

# Development of Remote Equipment for a DUPIC Fuel Fabrication at KAERI

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## Abstract

The DUPIC (Direct Use of spent PWR fuel in CANDU reactors) technology is to directly refabricate CANDU fuel from spent PWR fuel without any separation of the fissile materials and fission products. Thus, the DUPIC fuel material always remains in a highly radioactive state, which requires a remote fuel fabrication in a hot-cell. About 25 pieces of remote equipment including auxiliary systems such as a hot-cell shield plug were developed and installed in a hot cell. In order to supply a high electric current to a sintering furnace in-cell from an outside cell, a shield plug was developed. It consists of three components – a steel shield plug with an embedded spiral cooling line, stepped copper bus bars, and a shielding lead block. Experiments to evaluate the performance of the sintering furnace with the developed shield plug were carried out. It was concluded that, from the experimental results, the newly developed hot-cell shield plug satisfied all the requirements for a remote operation on a sintering furnace. DUPIC fuel pellets and elements were successfully fabricated with the developed remote equipment.

**KEYWORDS:** Remote equipment, Hot-cell facility, Shield plug, DUPIC fuel fabrication

## 1. Introduction

The DUPIC (Direct Use of spent PWR fuel in CANDU Reactors) concept was first proposed in a joint research program among KAERI, AECL and US DOS in 1991 [1,2]. The DUPIC technology, as its name implies, is to directly refabricate CANDU fuel from spent PWR fuel without any separation of the fissile materials and fission products. Thus, the DUPIC fuel material always remains in a highly radioactive state, which provides good proliferation resistant characteristics and great challenges for remotely fabricating a fuel. Although the overall process of fabricating a DUPIC fuel is almost the same as that of fabricating CANDU fuel using natural uranium, there are fundamental differences between them as follows;

- The DUPIC fuel material contains not only uranium but also all the actinides and fission products.
- The DUPIC fuel fabrication process should be remotely performed in a hot cell because of its high radioactivity.

In order to remotely fabricate a DUPIC fuel, it is required to use a shielded facility, so called, a hot cell, for a protection from a high radioactivity and to develop process equipment for a remote fabrication of fuel products. Among the DUPIC fuel fabrication processes is a sintering process in which green pellets are heated at a high temperature in a reduction atmosphere to obtain highly densified pellets. The furnace to be used in the sintering process was specially designed to allow a remote operation and maintenance with master-slave manipulators [3]. The existing penetration holes and solid steel shield plugs installed in the hot-cell facility were not able to transmit a high electric current because of their geometric limitations. No modifications on the cell wall itself, except for the shield plug are permitted. Therefore, it seemed clear that new techniques for a high current transmission through the cell wall should be developed to supply enough power to the sintering furnace and optimize its performance, and emphasis should also be on the shielding of a hot-cell facility.

## 2. Shielded Facility

Part of the existing hot cell facilities, that is, Irradiated Material Examination Facility (IMEF) at KAERI, were used for a DUPIC fuel fabrication (figure 1). The hot cell used for the main fabrication campaign of the DUPIC fuel was the IMEF M6 hot cell, called DFDF (DUPIC Fuel Development Facility), which is a 2 m deep, 23 m long, 1.1 m wide concrete shielding wall with 10 working windows. This M6 cell was divided into two parts. The M6a cell was used for the fuel powder and pellet fabrication and the M6b cell for the fuel element and bundle.

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However, at first, as the hot cell facilities were built for a general purpose for a post irradiation examination, some refurbishment such as a modification of the rear door for a padirac system and a supply of electric power was performed [4]. About 25 pieces of equipment for the remote fabrication of the DUPIC fuel element were developed and installed in the hot cell as shown in figure 2. As long as commercial equipment was available, it was purchased and modified for a hot cell use from the viewpoint of an easy remote operation and maintenance. The equipment was designed to be modular and remotely operable by using a master-slave manipulator. The mechanical parts of the equipment were located inside the hot cell, while the electronic parts were separated to be installed outside the hot cell for a minimal degradation of the performance of the equipment due to radioactivity.

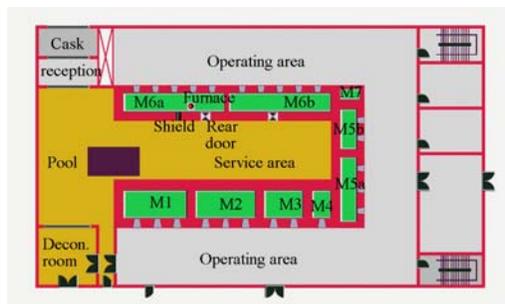


Fig.1 Layout of IMEF

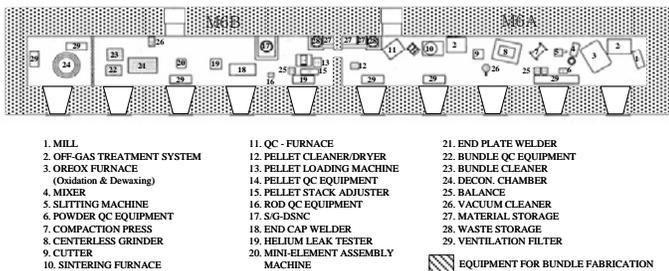


Fig. 2 In-cell arrangements of the remote process equipment

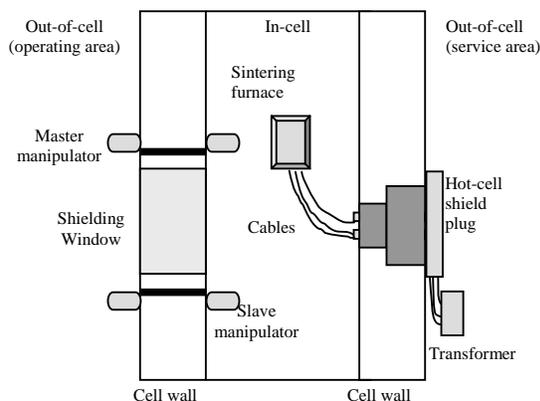
### 3. Remote Process Equipment

For the main fabrication campaign at the DDFD, 25 pieces of equipment for the fabrication of DUPIC pellets and elements were developed and installed in a hot cell in late 1999. From 1995 to 1996 the development of the design requirements and the conceptual design for the DUPIC fuel fabrication equipment were conducted in cooperation with AECL (Atomic Energy of Canada Limited) and ORNL (Oak Ridge National Laboratories) which have lots of experience in remote handling technology. Based on the results of the joint study, a detailed design and manufacture of the equipment were carried out according to the equipment development plan. And two off-gas treatment systems, one for the OREOX (Oxidation and REDuction of OXide fuel) furnace and the other for the sintering furnace, were manufactured. The off-gas treatment system consists of several trapping units, a heat exchanger and filter units. The piping and layout arrangements were formulated by considering a remote accessibility. The developed equipment was tested for all their function performances and moved to the mock-up cell to evaluate their remote operability. Considering the remote operation and maintenance in a hot cell, the operation procedures were set up and tested by using the manipulators in the mock-up cell. The troubles found during this test were fixed for an easy operation in a hot cell. After checking the remote operability, the equipment was installed in the DDFD with the necessary auxiliary systems such as a cooling water line, a reaction gas piping line and maintenance tools, etc.. After completing the installation of the equipment in the DDFD, a cold-test was carried out by using unirradiated natural UO<sub>2</sub> powders and the process parameters established during the development experiments for the DUPIC fuel fabrication process. The cold-test run was successful, and showed that the installed equipment was acceptable [5]. Based on these results, a DUPIC fuel pellet and element were fabricated by using spent PWR fuel materials.

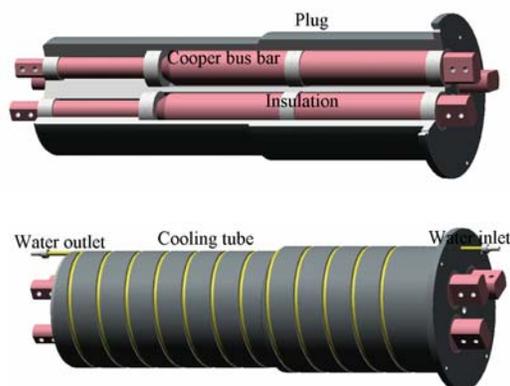
### 4. Shield Plug for Electric Current Transmission

There is a shield plug built in the back wall of the M6a cell. The original shield plug made of steel is in the shape of a cylindrical solid bar with a step at its middle. A new shield plug was designed and constructed for transmitting high a electric power supply to the in-cell. Figure 3 shows the concept of the M6a cell with the shield plug for transmitting a high electric current. Direct human access to the in-cell is limited because of the high radioactivity of spent nuclear fuel in a hot cell. The operator at the operating area controls, via the master manipulator, the slave manipulator located in-cell and performs specified tasks such as operating and maintaining the equipment. The shielding window provides the operator with visual information. In order to run the sintering furnace in a hot cell, a secondary current of about 1,000 amps is generated from the transformer located out-of-cell and flows to the furnace through copper bus bars. The shield plug has three subsystems – a steel shield plug, stepped copper bus bars, and a shielding lead block. Figure 4 shows the graphical diagram of the shield plug with three copper bus bars embedded. The shield plug was designed as

a means of carrying the power connection leads into the cell. To improve the shielding ability, the plug body was designed to be machined from solid steel with a high density. It also has three long holes inside it for a passage of the copper bus bars. The solid copper bus bars were designed to have a large diameter in order to reduce the excess heat due to the flow of a high electric current. In addition to the large diameter of the bus bar, a water-cooling system was adopted to remove the excess heat generated from the copper bus bars. The gap between the plug and the bus bars was designed to be as small as possible because the secondary maximum voltage supplied from the transformer is low at about 9 volts.



**Fig. 3** Concept of the hot-cell shielding system

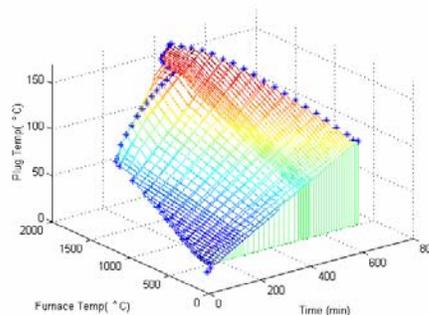


**Fig. 4** The shield plug for a high current transmission

As insulation between the plug and the bus bars, ceramic sleeves were used because of the high level of radiation hardening up to  $10^{10}$  rads. A shielding lead block located out-of-cell was designed to reinforce the shielding ability. The enclosure of this block is of a cylindrical geometry, and the lead is incased in stainless steel. During a sintering process of the DUPIC pellets, the furnace normally runs for over 20 hours. High electric current should be supplied in order to raise the furnace temperature to over  $1700^{\circ}\text{C}$  and to keep such a temperature for about 10 hours. Concerns are given to the temperature rise of the steel shield plug due to the heat generated by the copper bus bars. The excessive heat transfered to the shield plug may cause a degradation of its integrity and damage to the hot-cell wall, thereby resulting in considerable shielding problems for the hot-cell facilities. An experiment was carried out to investigate the effects of a high electric current flow on the hot-cell shield plug developed before it was put into service. The experimental setup at the inactive M6a in-cell is illustrated in figure 5. All the electric cables were connected to the furnace through the copper bus bars. The furnace was run over 10 hours under the same conditions for the pellet sintering process. As designated by points 1, 2, 3, and 4 in figure 5, four thermocouple sensors were mounted on the outer surfaces of the shield plug to measure its surface temperatures. Figure 6 shows the measured temperatures at point 3, which had the highest temperature distribution of the four points.

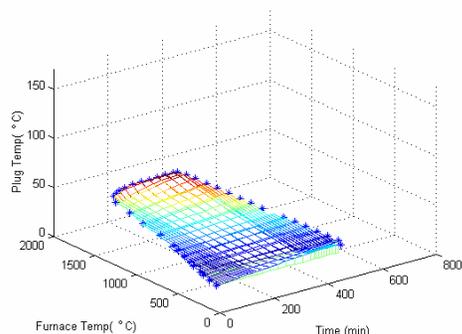


**Fig. 5** The experimental setup for a temperature measurement at the inactive M6a cell

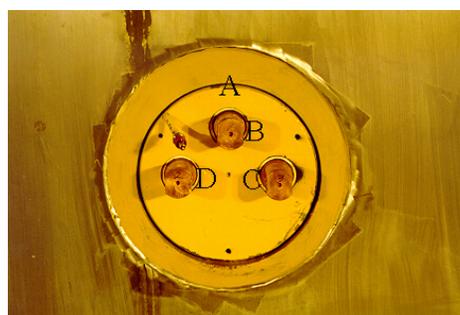


**Fig.6** The measured temperatures at point 3

As the furnace temperature increased with time, the plug surface temperature for all points rose by in range of about 120 to 160°C. The eddy currents made a great contribution to the excessive Joule heat-up of the steel plug. Such eddy currents were induced by the time varying field around the copper bus bars with a high permeability. In order to reduce the surface temperatures of the shield plug, modifications were made as shown in figure 4. Spiral grooves were constructed on the outer surface of the steel plug, and a flexible, continuous stainless tube with a small diameter for water supply was mounted on the grooves. The apertures between the grooves and the tube were filled with molten lead. The thermocouple sensors were carefully installed on the same outer surfaces of the plug as in the previous experiment, while avoiding the cooling tube. Figure 7 shows the temperatures measured at point 3. The maximum temperature was considerably reduced by about 73%, compared with the maximum temperature rise when there is no cooling. And, for all the points measured, the maximum temperatures were also relatively constant in a range of about 44 to 49°C. It is indicated that a water-cooling can suppress the excess heat induced by the eddy currents, and that this cooling technique is very effective for the hot-cell shield plug system.



**Fig. 7** The measured temperature on point 3 when cooling water was supplied



**Fig. 8** The shield plug installed into the cell wall

Each component of the modified hot-cell shield plug should be secured tightly at its right position when being assembled and installed into the cell wall. As shown in figure 8, the developed shield plug was installed into the M6a cell wall, and gamma-ray radiation survey experiments were carried out with a Co-60 source of 1.86 Ci/1.17 (1.35) MeV. For the experiments, the source and its probe were installed in-cell, and the cell was completely shielded. The operator located out-of-cell performed the tests remotely by manipulating the slave manipulator in-cell via the master manipulator. The slave manipulator was operated remotely while the operator held the probe with its gripper and traced the positions to be tested by a direct contact. The apertures (A) between the shield plug and the cell wall and the gaps (B, C, and D) between the shield plug and the copper bus bars were surveyed. The maximum dose rates measured out-of-cell were 19.5 rem/h for A, 22.0 rem/h for B, 18.8 rem/h for C and 20.3 rem/h for D. These dose rates were similar to the background of the-out-of-cell. The test results indicate that the developed shield plug is constructed well without any defects, is completely confined to the wall, and is safe for use.

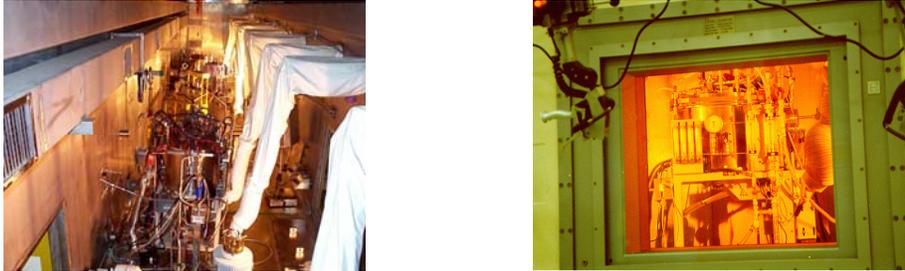
#### 4. In-cell Operation of Sintering Furnace

The sintering furnace was designed to be a vertical cylinder type and heated up to 2000 °C at a maximum by using a cylindrical tungsten mesh element. The furnace consists of a double skin water cooled stainless steel cylindrical vessel fitted with removable top and bottom flanges. The top flange contains the electric power feed throughs and the control/alarm thermocouples. The bottom flange is equipped with a lift mechanism for loading and unloading pellets into the hot zone of the furnace. Figure 9 shows the sintering furnace installed in a hot cell, DFDF.

In order to verify the performance of the sintering furnace with the developed shield plug, a sintering run was conducted with the test program shown in table 1. The test proceeded as programmed, took around 7.5 hours. The test was completed in a satisfactory manner thus fully meeting the requirements of the sintering

furnace for fabricating DUPIC pellets. Figure 10 shows the graphical representation obtained from the sintering run results.

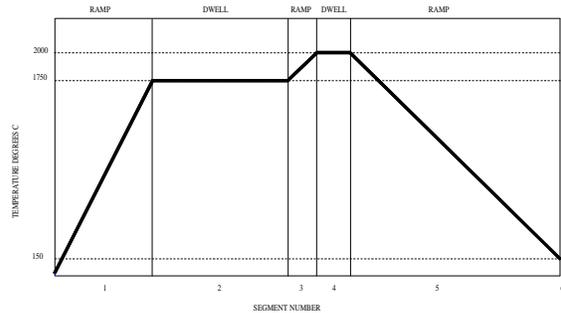
Based on the successful commissioning of the sintering furnace, a cold-test was conducted for a verification of the process conditions developed and the performance of the equipment installed in the DFDF. The cold-test run was successful, and showed that the installed equipment were acceptable and ready to fabricate DUPIC fuel [6].



**Fig. 9** The sintering furnace installed in a hot cell

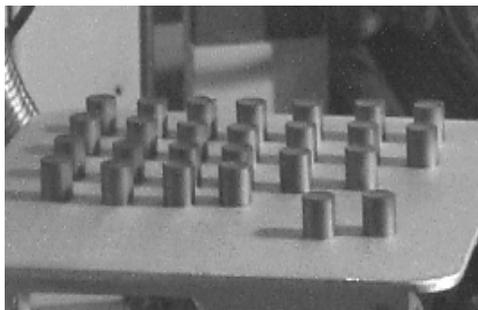
**Table 1** The program for the sintering run

Segment	Heating Rate ( /min)	Duration (min)	Target Temperature ( )
1	20		1750
2	HOLD	120	1750
3	10		2000
4	HOLD	30	2000
5	10		150

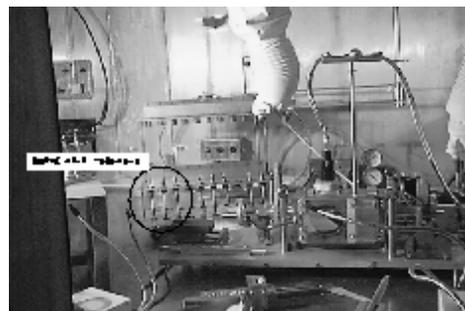


**Fig. 10** The results of the sintering run test

From 2000, a DUPIC fuel pellet and element fabrication campaign was launched using spent PWR fuel materials. The DUPIC fuel pellets were fabricated with satisfactory characteristics in terms of their dimensions, density, microstructure and homogeneity of a composition. Also the developed equipment was successfully operated in a remote manner. Until now, 850 DUPIC pellets have been made for fabrication experiments and fuel pellet irradiation tests. Nine mini-elements were manufactured for the irradiation tests in HANARO and five DUPIC elements were made to verify the DUPIC fuel fabrication technology. Figure 11 shows the fabricated DUPIC pellets and elements. The mini-elements were assembled in an irradiation rig and successfully irradiated. Now a series of DUPIC element fabrication experiments are underway for a further improvement of the fabrication technology and more irradiation tests to evaluate the performance of the DUPIC fuel.



(a) DUPIC sintered pellets



(b) DUPIC fuel elements

**Fig. 11** DUPIC fuel pellet and element fabricated in DFDF

## 5. Summary

A hot-cell shield plug for the sintering process of a DUPIC fuel fabrication was developed. The significance of the development is in providing a hot-cell shield plug that can transmit a high power supply to an in-cell sintering furnace from out-of-cell and that satisfies all the facility shielding requirements. The hot-cell shield plug was installed in the rear shield wall of the M6a cell. The experiments for measuring the temperature distribution of the hot-cell shield plug under the conditions of a normal furnace operation were carried out. As a result, modifications were made to include spiral grooves on the outer surface of the steel plug for a water circulation, and it showed that this cooling technique was very effective for the hot-cell shield plug system. The gamma-ray radiation survey experiments were also carried out with a Co-60 source to validate the structural confinement and integrity of the developed shield plug. It was validated that, from both computational and experimental results, the developed hot-cell shield plug met all the design requirements of the existing hot-cell facility. Through the performance test with the developed shield plug, the sintering furnace was verified in operation and met the design requirements. Based on the successful commissioning of the sintering furnace, a cold-test was conducted and proceeded in a satisfactory manner. From 2000, a DUPIC fuel pellet and element fabrication campaign was launched using spent PWR fuel, 850 DUPIC pellets and nine mini-elements have been successfully made. Now, a series of DUPIC element fabrication experiments are underway for a further improvement of the fabrication technology.

## ACKNOWLEDGEMENTS

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