo alloys - Design and assembling of irradiation and monitoring device for miniplates - Licensing of irradiation experiments - Irradiation program - Follow-up during irradiation - PIE	2008 - ?

4. Discussion

After HFR cycle 2004-05 the irradiation of the RECH-1 test fuel was interrupted for one cycle. The formal advice given by the Reactor Safety Committee (RSC-Petten) was based on an irradiation up to an initial burnup of 55% or 13 irradiation cycles. Since the fuel element burnup after 13 irradiation cycles (end of cycle 2004-05) was 58% ^{235}U, it was formally impossible to approve the continuation of the irradiation in cycle 2004-06. To restart the irradiation an updated report was prepared and submitted to the RSC in order to achieve a new regulatory approval to irradiate the fuel element to an increased burnup level of about 65 % ^{235}U. After consent of the RSC, the irradiation was restarted in HFR cycle 2004-07. As long as the coolant gap measurements showed no deviations, which meant that the caliper fitted smoothly into the coolant gaps, the irradiation could be continued until a calculated HFR-TEDDI burnup of approximately 65% ^{235}U. Finally, this desired burnup was reached at the end of irradiation cycle 2004-09, with a total of 16 irradiation cycles and 388.30 accumulated full power days. The total calculated burnup for the RECH-1 test fuel was approximately 65,75% ^{235}U. The irradiation was successful and no deviations from the initial values were observed during the periodic coolant gap measurements and visual inspections.

The periodic coolant gap measurements showed no indications of swelling, blistering or other irradiation or temperature induced mechanisms for the RECH-1 fuel.

Current HFR monitoring during RECH-1 fuel irradiation has shown that either fuels or fission products were not released to the reactor coolant

With regard to the PIE, the visual inspections revealed the usual light grey oxide layer surface over the exposed surfaces. It also shown that the fuel assembly has been resistant to local or general deterioration by normal corrosion and has been sufficiently rigid to withstand the mechanical and hydraulic forces associated with normal handling and irradiation in the HFR core. The fuel assembly was not deformed due to swelling, differential thermal expansion, hydraulic forces, etc.

The gamma scanning analysis showed a relatively normal distribution of fission products along the fuel meat. The spectrum in figure 7 (b) and (c) have a discontinuity (lower counts) due to an aluminum clamp and fix screw. In general, the current PIE results shown an excellent performance until the final burning level for the entire test fuel.

5. Conclusions

The final conclusion is that the irradiation test was successful and no deviations from the initial values and specifications for the fuel element were observed. This irradiation test fuel element at the HFR in Petten qualifies CCHEN as a LEU silicide fuel producer.

6. Acknowledgments

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