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Preliminary Study on Irradiation Device of Fission Molybdenum-Technetium Production Based on China Advanced Research Reactor

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Abstract: As a multipurpose research reactor, fission molybdenum-technetium irradiation production is one of the wide applications of China Advanced Research Reactor CARR. The goal of this study is to achieve "online loading and unloading" of the target during fission molybdenum-99 (99Mo) to technetium-99m (99mTc) irradiation production without affecting the normal reactor operation and other irradiation channels, which will make CARR more efficient in performing irradiation tasks. This paper introduces the design principles, requirements and concept structural design of the irradiation device of fission 99Mo-99mTc.

Keywords: CARR; Molybdenum-technetium production; Irradiation device

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1. Background

With the rapid development of nuclear medicine, 99Mo-99mTc is widely used in nuclear medicine field. In-reactor irradiation is an important method for producing 99Mo-99mTc isotopes in reactors. The world's main 99Mo-99mTc production reactors are the Open Pool Australian Lightwater Reactor (OPAL) in Australia, the Nuclear Technology Products Reactor (NTP) in South Africa, the High Flux Reactor (HFR) in the Netherlands, and the Belgian Reactor 2 (BR-2) in Belgium, all of which produce 99Mo-99mTc mainly through in-reactor target irradiation [1,2]. It is of great significance to achieve domestic self-sufficiency in 99Mo-99mTc isotope production.

Most of the current irradiation devices of fission 99Mo-99mTc in-reactor irradiation production focus on loading and unloading of the targets after reactor shutdown. Another option is "online loading and unloading" of the target of 99Mo-99mTc irradiation production during reactor operation. Its significance lies in not affecting the normal operation of the reactor and on other irradiation tasks accordingly. It reduces the time of shutdown and restart of the reactor. As a result, it can improve the reactor efficiency and the output of radioactive isotopes. Additionally, the continuous irradiation of the target without shutting down the reactor can reduce the transient impact on the reactor, therefore the reliability of the reactor is improved. Simultaneously, it also reduces the burden of operation personnel, so the risk of human accidents is reduced as well [3,4].

The China Advanced Research Reactor (CARR) is a light-water-cooled and moderated, heavy-water reflected, adverse neutron trap type, high-performance research reactor. There are 21 vertical channels with different sizes in the heavy water tank. The rated thermal power is 60 MW. The maximum unperturbed thermal neutron flux rate is 8 × 1014 n/cm^2·s. Various radioactive isotope irradiation, fuel, and material irradiation tests have been carried out.

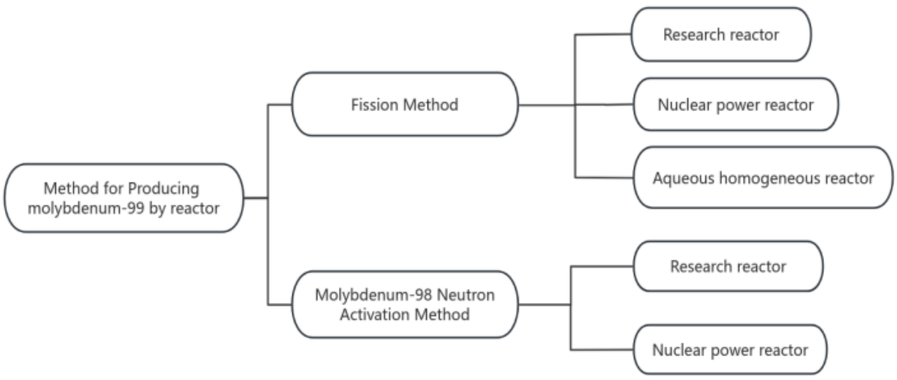

Figure 1. The way of producing 99Mo by reactor

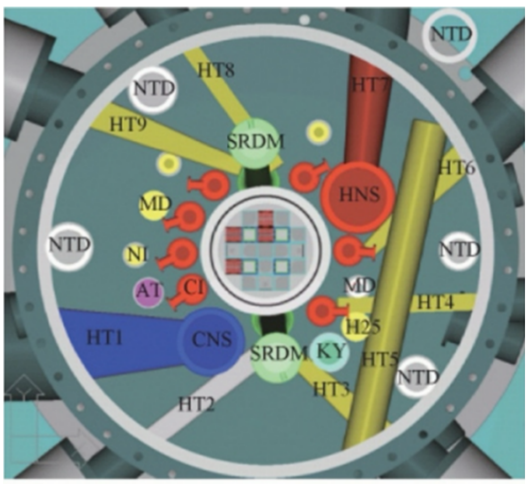

Figure 2. Outline of CARR

2. Design principles

The irradiation device of fission 99Mo-99mTc production is being studied on CARR at the China Institute of Atomic Energy, where the irradiation device was placed in the water-cooled isotope channel in the heavy water tank, taking into account the need to achieve continuous operation of the target and not affecting the normal use of other channels. The following principles should be met during the design of the irradiation device: (1) Reactivity insertion rate is no higher than 1e^{-4} ΔK/K/s; (2) Temperature of the coolant at the surface of the target is lower than saturation point; (3) Good water tightness; (4) Compact structure; (5) Proper materials; (6) No affect on other vertical channels nearby.

There are seven water-cooled isotope channels in CARR with an inner diameter of 70 mm. During the fission 99Mo-99mTc irradiation production process, the irradiation device operates under forced cooling by a cooling loop, which removes the heat generated by the target. The main operating parameters of the water-cooled loop are shown in **Table 1**. To achieve continuous operation other than shutting down the reactor during loading and unloading of the target, the local neutron flux rate of the target should be reduced, thus reducing the heat release power of the target. To achieve this goal, a drive mechanism is introduced to move an annular neutron absorber screen around of the target up and down. The irradiated target can be moved to a height above the reactor core after the neutron absorber screen is moved down to cover the target. In this way, the residual heat release power of the target can be removed by natural convection, so that the pump of cooling loop can be stopped. Then the plug on the top of the irradiation device is opened for loading and unloading of the target.

Table 1. The main technical parameters of CARR

Parameters	Value
Reactor power (MW)	60
The maximum unperturbed thermal neutron flux rate ($n \cdot cm^{-2} \cdot s^{-1}$):	
Central active zone	1×10^{15}
Heavy water reflector	8×10^{14}
Active zone height (m)	0.850
Equivalent diameter of active zone (m)	0.399
Reactor pool diameter (m)	5.5
Reactor pool depth (m)	15
Diameter of the heavy water tank (m)	0.479
Outer diameter of the heavy water tank (m)	2.2
Control rod absorber material	Hafnium
Safety bar (rod)	2
Compensation rod, adjusting rod (root)	4
Fuel element form	Tablet type
Number of standard fuel elements per box	17
Number of fuel elements per fuel assembly	4
Fuel core material	U3Si2-Al dispersion
Cladding material	6061 Aluminum alloy
U-235 Enrichment (wt%)	19.75
Total coolant flow rate (m^3/h)	2,385
Core coolant inlet pressure (MPa)	0.697
Core coolant outlet pressure (MPa)	0.12
Core coolant outlet temperature (°C)	35
Core coolant inlet temperature (°C)	56.2

Table 2. Operating parameters of the water-cooled loop

Design parameters	Value
Operating temperature (°C)	50
Work pressure (MPa)	0.6
Coolant	Demineralized water
Coolant flow rate (m^3/h)	7.14

In this study, the annular tube target is developed. Low-enriched uranium-aluminum alloy (U-Al) is used as the target material. The structure of the target is a sandwich type, which consists of U-Al foil in the center and aluminum (Al) cladding at both sides. The schematic diagram of the target is shown in **Figure 3**.

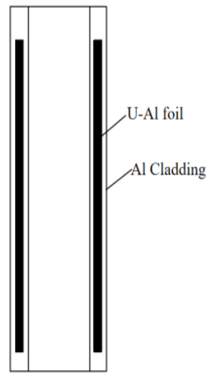

Figure 3. Schematic diagram of the target

3. Structural design

3.1. Structural features

The current water-cooled isotope channels of CARR are double-layer structures connected with a cooling loop. A pump draws water from the closed cooling loop into the annular gap of the irradiation channel, where it removes heat from the channel and then returns to the closed cooling loop through the outlet. This makes the space for irradiation very limited. Therefore, the design requires a compact structure. Secondly, the movement of the neutron absorber screen is driven by a mechanical transmission. Thirdly, the power of the target is adjusted by moving the neutron absorber screen up or down. The irradiation device is connected to the cooling loop via two connecting pipes, thus forming a closed system. The overall structure of the irradiation device is shown in **Figure 4**.

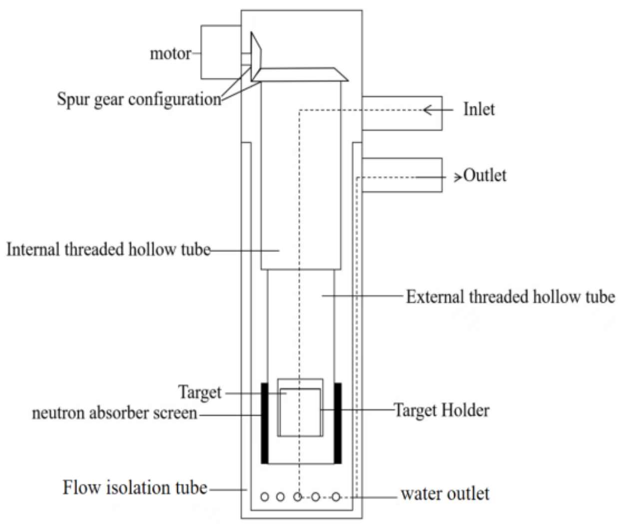

Figure 4. A schematic diagram of the irradiation device

3.2. Driving mechanism

The driving mechanism consists of coupling, large and small spur gears, positioning bearings, hollow screws, nuts, keyway tubes, support rings, etc. The coupling is the connecting component that transmits the motor power to the gears. One coupling end is rigidly connected to the motor shaft, and the other is precisely connected to the small spur gear shaft. It smoothly transmits the rotational power of the motor to the small spur gear. The spur gear configuration allows the rotational motion of the motor to be transmitted to the hollow screw through the meshing of the large and small spur gears. The large spur gear is connected to the hollow screw through a key, and the hollow screw is connected to the nut through a threaded connection. These three components form a single unit and are supported and positioned precisely by the positioning bearings, which ensure that all components remain aligned correctly during operation. The keyway on the keyway tube corresponds to the keyway on the hollow screw, and the key is inserted into these keyways to fix the keyway tube and the hollow screw axially and synchronize their rotation. The outer ring of the nut has symmetrical protruding keys that fall into the key slots of the keyway tube. The neutron absorber screen is connected to the low part of the externally threaded hollow tube.

3.3. Manipulate tools

(1) Irradiation device plug grabber: The plug grabber connects to the refueling machine above the reactor pool. The plug grabber resembles a long pole structure and consists of a double-layer sleeve. The outer sleeve has notches on its outer ring to clamp the plug, while the inner sleeve enables the plug to move up and down. The refueling machine moves to the correct position above the channel, guided by software-preset positioning. An underwater camera is used to verify that the grabber is correctly aligned. Once positioned, a wrench is used to either remove or screw in the plug.

(2) Target grabber: It is driven by compressed air and the hook grips are pulled inward when inflated whereas they are pushed outward when deflated, thus grabbing the target and forming a self-lock.

3.4. Basket

The basket is the holder of the target during the irradiation. It also provides the interface for handling the loading and unloading of the target. There is a grasping structure for the gripper on top of the basket.

4. Conclusion

An irradiation device is designed for the fission 99Mo-99mTc irradiation production on CARR. The irradiation device meets the requirements of “online loading and unloading” without shutdown of the reactor during the irradiation of fission 99Mo-99mTc. Subsequent research will be based on this foundation for further in-depth study.

Disclosure statement

The authors declare no conflict of interest.

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