FUEL ELEMENTS OF RESEARCH REACTORS IN CHINA

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ABSTRACT

This paper describes the current status of design, fabrication of fuel elements for research reactors in China, emphasis is placed on the technology of fuel elements for the High Flux Engineering Test Reactor (HFETR).

INTRODUCTION

After the first Heavy Water Research Reactor (HWRR) was built in 1958 with the help of the USSR, China has since constructed five research reactors through our own effort, namely: three Swimming Pool Reactors (SPR), one High Flux Engineering Test Reactor (HFETR) and one Miniature Neutron Source Reactor (MNSR) (Table 1). Up to now, 94 full operating reactor years have been reached. These reactors have played important roles in our nuclear research and development [1,2].

The HWRR had been operated successfully for a variety of research works for more than 20 years before it was reconstructed during 1979—1980[3]. The new core of the HWRR after reconstruction has a compact lattice with a heavy water cavity in the centre, an outer heavy water reflector, and a change of enrichment of the fuel in ^{235}U from 2% to 3%. Having also increased irradiation space and excess reactivity, the reconstructed HWRR core can provide better service for different kinds of experiments and irradiation work including neutron scattering experiments, radioisotope production, activation analysis, neutron transmutation doping of silicon, biological experiments, fuel and material irradiation and personnel training etc. For example, the fuel assembly in-pile test for Qinshan nuclear power plant had been irradiated in this reactor, and a maximum burnup of 34000 MWd/tU had been reached [4].

Swimming pool type reactors with different designed powers to suit their purposes were built during 1964—1979.

And the 125MW HFETR with maximum fast neutron flux of 1.7×10^{15}n/ cm²·s and maximum thermal flux of 6.2×10^{14}n/ cm²·s was built in 1979.

The MNSR with 27KW power and 1×10^{12}n/ cm²·s maximum thermal flux was built in 1984 at the Institute of Atomic Energy (IAE) in Beijing. This simple, safe and "portable" facility is mainly used for activation analysis and production of short-lived isotopes for medical purposes.

FUEL ELEMENTS AND PERFORMANCE

Research and development work and fabrication facility for nuclear fuel elements for the above mentioned research reactors were started and carried out to keep pace with reactor requirements. At present, five types of fuel elements are produced or had been produced in our nuclear fuel plants as described bellow.

- Uranium metal tubular fuel element for the old core of the HWRR, with 2% ^{235}U enriched uranium metal as fuel tube and aluminium alloy as tube cladding. It had been operated successfully for 23 years before the reactor was reconstructed. The average burnup of this type of fuel element was about 6900MWd/tU and the maximum burnup reached 12200MWd/tU. Post irradiation examination showed that the fuel element has good irradiation stability [5].

- Uranium dioxide fuel rods in circular array (Fig.1), with 3% ^{235}U enriched uranium dioxide pellets and zircaloy-2 cladding, used in the reconstructed HWRR core. This fuel gives very good performance.

Table 1. Research Reactors in China

Reactors	Critical Date	Power (MW)	Max. Thermal Flux n/cm², s	Fuel	Location
HWRR	1958	15	2.3×10^{14}	UO_2, 3% ^{235}U, Zr-2 cladding	Institute of Atomic Energy, Beijing
SPR-492	1964	3.5	5.3×10^{13}	87 wt%UO_2(10%^{235}U) particles dispersed in 13 wt%Mg	Institute of Atomic Energy, Beijing
SPR-200	1964	2.8	4.9×10^{13}	"	Qinghua University, Beijing
SPR-300	1979	2.0	3.0×10^{13}	"	Institute of Nuclear Physics and Chemistry, Sichuan
HFETR	1979	125	6.2×10^{14}	Six concentric tubes, Al-25.4wt%U, 90% ^{235}U, Al alloy cladding	South-west Center for Reactor Engineering Research and Design, Chengdu
MNSR	1984	27(kW)	1.0×10^{12}	Al-26.18wt%U, 90%^{235}U, Al alloy cladding	Institute of Atomic Energy, Beijing

- Uranium dioxide particles dispersed in Mg matrix and extruded into rod shape, with 13wt%Mg and 87wt%UO_2 enriched 10% ^{235}U cladded in aluminium alloy sheath for the SPR type reactor. Fuel rods used in SPR-492 reached 45% average burnup without any trouble [6].

- Fuel element for the MNSR with Al-26.18wt%U alloy enriched 90% ^{235}U fuel and aluminium alloy cladding. The designed life is 12 years, and the behaviour of the fuel rod is as good as expected.

- Aluminium-uranium alloy concentric tubes fuel element for HFETR (Fig. 2), which consists of six concentric fuel tubes and two aluminium alloy outer and inner sleeve tubes. Except the outer aluminium alloy tube, there are three longitudinal ribs on the outer surface of each tube, which serve to increace tube rigidity and act as spacers at the same time. The maximum outer diameter of the fuel tube is 56mm and the minimum inner diameter of fuel tube is 18mm. And the water gap is 2mm. All six fuel tubes are thin-walled sandwich-type with 0.5mm thick fuel and 0.5mm aluminium alloy cladding on each side. The active length is 1000mm. The fuel is made of aluminium-25.4wt% uranium alloy enriched 90% ^{235}U. At a coolant flow rate of 10 m/s, the maximum heat flux is 3.06×10^6 kcal/m²·h and the maximum wall temperature is about 195 °C. Up to now, this type of fuel element has been operated in the HFETR for 7 years with satisfactory performance and the maximum burnup has reched 64.8% [7].

FABRICATION TECHNOLOGY OF HFETR FUEL ELEMENT

A brief illustration of the fabrication technology of the HFETR fuel element may give some idea of the capability of the Chinese fuel element manufacturing plants. Fig. 3 is a flow sheet of the manufacturing steps of the HFETR fuel element. Some of the key steps are described in the following sections.

Centrifugal Casting and Spheroidization Annealing

Uniform distribution of uranium is necessary in a fuel element from the viewpoint of reactor physics and heat transfer. In order to decrease segregation of uranium in aluminium-uranium alloy, a centrifugal casting technology with rapid cooling has been developed for the casting of tube shell. Each of this shell is to be extruded into a single fuel tube. During the cooling of aluminium-uranium alloy by centrifugal casting, two kinds of phenomena, gravitational segregation and inverse

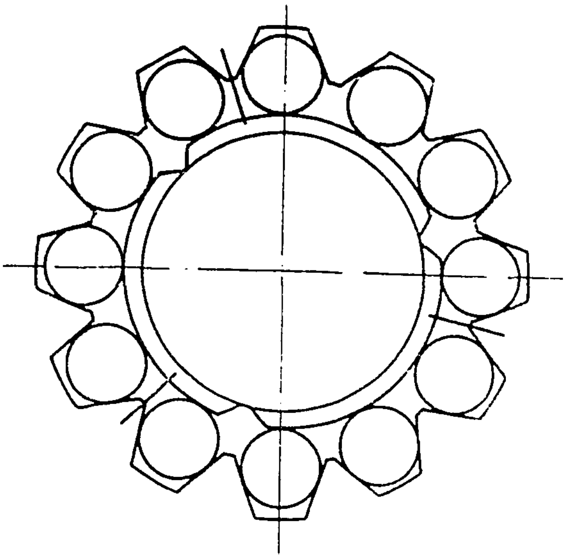

Fig. 1. Cross Secton of HWRR Fuel Element

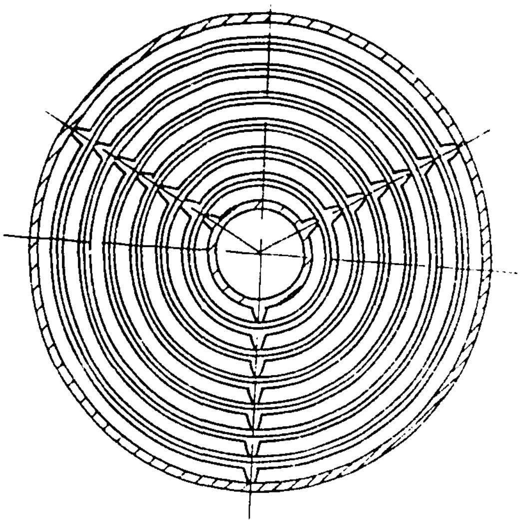

Fig. 2. Cross Section of HFETR Fuel Element

segregation will take place. By choosing a proper rotation speed of the casting mould combining with a proper cooling rate, it is possible to compensate the two opposite segregations and a uniform distribution of uranium can be obtained in the casting of aluminium-uranium alloy tube shell. The typical result of analysis of uranium distribution in a tube is as follow: for an aluminium-25.4wt% uranium alloy tube shell uranium segregation in the radial direction of casting is within 25.4 ± 1 wt% uranium and in the longitudinal direction is within 25.4 ± 0.8 wt% uranium [8,9].

The hardness of alloy as-cast is too high, and an annealing step to soften the material is necessary for the compatibility with the cladding alloy in order to co-extrude satisfactorily. A spheroidization annealing at high enough temperature and long duration will result in eutectic spheroidization and the transition of UAl_3 to UAl_4 , therefore increasing the ductility of the alloy [10,11].

Coextrusion and Tension Straightening

Based on extensive experiments, we have successfully developed a coextrusion technology that uses round extrusion billet a composite of fuel alloy tube shell and aluminium cladding and special shaped extrusion mould to produce thin-walled and sandwich-like fuel tube with three longitudinal spacing ribs on the outer surface. The extrusion mould has three extra special channels to guide metal flow, and during coextrusion process, part of the cladding metal of the billet will flow into the channels to form ribs. The amount of extra metal flowed to form ribs must be controlled, to make the fuel layer under the rib is uniform in thickness. In addition, suitable lubricating during coextrusion is also very important to make a good fuel tube [12].

Photographs of cross section of the fuel tubes are shown in Fig. 4 and Fig.5. It can be seen that a satisfactory fuel tube has very uniform fuel distribution under the ribs.

Straightening process have to be carried out after coextrusion and cold drawing, but obviously it can not be done with a rolling straightening machine since the fuel tube has three ribs on outer surface. Thus, we have

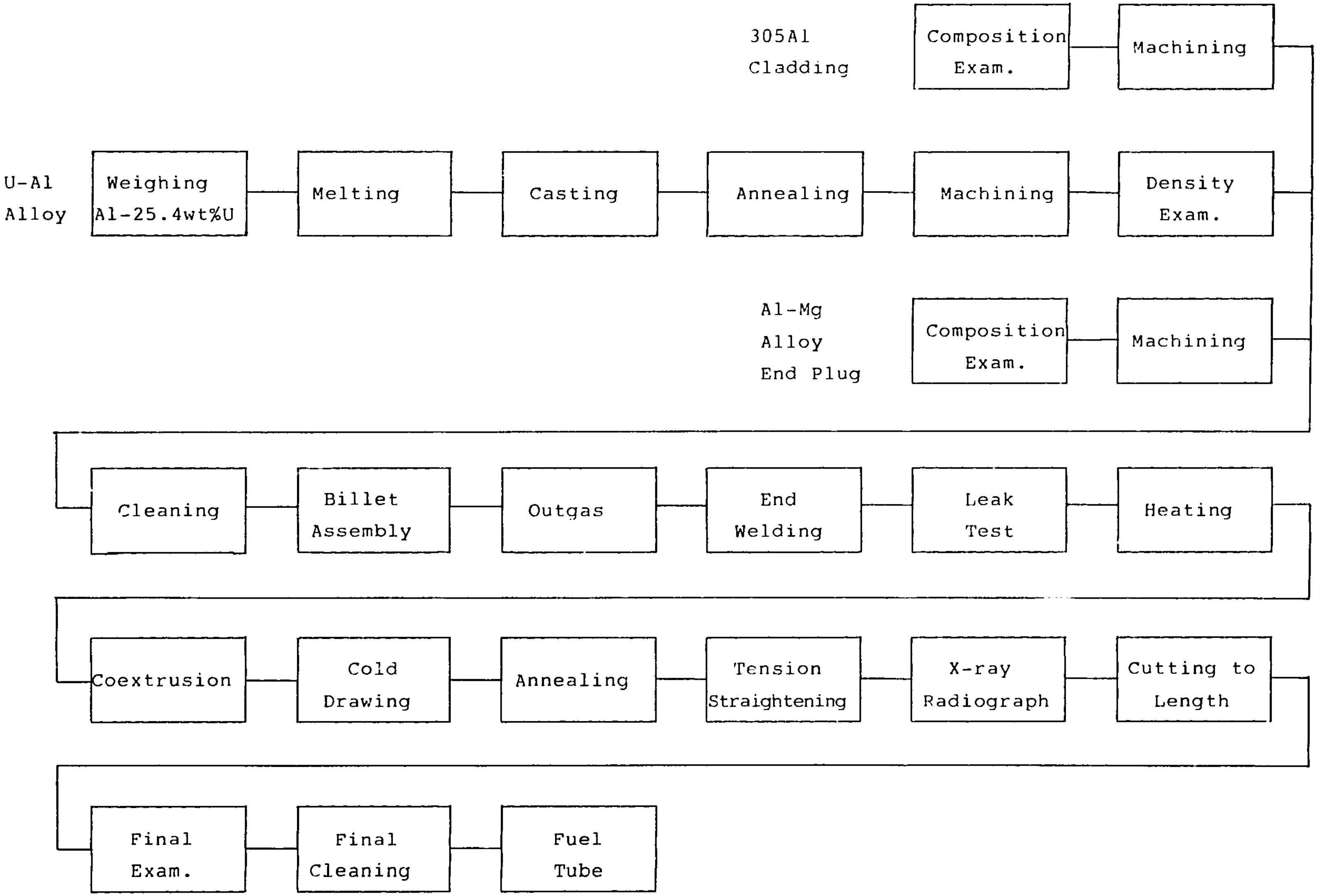

Fig. 3. Flow Sheet of Fuel Tube for HFETR

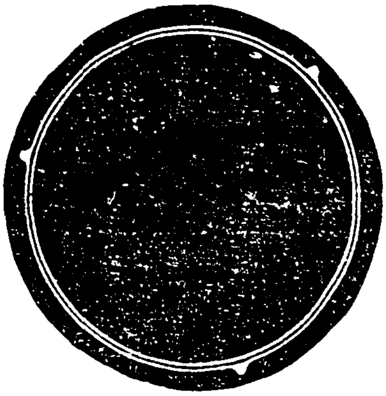

Fig. 4. Photograph of a HFETR Fuel Tube—Showing Satisfactory Fuel Distribution beneath Rib

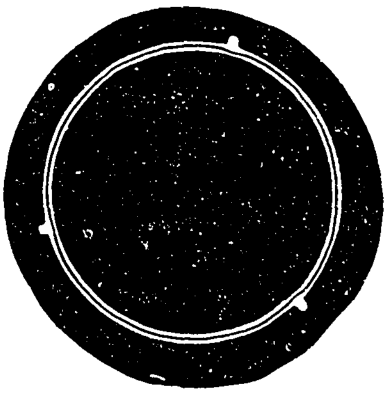

Fig. 5. Photograph of a HFETR Fuel Tube—Showing Unsatisfactory Fuel Distribution beneath Rib

developed tension straightening technology using long mandrel with high precision diameter and smooth surface inserted in fuel tubing. Deformation will be controlled by the mandrel [13].

FUEL ELEMENT PRODUCTION FACILITY

Nuclear fuel element production lines for research reactors have been built in our country, which enable us to produce a number of different fuel elements in quantities and with proved technology.

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