CURRENT STATUS OF U_3Si_2 FUEL ELEMENT FABRICATION IN BRAZIL

M. Durazzo, E.F. Urano de Carvalho, A.M. Saliba-Silva, J.A.B Souza

Centro do Combustível Nuclear
Instituto de Pesquisas Energéticas e Nucleares, IPEN – CNEN/SP
Av. Prof. Lineu Prestes, 2242 – Cidade Universitária – CEP 05508-000, São Paulo – SP – Brasil

and

H.G. Riella

Departamento de Engenharia Química
Universidade Federal de Santa Catarina, Florianópolis, Santa Catarina – SC – Brasil

ABSTRACT

IPEN has been working for increasing radioisotope production in order to supply the expanding demand for radiopharmaceutical medicines requested by the Brazilian welfare. To reach this objective, the IEA-R1 research reactor power capacity was recently increased from 2 MW to 4 MW. Since 1988 IPEN has been manufacturing its own fuel element, initially based on U_3O_8-Al dispersion fuel plates with 2.3 gU/cm^3. To support the reactor power increase, higher uranium density in the fuel plate meat had to be achieved for better irradiation flux and also to minimize the irradiated fuel elements to be stored. Uranium silicide was the chosen option and the fuel fabrication development started with the support of the IAEA BRA/4/047 Technical Cooperation Project. This paper describes the results of this program and the current status of silicide fuel fabrication and its qualification.

1. Introduction

The use of radioisotopes in medicine is certainly one of the most important social uses of nuclear energy and IPEN/CNEN-SP has a special place on the history of nuclear medicine in Brazil. Due to the federal monopoly, only the Institutes that belong to CNEN (Comissão Nacional de Energia Nuclear) can produce radioisotopes and radiopharmaceuticals for use in nuclear medicine. The production of IPEN represents nearly 98% of the total demand.

There has been a significant increase in the demand of radioisotopes over the years. Between 2002 and 2004 the increase in the demand was about 30%. Distributed to Brazilian hospitals and clinics, radiopharmaceutical products were used, in 2006, to attend more than 3 million patients, an increase of about 10% relative to the year before. To face this scenario, IPEN has been increasing continuously its production of radiopharmaceutical medicines to come along with the expanding demand imposed by the Brazilian welfare. One of the most important project aims at own production of Mo-99 in order to provide cheaper Tc-99 generators than the ones produced from imported raw materials. So, this medicine will be accessible to a bigger amount of patients. To reach the objective of this project, IPEN for years has been working on upgrading the IEA-R1 research reactor to increase its power (from 2 to 5 MW) and its operational time (from 64 to 120 hours by week). The reactor control board and ventilation system were upgraded and additional safety items were incorporated. Besides, CNEN is planning to build a new facility in order to expand and spread the use of radiopharmaceutical medicines all over the country.

Once the reactor power was planned to be raised from 2 to 5 MW, in 1997 IPEN started research activities aiming at the elevation of the uranium loading inside the fuel, in order to allow the reactor power increase. This was accomplished with the development of the silicide technology, which has been done under support of the IAEA. The Technical Cooperation Project BRA/4/047 "Fuel Improvement for the IPEN Research Reactor" was the objective to develop high-density fuel to improve the efficiency and applicability of the IPEN reactor. Until this time, fourteen silicide fuel elements ($3.0gU/cm^3$) had been irradiated at the IEA-R1 research reactor. The irradiation was closely followed by visual inspections and sipping tests. After 40% burn up (average), no problems regarding to fuel performance was recorded. The enriched U_3Si_2 powder was imported from the international market until 2002, when IPEN started the development of the conversion technology to get de U_3Si_2 powder using national enriched UF_6 produced by CTMSP (Marine Technological Center in São Paulo). Nowadays, IPEN is able to fabricate the enriched U_3Si_2 powder, allowing the nationalization of all the fabrication cycle of dispersion fuel for research reactors. After mining and enrichment steps, IPEN is able to execute all the other fabrication steps. Recently, on 2007 June 26, the first fuel element fabricated with national materials and technology was put in operation at IEA-R1 reactor core. This work describes the journey of IPEN heading on to acquire uranium silicide technology.

2. Historical Background

The beginning of the development of the fuel element fabrication technology in IPEN is very old. The work started in 1960 aiming at fabrication of the fuel for the ARGONAUTA research reactor. Between 1964 and 1965 the fuel elements were manufactured with 20% enriched U_3O_8 powder provided by IAEA in the program Atoms for Peace. In spite of the low technological demand of the ARGONAUTA fuel (very low power), a seed was planted and would come to germinate 20 years later, in the decade of 80, and to bloom definitively in the decade of 90, when IPEN dominated the fabrication technology and began the production of the fuel for the IEA-R1 research reactor. The relative high power (2 MW) demanded a significant technological progress in the fabrication techniques.

Starting from 1980, IPEN intensified their efforts to develop the fabrication technology of dispersion fuel element, aiming at improving the technology for manufacturing fuels more advanced, substantially superior to the old ARGONAUTA fuel type. In that time, IPEN could not acquire fuel elements from the international market in order to supply the IEA-R1 research reactor. The growing difficulty to get fuel elements in the international market acted as an initial impelling force for IPEN to deflagrate their program for fuel element fabrication. The technology previously developed in the 60's was updated starting from 1985, with base in the recent technological advances in the area. Between 1985 and 1988, IPEN worked in assembling a small fuel fabrication facility as a laboratory level, with capacity to produce 6 fuel elements by year. This was enough to supply the IEA-R1 reactor operating at 2 MW and 40 hours a week.

On 1988 August 31, as part of the commemorations of their 32^o anniversary, IPEN provided the IEA-R1 reactor with the first fuel element fabricated in Brazil, only fifteen days before the exhaustion of the reactor fuel. The fissile material used was the same U_3O_8 powder previously used for the production of the ARGONAUTA fuel. There was a reserve of about 30kg of this material. Starting from 1988, after the production of the first fuel element, IPEN began a continuous production of fuel element, which continues until nowadays.

After the production of 26 fuel element, the enriched U_3O_8 powder finished in 1996. So, in 1994 IPEN started developing the processes for UF_6 conversion to U_3O_8 and for recovering the

uranium scraps generated in fuel plate fabrication. In 1996, IPEN did the conversion of about 20kg of imported enriched UF_6. IPEN was then prepared for the routine production of fuel elements starting from UF_6 as raw material. In 1997, IPEN raised the fuel production capacity from 6 annual fuel elements to 10, which was the maximum considering the infrastructure available.

As mentioned before, in order to increase the radioisotope production of IPEN, the IEA-R1 reactor power capacity was increased from 2 MW to 5 MW. In 1997, the development of a new higher uranium density fuel started, in order to attend the reactivity needs for continuous operation, to have a compact core for better irradiation flux and also to have a low number of irradiated fuel elements to be stored at the spent fuel pool. The new fuel was based on the U_3Si_2-Al dispersion with uranium loading of 3.0 gU/cm^3. In 1998, the fuel plate fabrication technology of the new silicide fuel was implanted. At that time, U_3Si_2 powder was imported from France. Between 1999 and 2000 sixteen silicide fuel elements were manufactured. Starting from 1998, the efforts to develop the U_3Si_2 powder production technology began, aiming at the nationalization of all the production process, starting from enriched UF_6 leading to the conversion to UF_4; its reduction to metallic uranium; U_3Si_2 powder fabrication and, finally, arriving at the fuel plate fabrication and fuel element and assembly. At this time, IPEN participated in an international cooperation through IAEA under the Technical Cooperation Project TC BRA/4/047.

With the help of IAEA, in 1999 IPEN get the technology for UF_4 production using $SnCl_2$ as reducing agent. In the area of metallic uranium, IPEN was a valuable previous experience in producing 150kg natural uranium ingots in 90's. Based on that experience, IPEN initiates efforts aiming at scaling down the size of the metallic uranium pieces, trying to produce pieces of about 3kg using 20% enriched material as raw material for the U_3Si_2 production. In 2002, the process for producing metallic uranium was dominated, which allowed the development of the U_3Si_2 intermetallic. In 2004, IPEN obtained the first lot of natural U_3Si_2 powder, manufactured with national technology, dominating then the "uranium silicide cycle". In 2006, IPEN consolidated the fabrication technology of the silicide fuel by manufacturing the first fuel element with fully national technology. This fuel element was put in the IEA-R1 reactor core this year, on June 26. Now, efforts have been made to produce and qualify high loaded fuel elements with 4.8 gU/cm^3.

Due to the emergent increase in radiopharmaceuticals demand and the consequent increase in the IEA-R1 power, the reactor needed an increase of fuel, from 6 (U_3O_8-Al) to 18 elements (U_3Si_2-Al) a year. In addition, a new reactor for radioisotope production was cogitated to be constructed in the Northeast region of Brazil. This decision would be very significant in near future, since IEA-R1 reactor is quite aged (50 years) and this reactor is practically the only one producer of radioisotope in the country. The new reactor (probably 20 MW) would consume about 30 annual U_3Si_2-Al fuel elements. Therefore, a demand for about 50 annual fuel elements seems to be quite realistic.

Based on this forecast demand for fuel elements and the increasing need for fuel element production to supply IEA-R1 reactor in the near future, IPEN began a project in 2001 seeking to adapt the production facilities seeking on improving the producing capacity. This project is nowadays under way aiming at replacing the current facilities by a fully new one, but with a researching laboratorial style. The new facility is planned to have nominal capacity for producing 30 fuel elements in yearly basis. That will attend wholly the fuel element demand in a short period. The producing capacity of the new facility should reach 80 annual fuel elements,

which would supply also the new research reactor planned to be constructed. The conclusion of this project is foreseen for 2008-2009.

Looking at the future, in 2001, IPEN started working with the U-Mo fuel in contribution to RERTR program for developing high uranium loaded fuels. This fuel could eventually substitute with advantages the U_3Si_2 fuel. Nowadays this work is on course [1] and was also supported by the IAEA TC BRA/4/053 “Development of Alternative High-Density Fuel Based on Uranium-Molybdenum Alloys”.

The production increased of fuel element will generate larger amount of waste (liquid, solids and gaseous) and pollutant, which has to be handled adequately. The higher fabrication scale of the new installation arise technical difficulties related to upgrading uranium recovery procedures and effluent treatment and waste disposal. As the facilities for fuel plates production are adequate to stand up the new production level, the main modifications and adjustments must be performed in the chemical processes for uranium recovery from scrap and for treatment on liquid waste and gaseous or aerosol-type pollutants, generated in fabrication plant. To face this new challenge, IPEN rely on the international skill in these subjects with support of the IAEA TC BRA/3/012 “Nuclear Fuel for Research Reactors: Improving Fabrication and Performance Evaluation in Brazil”.

3. Silicide Fuel Development

The IEA-R1 Reactor of IPEN/CNEN-SP is a pool type reactor operating since 1957. This reactor uses MTR type dispersion fuel element in a 5 X 5 core arrangement. The Nuclear Fuel Center of IPEN is responsible for the production of the necessary nuclear fuel to keep the continuous operation of the reactor. Development of new fuel technologies is also a permanent concern. The Nuclear Fuel Center had produced 77 fuel elements until now, including 14 control fuel elements.

The fuel meat is fabricated according to conventional powder metallurgy techniques. The fuel element contains 18 fuel plates, each one 1.52 mm thick. Cladding and frame plates are made with the ASTM 6061 aluminum alloy. The fuel assembly is performed by a well-known picture-frame technique. The fuel element results from mechanical assembling of 18 fuel plates and other structural components. Figure 1 shows the details of the plate fabrication and fuel element geometry.

As, in Brazil, we have not available hot cell laboratories to test irradiated fuels and as the irradiation tests abroad would be very expensive, IPEN decided to risk the testing and evaluating in pile for its own fuel, checking the performance under reactor operation. This was possible since IPEN fuel specification is conservative for dispersion fuel and the power of reactor is low. A program for fuel qualification was started with irradiation of some miniplates at the border of the reactor core just to identify any abnormal event. In July 1985 a partial fuel element with only two fuel plates (the external plates) and 16 aluminum plates was placed in the core to start fuel qualification. After this, other partial fuel element with 10 fuel plates and 8 aluminum plates was also placed in the core (November 1985). These two fuel element were identified as the precursor fuels. A periodic monitoring and evaluation was done upon them. After good results with these precursor fuels, it was decided to start loading standard fuel elements in the reactor core (August 1988), with 1.9 gU/cm^3 U_3O_8-Al. The adopted criteria was that each IPEN fuel element had to start irradiation at peripheral positions of the core, with lower power densities, up to 4 % burnup (almost one year of irradiation) and then it could go to higher power density

positions in the core. It was decided that the precursor fuels had to stay in the core up to the same time that a complete fuel element would stay. The last precursor fuel assembly was taken out of the reactor core without any operational problems. Previous paper presented details about the fuel qualification program [2]. To qualify the U_3Si_2-Al fuel the same strategy was adopted. In this case, the volume fraction of the fissile material in the dispersion was kept the same, around 27 %, resulting in an uranium loading of 3.0 gU/cm^3.

The program for silicide fuel development at IPEN had great impulse after the approval of the IAEA TC BRA/4/047 "Fuel Improvement for the IPEN Research Reactor" in 1999. The primary purpose of this program was to develop the whole fabrication process of U_3Si_2-Al dispersion fuel plate (including 4.8 gU/cm^3), its irradiation test at the IEA-R1 reactor and post-irradiation analysis. This project proposal would give the necessary background to IPEN to produce and qualify its own U_3Si_2 powder and silicide based dispersion fuel plates for the IEA-R1 fuel element fabrication. The project steps to achieve the objectives included the following steps:

a) to develop the process for producing UF_4 starting from UF_6;
b) to develop the process for producing metallic uranium starting from UF_4;
c) to develop the process for producing U_3Si_2 powder;
d) to produce miniplates with 20% enrichment for irradiation tests;
e) to irradiate miniplates at the IEA-Rl reactor and to perform non-destructive analysis on the irradiated fuel miniplates inside the spent fuel pool.

Figure 2 shows a flow-sheet of the main project activities. More information of the project activities and results are available in the Project Progress Reports [3,4,5].

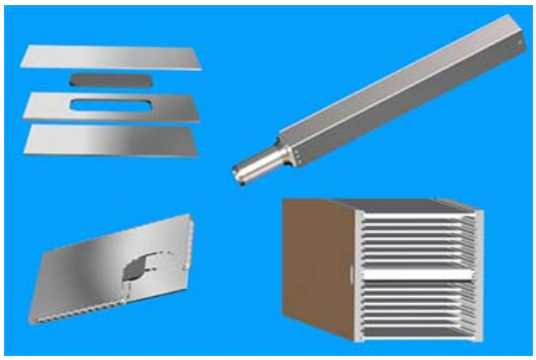

Figure 1 – Fuel Element Fabricated at IPEN.

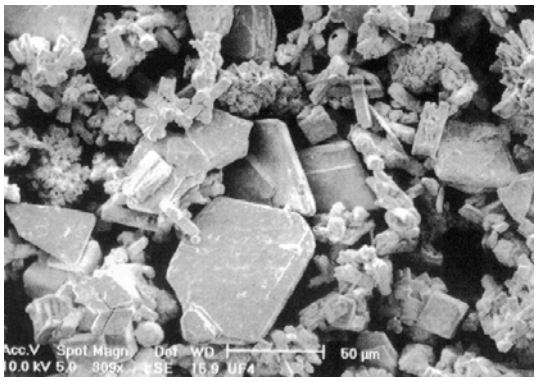

Figure 3 – UF_4 crystals (SEM micrography).

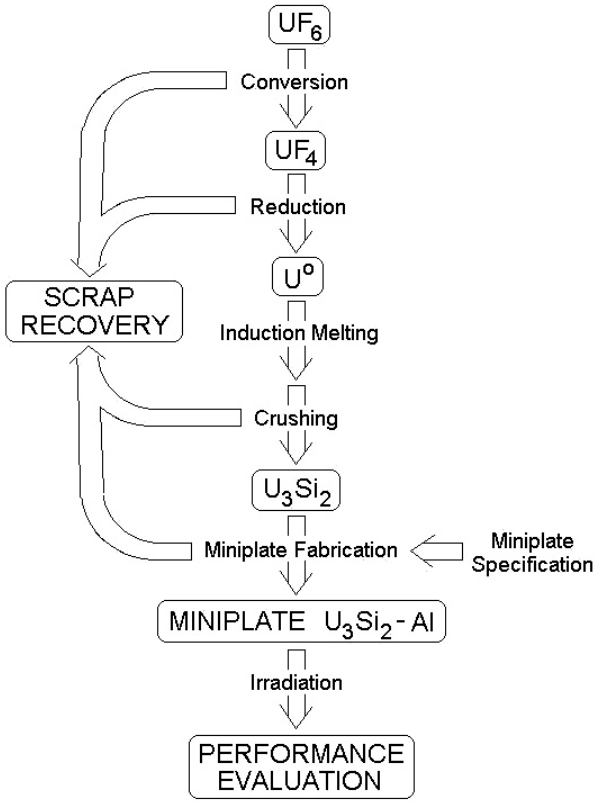

Figure 2 – Main BRA/4/047 Project activities.

UF_6 Conversion Towards UF_4

Essentially, the process to get UF_4 from UF_6 uses the reduction of hexavalent uranium present in aqueous solution to the tetravalent state and its precipitation as UF_4 by means of the HF solution. The preparation of UF_4 using chemical reduction has been carried out starting from UO_2F_2 solution resulting from UF_6 hydrolysis. The solution is heated under continuous stirring to reach a temperature set point and then the reducing agent added. Next, the hydrofluoric acid HF precipitating agent solution is slowly added. Tests have been carried out using different reducing agents, such: $SnCl_2$, CuCl, $FeCl_2$, and $Na_2S_2O_4$. The reducing agent $SnCl_2$ was the one that showed the best results and achieved a level of UF_4 precipitation in the range of 98%. However, during the UF_4 preparation an amount of water is absorbed by the UF_4 crystal. This water could interfere in the other process steps, and to avoid problems it must be removed.

The elimination of crystallization water from the UF_4 is carried out in temperatures near 400ºC, under a constant flow of argon over the surface of the powder, which avoid the UF_4 oxidation to UO_2F_2 or UO_2 and drag the water vapor released. The material, in a powder form, is placed in a small Monel boat and introduced inside the heating chamber. After purging with argon for 1 hour the system is heated to 400^{o}C under flow of gas. The UF_4 powder remains in this temperature for 1 hour, which is a sufficient time to complete the water elimination. The subsequent cooling is carried out keeping the flow of argon till the temperature reaches 100^{o}C. Details of the UF_4 precipitation procedures were presented in a previous work [6]. In Figure 3, it is presented a typical representation of the UF_4 morphology.

UF_4 Reduction to Metallic Uranium

The intermetallic U_3Si_2 is produced from metallic uranium. To produce metallic uranium in the required quantity (up 80 kg/year) IPEN has developed a process to produce small quantities of uranium (1000g) through magnesiothermic routine. The 1000g ingot of metallic uranium is rather small if compared to previous practice of IPEN. In 1980's, ingots of natural uranium ranged up to 100kg. The downscaling was difficult, since not only the reduced scale for the crucible was conceived, but also lower material amount to be reduced implied in difficulties to get reasonable metallic yields. The crucible itself has been planned several times to achieve the final format using a bottom extractable system to help removing the cast ingot from the crucible. The thermal profile of the furnace has already been achieved by experimentation and calculations, but to reach optimized yields it was necessary to identify the exact moment of the reaction. It was got by means of an accelerometer in order to recognize the sound waves perturbation during the reaction moment.

Optimization of this method was met only after 25 experiments with natural uranium simulations in the last 3 years. Once settled down this technology, IPEN started to produce the 20% LEU enriched uranium. The yield of this system is around 82-85% of metallic uranium. The thermal cycle used nowadays is indicated in the diagram of figure 4. The enriched material was already produced with good operation and quality results. Figure 5 shows the enriched ingots produced by our IPEN methodology.

U_3Si_2 Fusion and Powder Fabrication

Since 2000, the Nuclear Fuel Center of IPEN has been dedicating great efforts to achieve expertise in production of intermetallic alloy U_3Si_2. After facing some difficulties, as reported previously [7], in 2004 IPEN has arrived to the full experimental route to produce, in production

scale, the necessary alloy for nuclear fuel.

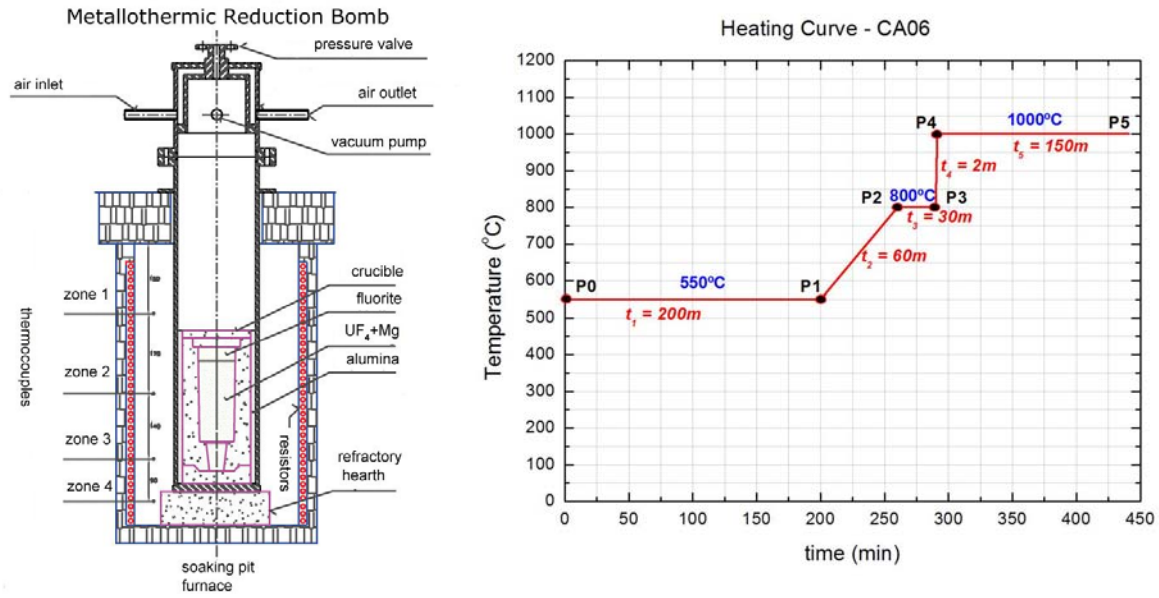

Figure 4 – Magnesiothermic bomb for metallic uranium reduction and reaction thermal cycle.

From the produced uranium ingot, the metal was melted inside an induction furnace with silicon addition, with an adequate vacuum instrumentation and facilities for handling and melting uranium and uranium alloys. The zirconia crucible was specially designed to reach temperatures higher than 1750°C and to support the aggressive environment created by uranium chemical attack. The load arrangement inside the crucible was studied to help the sequence of melting in the several stages of that molten alloy, before reaching the final intermetallic composition, as shown in figure 6. More than 20 trials were carried out, using natural uranium, before the first LEU U_3Si_2 were successfully made. It was produced 3 enriched U_3Si_2 melting in 2005, which consisted the first own produced load of fuel plate fabrication in IPEN. In general terms, the quality of this intermetallic has fully met the needs postulated by the requirements for a routine nuclear material. The X-ray difractogram (figure 7) attests the presence of the expected phases in the produced powder of this alloy.

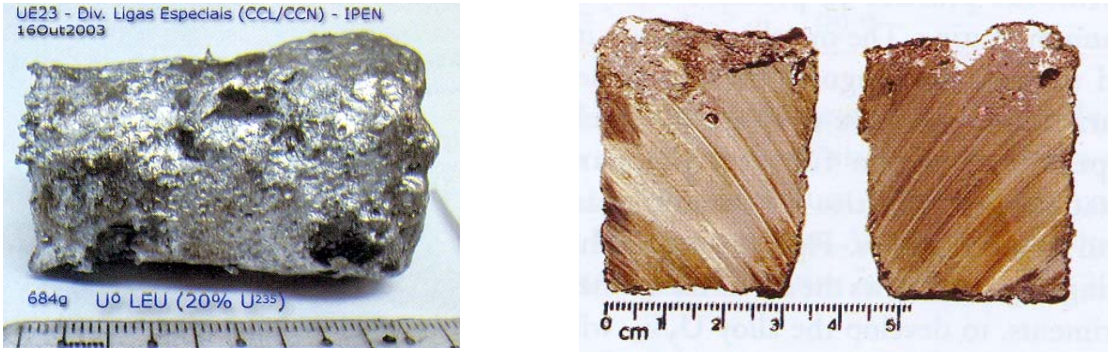

Figure 5 – IPEN enriched metallic uranium pieces.

Miniplate Fabrication

As previously mentioned, IPEN started manufacturing its own fuel element by using U_3O_8-Al dispersion fuel plates with 1.9 gU/cm^3. This uranium loading represents a U_3O_8 volume

fraction of 27 %. If this same volume fraction is used, the direct substitution of the U_3O_8 by U_3Si_2 would result in an increasing of uranium loading to 3.0 gU/cm^3.

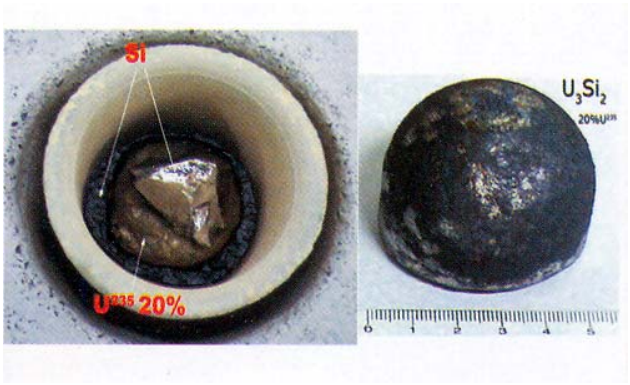

Figure 6 – Assembling of U_3Si_2 crucible load before melting and the resulting ingot after induction melting.

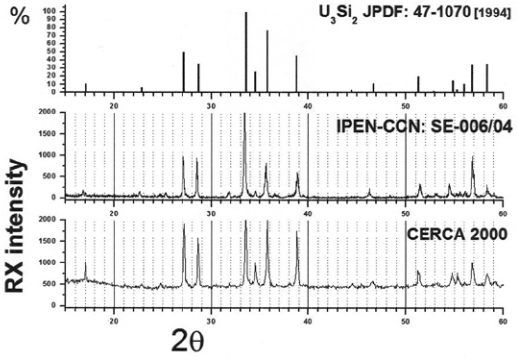

Figure 7 – X-ray Difractogram showing the U_3Si_2 produced by IPEN contrasted to the already used imported powder (CERCA).

The increasing of U_3Si_2 volume fraction in the dispersion has a technological limit of 45 %, in order to allow fabrication of fuel plates. This means maximum uranium loading of 4.8 gU/cm^3. This is the objective to be reached in the future. The increase in the volume fraction of both U_3O_8 and U_3Si_2 to 45 % implies in implementing modifications in the fabrication procedures in contrast to the currently adopted ones for LEU fuel. The necessary research work to adequate the fabrication procedures have been done under the IAEA TC BRA/4/047. It was fabricated 22 miniplates with approximately 120 mm length and 42 mm width fuel meats. The compacts were 20 X 40 mm. Aluminum alloy 6061 was used for the frames and covers in fuel plate assemblies. The hot rolling temperature was 440°C. The fuel plates were fabricated by hot and cold rolling according to the pass plan presented in table 1. The cladding thickness over the defect zones (dog-boning) was 0.28 mm (specification states a minimum of 0.25 mm). All the fabricated miniplates showed good metallurgical bonding. In the first fabrication tests it could be observed some oxidation of U_3Si_2 particles located near the interface core/cladding. The volume fraction of the oxidized phase was quantified by means of image analysis and the results indicated that a volume fraction between 2 and 4 % of the U_3Si_2 particles has been oxidized. The presence of the measured volume fraction of this oxide phase, within the fuel core, was considered to be no deleterious to the fuel performance during irradiation. However, the study the oxidation phenomenon was carried out to eliminate or minimize the oxide formation during the fabrication. The cause was determined to be the welding procedure. A modification in the welding device was done to minimize the air entrapment in the weld assembly. This was possible with the use of a glove-box with argon atmosphere. The oxidation problem was no more observed ever since. Figure 8 shows a radiography taken from the miniplates fabricated with 4.8 gU/cm^3 U_3Si_2-Al dispersion. Figure 9 shows a radiography illustration with the final dimensions of the miniplate.

Miniplate Irradiation at IEA-R1 Research Reactor

The irradiation device was planned to be placed at the IEA-R1 core support plate. Its overall dimensions were similar to the fuel assembly dimensions. It was projected to contain miniplates for irradiation and also to allow their removal for post-irradiation NDT to be performed at the spent fuel pool. The project assumed the possibility to irradiate up to 10 fuel miniplates at once. It was designed an internal support for the miniplates, which could be assembled inside the irradiation box. Figure 10 illustrates the irradiation device components (miniplates; miniplate support, irradiation box).

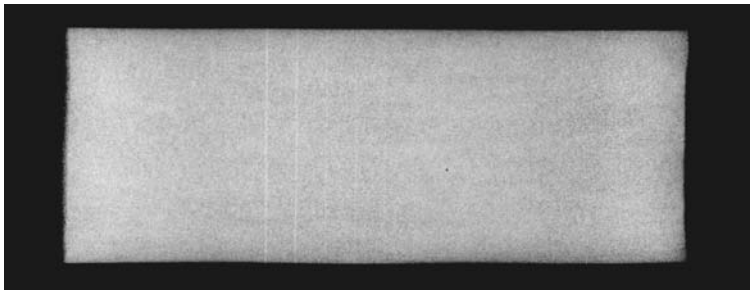

Figure 8 - X-ray radiograph taken from U_3Si_2-Al fuel meat (4.8 gU/cm^3).

Figure 9 - X-ray radiograph taken from a finished miniplate.

Table 1 – Typical pass plan adopted for rolling the miniplates.

Hot-Rolling		
Pass Number	**Plate Thickness** (mm)	**Reduction in Thickness** (%)
Start	9.14	
1	7.17	21.5
2	5.39	24.8
3	4.62	14.3
4	3.93	14.9
5	3.31	15.8
6	2.79	15.7
7	2.37	15.1
8	2.01	15.2
9	1.70	15.4
Cold-Rolling		
10	1.52	10.6

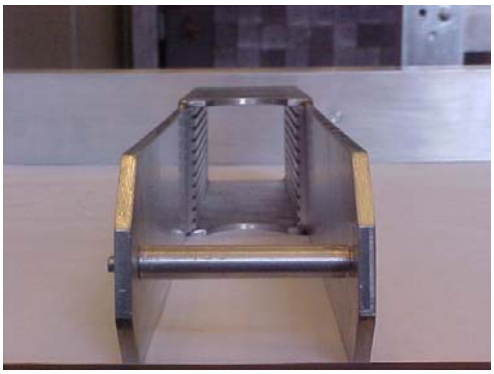

Figure 10 – Irradiation device components: irradiation box, miniplates and miniplate support.

The post irradiation examination includes miniplate thickness measurement, visual inspection and sipping. The fuel miniplate thickness measurement device will be used inside the reactor pool, in the spent fuel storage area. It will be operated from the reactor pool border and will be able to measure the fuel miniplate thickness variation along its surface. This device is based on a mechanical structure for positioning the miniplate and to perform the scanning along the miniplate surface. The thickness measurement will be performed by electronic probes (LVDT probes). The results are obtained by measurement instrumentation connected to the probes and the data are stored and processed by a laptop computer. Figure 11 shows the support structure and close-ups of the miniplate thickness measuring system.

4. Conclusion

The developments involving fuel fabrication was satisfactorily completed. The next step is to fabricate full sized U_3Si_2-Al fuel plates with 4.8 gU/cm^3. This work was already started. The experimental activities using the reactor have to be defined in written documents. Operational procedures was already written and analyzed by the reactor operational staff. The beginning of irradiation is waiting for a final approval of the Reactor Safety Review Committee for the experiment.

Figure 11 – Thickness measurement device: support and miniplate measurement system.

Acknowledgements

We want to express our gratitude to IAEA for the continuous support received along the years in developing the fuel fabrication in IPEN. This support certainly did the difference for the success of the fuel development program and helps us to follow the advances in the fuel technology.

5. References

[1] F.B.V. Oliveira, M. Durazzo, E.U.F. Carvalho, A.M. Saliba Silva , H.G. Riella, "Powder Formation of γ-UMo Alloys Via Hidration-Dehydration". 2007 RERTR Meeting.

[2] J.A. Perrota, A.M. Neto, M. Durazzo, J.A.B. Souza, R. Frajndlich, "Irradiation Experience of IPEN Fuel at IEA-R1 Research Reactor". Proceedings of the XXI International Meeting on Reduced Enrichment for Research and Test Reactors, São Paulo, Brazil, 18-23 October 1998.

[3] M. Durazzo, J.A. Perrota, "Fuel Improvement for the IPEN Research Reactor". Semiannual Progress Report January-June 1999. IAEA Project Number BRA/4/047. IPEN, São Paulo, 1999.

[4] M. Durazzo, J.A. Perrota, "Fuel Improvement for the IPEN Research Reactor". Semiannual Progress Report July-December 1999. IAEA Project Number BRA/4/047. IPEN, São Paulo, 1999.

[5] M. Durazzo, J.A. Perrota, "Fuel Improvement for the IPEN Research Reactor". Semiannual Progress Report January-June 2000. IAEA Project Number BRA/4/047. IPEN, São Paulo, 2000.

[6] E.U.C. Frajndlich, A.M. Saliba Silva, M.A Zorzetto, "Alternative Route For UF_6 Conversion Towards UF_4 to Produce metallic Uranium". Proceedings of the XXI International Meeting on Reduced Enrichment for Research and Test Reactors, São Paulo, Brazil, 18-23 October 1998.

[7] A.M. Saliba Silva, J.A.B. Souza, E.U.C. Frajndlich, J.A. Perrota, M. Durazzo, "First Results of U_3Si_2 Production and its Relevance in the Power Scale-up of IPEN Research Reactor IEA-R1m". Proceedings of the XX International Meeting on Reduced Enrichment for Research and Test Reactors, Jackson Hole, Wyoming, 5-10 October 1997.