DEVELOPMENT AND APPLICATION OF COBALT ADJUSTER ROD FOR ^{60}Co MEDICAL RADIOACTIVE SOURCES PRODUCTION IN CANDU-6 REACTOR

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ABSTRACT: *^{60}Co radioactive sources are widely used in industrial and medical field. In 2008, Cobalt adjuster rod assemblies were loaded in the core of CANDU-6 reactor in order to produce industrial radioactive sources. Based on successful production and application of ^{60}Co industrial radioactive sources, the program of developing cobalt adjuster rod for ^{60}Co medical radioactive sources production was launched. Comparing with industrial radioactive sources, medical radioactive sources require higher activity ~220Ci/g and smaller sources size, which cause challenges to cobalt adjuster rod design and manufacturing. In this paper, several types of cobalt pellets have been developed to match the medical radioactive sources size and the corresponding nuclear design, TH design & safety analysis, shielding design & safety analysis was also completed to prove that the design requirements could be satisfied. By now the development of cobalt adjuster rod for ^{60}Co medical radioactive sources production has finished and the first batch of cobalt adjuster rod assemblies have been successfully loaded in core. The first batch of ^{60}Co medical radioactive sources is expected to be put into application in 2019.*

KEYWORDS: *^{60}Co Medical Industrial Sources, ^{60}Co Medical Radioactive Sources, Cobalt Pellets Design, Nuclear Design, Thermal Hydraulic Design, Shielding Design.*

1. INTRODUCTION

^{60}Co radioactive source is a good gamma-ray source with a half-life of 5.26 years. The radioactive sources are widely used in industry, medical and other fields. ^{60}Co medical sources are utilized for Gamma ray treatment of malignant tumors. Most of the ^{60}Co medical sources are dependent on importing in China, while the global ^{60}Co medical sources supply is very limited, which will not meet the blooming medical market needs. Therefore, using domestic nuclear reactors to self-product ^{60}Co medical sources is the urgent issue in China.

China has two CANDU heavy water reactors operating. The reactor is loaded with natural uranium fuel or equivalent natural uranium fuel, and used heavy water as a neutron moderator and coolant. The calandria vessel is a horizontal cylindrical container, and both ends are sealed by flanges. The vessel contains 380 calandria tubes for separating heavy water moderator and coolant. The entire reactor is supported by end shields in the concrete chamber. The fuel channels are filled with fuel rod clusters.

Reactivity and capacity control is achieved by injecting light water and adjusting top solid neutron absorbers.

Cobalt adjuster rod assemblies are part of reactive adjustment components in a CANDU heavy water reactor that serves to flatten the core neutron flux distribution and power distribution by absorbing neutrons. They also can produce ^{60}Co radioactive source for medical and industrial use after irradiation in the reactor. Without affecting the safety and power generating capacity of the nuclear power plant, they realize the reuse of loss neutrons.

In 2008, cobalt adjuster rod assemblies were developed to replace stainless steel rod assemblies in order to produce industrial radioactive sources. By now, several batches of cobalt adjuster rod assemblies were successfully loaded in the core, maintaining the safe operation of CANDU-6 reactor, meanwhile continuously producing ^{60}Co source every year. Based on the successful development of ^{60}Co industrial radioactive sources, the program of developing cobalt adjuster rod for ^{60}Co medical radioactive sources production was launched.

The main differences between industrial and medical ^{60}Co source are the requirement of specific activity and size of the cobalt pellets. The specific activity requirement of medical ^{60}Co radioactive source is more than 220Ci/g. After the outage period of Qinshan CANDU-6 heavy water reactor was extended to 24 months, the ^{60}Co specific activity of industrial cobalt adjuster rod assemblies has achieved the requirements. Therefore by modifying the cobalt pellets structure of cobalt adjuster rod, the medical ^{60}Co radioactive source can be produced.

In this paper, several types of cobalt pellets have been developed to match the medical radioactive source size of gamma-ray equipment. The corresponding nuclear design, TH design & safety analysis, shielding design & safety analysis was also completed to prove that the design requirements is satisfied.

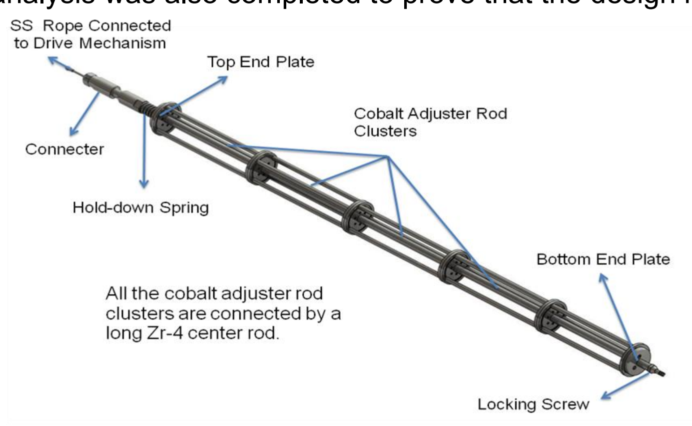

Fig.1 Medical cobalt adjuster rod assembly structure

2. DESIGN REQUIREMENTS

2.1 RADIOACTIVE SOURCES REQUIREMNETS

The size of cobalt pellets shall match with the majority of medical ^{60}Co radioactive source equipment. And specific activity of medical ^{60}Co radioactive source shall not less than 220Ci/g.

2.2 REACTOR COMPATIBILITY REQUIRMENTS

The medical cobalt adjuster rod assembly structure must compatible with the reactor as the industrial cobalt adjuster assembly. To ensure structural compatibility with the guide tube, the outer diameter of the medical cobalt adjuster rod assembly should not exceed inner diameter of the guide tube. To ensure compatibility with the wire rope component, the weight of the cobalt adjuster rod assembly should not exceed 20 Kg. And medical cobalt adjuster rod assembly is inserted into or withdrew from the core, must be at the desired reactivity and defined period of time.

The main structural materials of the medical cobalt adjuster rod assembly should be selected for their neutron absorption in core as small as possible. And the materials of the adjuster rod assembly should have sufficient strength and corrosion resistance, so as to meet the maximum operation time of 3FPY requirements.

2.3 NULEAR DESIGN REQUIREMNETS

The reactivity value of the ^{59}Co absorber in the medical cobalt adjuster rod assembly shall have a reactivity value of 15mk from the fully inserted core to the fully withdrawn core. The number, size and distribution of the cobalt rod assemblies were determined by iterative analysis of the structural design and the nuclear design

2.4 TRANSPORTATION REQUIREMENTS

The irradiated cobalt assembly is disassembled into the cobalt adjuster rod clusters in transportation flask. The transportation flask should have structural compatibility with the cobalt adjuster rod clusters and be able to guarantee the radiation dose on the surface of the transport container under the limit value during transportation.

2.5 DISASSEMBLY REQUIREMENTS IN HOT CELL

The structural design of medical cobalt adjuster rod clusters should be disassembled into the cobalt rods in the hot cell and sealed to the medical radiation source easily.

3. STRUCTURE DESIGN DESCRIPTION

3.1 COBALT ADJUSTER ROD ASSEMBLY

As shown in Fig.1, each cobalt adjuster rod assembly includes 6 cobalt adjuster rod clusters with a zirconium alloy rod at the center. The lower end of the assembly includes a bottom end plate and locking screw. The top of the assembly includes the top end plate, hold-down spring, connecter, and stainless steel rope. The hold-down spring is arranged between the connecter and top end plate in order to prevent cobalt adjuster rod clusters rotation and compensation of differential thermal expansion and dimension change between different components.

3.2 COBALT ADJUSTER ROD CLUSTERS

Comparing to the industrial cobalt adjuster rod cluster which including 2 cobalt rods and 1 Zr-4 rod of each cobalt adjuster rod clusters, every medical cobalt adjuster rod cluster includes 3 cobalt rods in order to compensate the cobalt loading

3.3 COBALT RODS

The pellets are sealed by cladding in order to separate with moderator. There is little clearance between pellets and cladding to avoid the interaction. And both ends of cladding are sealed by end plugs.

3.4 COBALT PELLETS

According to the radioactive sources requirements, several types of cobalt pellets have been developed to match over 90% of ^{60}Co medical radioactive sources market need. Specific activity of medical cobalt pellets is calculated, the results show it is more than 220Ci/g. There are three pellets loaded in the cross section of each cobalt rod.

4 STRUCTURAL STRENGTH ANALYSIS

According to the reference [1], industrial cobalt adjuster rod assembly is proved to maintain structural integrity during transport, handling, and operational condition. Except for the cobalt pellets and the number of cobalt rods, the main structure of medical cobalt adjuster rod assembly is almost the same. The structural integrity of the core components of the cobalt adjuster rod assembly is analyzed below.

4.1 HOLDDOWN SPRING ANALYSIS

The function of hold down spring is to prevent the cobalt adjuster rod assembly from slipping during the lifting operation; prevent the assembly from moving due to hydraulic lifting; avoid the relative rotation of the cobalt adjuster rod clusters; and compensate the thermal expansion and irradiation dimension change between the different components.

The calculated shear stress of the spring wire under the maximum working pressure is 689.7MPa. Spring wire allowable shear stress is 740MPa, so the spring shear stress under the maximum working pressure is less than the allowable shear stress, the strength requirements are met.

4.2 WIRE ROPE STRENGTH ANALYSIS

Wire rope material is stainless steel. In order to maintain the handing safety, a conservative safety factor of 6 is selected to calculate the wire rope strength. The calculation result shows the breaking force of rope is 7850N, which is greater than the maximum working static tensile force 5340N.

4.3 COBALT ROD CLADDING ANALYSIS

The irradiation reaction of cobalt pellets in the reactor is (n,γ) reaction, which will not produce fission gas. In order to improve the heat conduction, cladding is filled with helium. The equivalent stress of cladding considering the worst situation is 4.3MPa, which is much less than the allowable stress of Zr-4 cladding.

4.4 PELLECT CLADDING CLEARANCE CALCULATION

Clearance calculations include axial and radial clearance. Cobalt pellets deformation is mainly caused by irradiation swelling and thermal expansion. Under normal operating conditions, the axial clearance between pellets and cladding is 0.89 mm and the radial gap is 0.35mm. The calculated results show that there are still enough axial and radial gaps between cladding and the cobalt pellets in the cobalt rods which will prevent mechanical interaction.

4.5 WELDING STRENGTH CALCULATION

The shear force acting on the welding seam between center tube and the top or bottom end plate is conservatively considered to be equal to the maximum hold force of the spring. It is calculated that the shear stress is 11.69MPa, which is lower than the allowable shear stress of Zr-4 material.

5 NUCLEAR DESIGN ANALYSIS

Based on the optimized ^{59}Co pellet loading pattern[2],[3], the reactive value of medical cobalt adjuster rod assembly is designed equivalent to that of industrial cobalt adjuster rod assembly. The geometric equivalent treatment of the real geometry structure of the medical cobalt adjuster rod was performed. The analysis results show that the design of medical cobalt adjuster rod assembly is equivalent to industrial cobalt adjuster rod assembly, and the neutron characteristics remains the same which ensure the safe operation of the core.

6 THERMAL HYDRAULIC ANALYSIS

The mainly purpose of thermal hydraulic analysis is to analyze the temperature field and flow field of moderator and the temperature field of cobalt adjuster rod assembly during normal operation condition. In addition, the temperature field of cobalt adjuster rod assembly during transport and accident condition was also carried out.

6.1 TEMPERATURE AND FLOW FIELD ANALYSIS OF MODERATOR

Base on temperature field and flow field analysis of CANDU-6 heavy water reactor moderator [4], the calandria vessel of the CANDU-6 heavy water reactor is divided into Core and reflector region when calculating the moderator flow field and temperature field. There are 8 moderator inlets (Nozzles) and 2 moderator outlets in the row of tubes; the calandria vessel container includes 380 rows of calandria vessel, since the effect of other devices on the main flow field of the moderator is neglectable, there is no simulation in the three-dimensional geometric model. The structure of the calandria vessel and the location of the moderator inlet and outlet.

The flow field and temperature field calculation results shows the temperature of moderator system is 84℃. The moderator temperature field calculation results as shown in Fig.2 were used as the input parameters for the thermal calculation of the cobalt rod cladding tube under normal operation conditions.

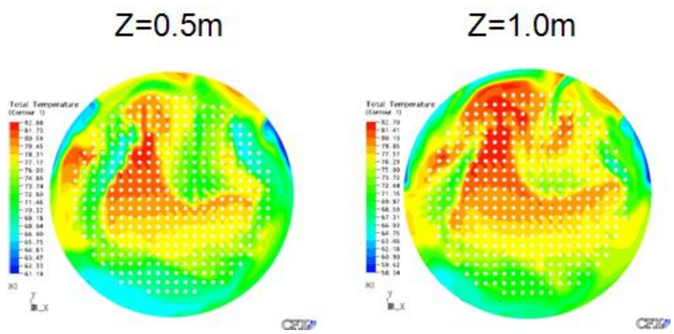

Fig.2 Moderator temperature field calculation results of different elevation

6.2 TEMPERATURE ANALYSIS OF COBALT ROD

Temperature field analysis of industrial cobalt adjuster rod assembly is completed in reference [5]. The guide tube of the cobalt adjuster rod assembly has a perforated hole in the wall, and the moderator enters the guide tube to take away the heat of the cobalt rod to control the temperature within the allowable range. The helium gap of cobalt rod is very small, so the influence of radioactive heat transfer is neglected. It is considered that the domain heat transfer inside cobalt rod is heat conduction, and the way of cobalt rod and moderator is convective heat transfer.

The same methodology was used in the temperature analysis of medical cobalt rod. The temperature analysis of cobalt rod focuses on the maximum surface temperature of the cobalt rod claddings and the maximum center temperature of cobalt pellets. The analysis results show that under normal condition, the maximum temperature of the cladding is 112.3℃, lower than the nucleate boiling temperature 113.1℃. The maximum center temperature of the pellets is 321.2℃, which are much lower than the melting temperature 1460 ℃. Under loss of moderator accident condition, the maximum temperature of the cladding is 650.1℃. The maximum temperature of the center of pellets is 667.6℃. Under transport condition, the two temperature is 630.5℃ and 643.4℃. The temperature under loss of moderator accident and transport is also below the melting temperature.

7 IRRADIATION SHIELDING DESIGN

^{60}Co emits two photons with energy of 1.17MeV and 1.33MeV for each decay, it is necessary to take into account the radiation safety of person who works in the production of ^{60}Co, and make the absorb dose less than the acceptable limit. The radiation safety design of ^{60}Co production process mainly includes radiation safety on reaction mechanism platform, spent fuel pool and transport container. The results show the radiation dose on the surface of the transport container and operating platform is under the limit value during transportation and operation. The radiation safety of the surrounding environment can be guaranteed.

8 CONCLUSION

Based on the successful application and operation of industrial cobalt absorber assembly, several types of cobalt pellets have been developed to produce ^{60}Co source which meet the specific requirement of activity and size. Through mechanical design, nuclear design, thermal hydraulic design, irradiation shielding design, the medical cobalt absorber assembly has been proved to be equivalent to industrial cobalt absorber assembly, thus maintaining the safe operation of CANDU-6 reactor.

By now the medical cobalt pellets and cobalt absorber assembly have been successfully fabricated and successfully loaded in the CANDU-6 reactor. The first batch of ^{60}Co medical radioactive sources is expected to be put into application in 2019 which will continuously meet the blooming needs of medical match the medical irradiation source market in China.

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