Structural Integrity Assessment for SSDM Hydraulic Cylinder of JRTR

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1. Introduction

There are two types of reactor shutdown mechanisms in HANARO. One is the mechanism driven by a hydraulic system, and the other is driven by a stepping motor. In HANARO, there are four Control Rod Drive Mechanisms (CRDMs) with an individual step motor and four Shutoff (SO) Units with an individual hydraulic system located at the top of reactor pool. The absorber rods in SO units are poised at the top of the core by the hydraulic force during normal operation. The rods of SO units drop by gravity as the first reactor showdown mechanism when a trip is commended by the reactor protection system (RPS). The rods in CRDMs also drop by gravity together as a redundant shutdown mechanism.

The reactivity control mechanisms of in JRTR, one of the new research reactor with plate type fuels, consist of four CRDMs driven by an individual step motor and two second shutdown drive mechanisms (SSDMs) driven by an individual hydraulic system as shown in Fig. 1. The CRDMs act as the first reactor shutdown mechanism and reactor regulating as well. The top-mounted SSDM driven by the hydraulic system for the JRTR is under design in KAERI. The SSDM provides an alternate and independent means of reactor shutdown. The second shutdown rods (SSRs) of the SSDM are poised at the top of the core by the hydraulic system during the normal operation and drop by gravity for the reactor trip. Based on the proven technology of the design, operation and maintenance for HANARO, the SSDM for the JRTR has been optimized by the design improvement [1] from the experience and test [2]. This paper aims for the structural integrity assessment for SSDM hydraulic cylinder which is designed on the basis of the SO unit of HANARO but optimized with the new core environment (i.e., geometrical, physical, etc.) of JRTR.

2. Design Features

The JRTR is a pool type research reactor with 5MW power. The layout of four CRDMs and two SSDMs are shown in Fig. 1. The basic design of the top-mounted SSDM has been started on the same or similar concept with the SO unit in HANARO. Therefore, many design features of components can be applicable to the new reactors. However, due to the differences in the fuel types, core configuration and so on, it is necessary to modify and optimize for the new reactors.

Table 1 presents the differences in design features of the shutdown mechanism driven by hydraulic system between HANARO and JRTR.

Table 1 Comparison of shutdown mechanism by hydraulic system between HANARO and JRTR

	HANARO	JRTR
Function	First shutdown mechanism	Second shutdown mechanism
Qty. of system	4	2
Absorber shape	Cylindrical tube	Cylindrical tube
Absorber mat'l.	Hf	B_4C (Powder type)
Absorber stroke	700 mm	655 mm
Absorber drop time	<1.08s (Before damping)	<1.50s (Before damping)
	<1.5s (Including damping)	<5.0s (Including damping)
Absorber withdrawal time	>28s	15~60s
No. of gimbal joint in absorber	2 joints	1 joint
Absorber guide tube	Cylindrical shroud tube & flow tube	Cylindrical tube
Guide above core	Track & carriage	Same concept and optimized
Actuating mechanism	Hydraulic cylinder with damper	Same concept and optimized
Actuating system	Hydraulic system	Same concept and optimized
Solenoid & piston valve	2 out of 3 for normal function	1 out of 2 for normal function

3. Summary of System and Structures

The SSDM consists of a SSR, a SSR guide tube, a carriage, a track, a hydraulic cylinder, a cylinder mount bracket and a hydraulic system as shown in Fig.2. The hydraulic force derived from the hydraulic system raises the piston in the hydraulic cylinder. The piston is connected to the SSR through the carriage which is guided by the track in the Upper Guide Structure (UGS). The SSR is guided by the Zircaloy (Zr-4) SSR guide tube in the core. There are various universal joints on the connection points to improve the drop or withdrawal performance of the moving parts.

During the normal operation, the SSRs are raised to the top of the core and poised. When the reactor trip is required, the SSRs drop by gravity into the core by the de-energizing the two solenoid valves to dump the pumping water to the reactor pool through opening of the air-operating piston valves. There is a proper hydraulic damping mechanism in the hydraulic cylinder to absorb the impact during the SSR drop. The SSRs drop also under the abnormal operation transients such as a loss of electric power for the pump or a low-low level of pool water. The top and bottom positions of SSR are monitored by the two pressure switches respectively.

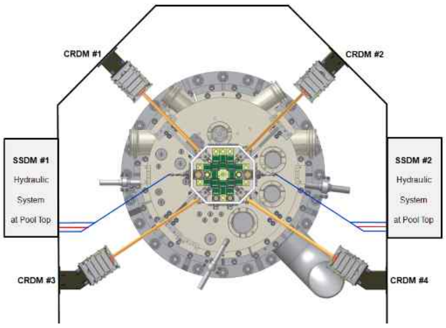

Fig. 1 Layout of the CRDMs and SSDMs.

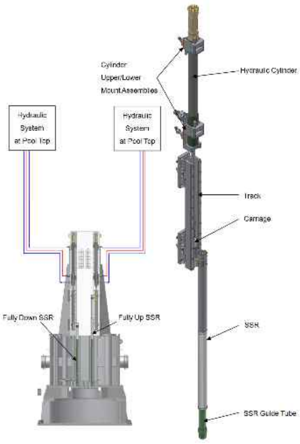

Fig. 2 Overall view of the SSDM.

Fig. 3 Shape of the SSR and SSR guide tube.

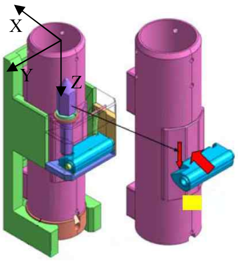

Fig. 4 Clamping Mechanism between the Damper Cylinder and the Lower Mount Bracket.

3.1 SSR and SSR guide tube

The SSR and SSR guide tube as shown in Fig. 3 are cylindrical shape. The SSR is a cylindrical tube with the neutron absorbing material of B_4C powder that is contained in inconel cladding can with a certain tap density. It consists of a bearing skirt, an absorber element, a support tube and a mounting ring. The mounting ring and support tube is connected by a gimbal joint which permits the absorber element and guidance components to be misaligned within the limit of the tolerances. The SSR guide tube is zirconium alloy single cylindrical tube aligned coaxially into the SSR to absorb the flow induced forces on the exposed parts of the absorber element in the core. The lower part of the guide tube is thread-mounted into the grid plate. The SSR is guided by a bearing running on the outside of the SSR guide tube.

3.2 Track and Carriage

The SSDM includes one set of track and carriage. The track is mounted on the upper guide structure (UGS) wall for the guide of the carriage above the core. The linkage formed by the carriages and the piston rod connects the absorber element to the hydraulic cylinder to effect and guide the motion of the absorber element.

3.3 Hydraulic Cylinder Assembly and Hydraulic System

The cylinder assembly is mounted by the upper and lower mount brackets which are attached to the UGS. The lower end rests on stops of the lower mount bracket and two clamps force the cylinder tightly against the base plates which are attached to the UGS as shown in Fig. 2 and 4. A clamp consists of a pivoted crank which is forced against the cylinder by a clamping bolt.

The hydraulic cylinder consists of a cylinder, a main piston, a damper cylinder, a damper piston, and so on. Mechanical and hydraulic damping during SSR drop is applied simultaneously in this system. The SSR is poised by hydraulic force and drops by loosing hydraulic force by bypassing the pumping water. The direct injecting and bypassing of pumping water are changed by two sets of solenoid-piston valves.

4. Code Classification and Limits

The ASME Code criteria for a Class 3 component will be used as a guide for design of the hydraulic cylinder. Fig. NG-3221-1 and NG-3225 in Section III of the Code gives the limits. The limits of stress intensity for design and seismic conditions are as follows:

Design Condition		Seismic Condition (Level D)	
P_m	$< 1.0S_m$	P_m	$< 2\times1.0S_y$
$(P_m \text{ or } P_L)+P_b$	$< 1.5S_m$	$(P_m \text{ or } P_L)+P_b$	$< 2\times1.5S_y$

* The average and maximum primary shear stress according to NG-3227.2 shall be limited to $0.6S_m$ and $0.8S_m$, respectively. For the Level D Limit, the calculated stress shall not exceed twice the stress limits which Level A Limits are designated and given in NG-3227.

Where, S_m is the design stress intensity from Table 2A, Section II, Part D, Subpart 1, of the ASME Code. The design stress intensity (minimum yield strength) of SA240-304 and SA564-630-H1100 is 138 (205) MPa and 322 (795) MPa at 65 °C, respectively.

5. Pinch Load Calculation for Hydraulic Cylinder

Force equilibrium diagram for the clamping mechanism is described in Fig. 5. From a linear contact finite element analysis using a certain vertical load (a sort of simulation load) on crank by clamping bolt, the relationship between $F2_x$ and $F2_y$ is as follows:

$$\mathrm{Tan}\theta = \frac{F2_y}{F2_x} = 0.235461 \tag{1}$$

Also, $F2_x$ and $F2_y$ are resulted from a line distributed load $Q2_x$ and $Q2_y$, respectively. The length (L_c) of line distribution load is 20.0 mm.

$$\begin{aligned} & F2_x = Q2_x \times L_c \,,\quad F2_y = Q2_y \times L_c \\ & L_c = 20.0\ \mathrm{mm} \end{aligned} \tag{2}$$

There shall not be any slip between the bearing (stiffener) plate of hydraulic cylinder and base plate of mount bracket after clamping during Safe Shutdown Earthquake (SSE) by push-down loads that are $F2_y$ and friction load between both contact surfaces. For conservative consideration, the mass including the hydraulic cylinder (20 kg) and moving part (19 kg) that consists of piston rod, carriage, and SSR is considered for it structural integrity. Therefore the total mass (m_{total}) is 39 kg.

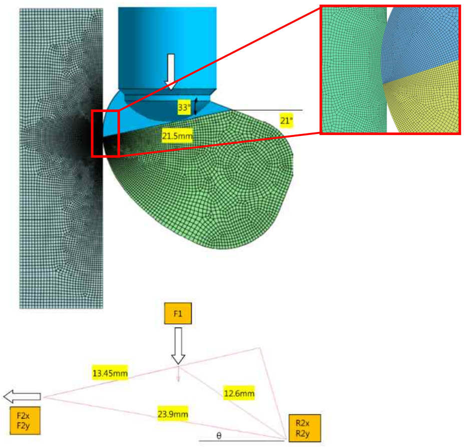

Fig. 5 Force Equilibrium Diagram for Clamping between the Cylinder and Mount Bracket.

The number of pinch load (N_p) is 2 (upper and lower point) as shown in Fig. 2. The push-down acceleration load factor of hydraulic cylinder by crank and clamping bolt is assumed as follows:

$$A_{cy} = \frac{N_p \times F2_y}{m_{total} \times g} \tag{3}$$

The vertical seismic acceleration load factor (A_{se}) on Upper Guide Structure (UGS) during SSE with 2% damping is 2.75. Therefore the equivalent combined seismic load factor is as follows:

$$A_{se\_e} = A_{se} + A_{cy} = 2.75 - \frac{N_p \times F2_y}{m_{total} \times g} \tag{4}$$

The friction factor (μ) and safety load factor (S_f) is assumed 0.1 and 1.2 for conservatism, respectively. The inequality relationship with no slip between both contact surfaces during SSE is derived as follows:

$$N_p \times F2_x \times \mu \ \geq \ m_{total} \times A_{se\_e} \times g \times S_f \tag{5}$$

Using Eq. (1), (3) and (4), the inequality (5) is derived as follows:

$$F2_y \ \geq \ \frac{m_{total} \times 2.75 \times g \times S_f}{N_p \times \left(\dfrac{\mu}{\mathrm{Tan}\theta} + S_f \right)} \ \cong \ 390\ \mathrm{N} \tag{6}$$

$F2_y$ shall be minimum 390 N for no slip during SSE and the pinch load, that is, $F2_x$ shall be minimum 1660 N. Therefore the vertical load (F1) applied on crank by clamping bolt shall be minimum 1530 N.

Also, the seismic load in horizontal X-direction with 2% damping is about 22.9g. An additional seismic load can be applied to both the cylinder (26 kg) including the piston rod (6 kg) and the crank. This additional seismic load is derived as follows:

$$F_{add} = \frac{22.9g \times M_{cy+pis}}{N_P} \cong 2921\ \mathrm{N} \tag{7}$$

Therefore the final pinch load shall be minimum 4450 N.

$$F_{pinch} = F2_x + F_{add} \geq 4450\ \mathrm{N} \tag{8}$$

From Eq. (2), the line distributed load applied on the hydraulic cylinder or crank by clamping bolt is derived as follows:

$$\begin{aligned} & Q2_x \geq 76.5\ \mathrm{N/mm} \\ & Q2_y \geq 19.5\ \mathrm{N/mm} \end{aligned} \tag{9}$$

6. Finite Element Model and Boundary Condition

A nonlinear contact analysis using ABAQUS finite element analysis software was done under design and seismic load combination.

The damper cylinder is modeled with solid elements. The Z-axis is along the axis of the cylinder and is positive downwards. As shown in Fig. 4, the X-axis is perpendicular and positive towards the UGS wall. The Y-axis is horizontal and relates to the X and Z axes according to the right-hand rule.

The internal components which are not integral with the damper cylinder are not modeled with finite elements. Such parts include the damper piston, main piston, piston rod, damper cylinder bushing, bushing nut, damper piston spring and overlap portion of the main cylinder which fits inside the damper cylinder. Although the main cylinder is structurally connected to the damper cylinder through a series of dowels, it is considered simpler and more conservative not to include elements for the main cylinder fitting inside the damper cylinder.

The mass effects of the internal and moving parts are included as forces representing weights in the design case and as modified accelerations in the seismic cases. Calculations for weights and Modified accelerations are described and calculated in Section 5.

Fixed displacement constraints for the analysis are as follows: (a) UX and UY for nodes on the base of the damper cylinder bearing (stiffener) plates, (b) UZ for nodes contacting the stops at the bottom of the damper cylinder.

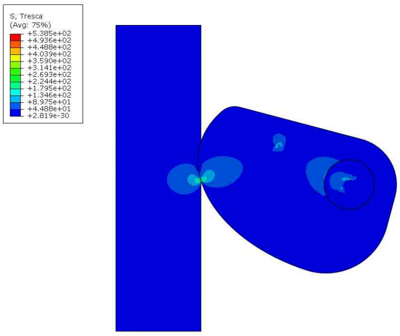

Fig. 6 Tresca Stress Contour by Clamping

7. Loads and Load Combinations

7.1 Loads

The cylinder is subjected to deadweight including internals and moving parts, clamping force and seismic load. Here, a pressure, busing nut preload and piston rod loads are not considered in the system design step and the water weight in the cylinder is not considered for a compensatory conservatism because of positive load effect. But all possible loads shall be considered in the detail design step according to service loadings.

For earthquake induced inertia loading, a quasi-static approach is used. With this method, the FRS accelerations corresponding to the rigid frequency are applied. This method is considered suitable since the hydraulic cylinder is a rigid component having natural frequencies greater than the 33 Hz cut-off frequency.

The FRS curves for the top of UGS were used to determine seismic accelerations for the hydraulic cylinder. The enveloped values at 33 Hz, for minimum damping (2%), described in Section 5 are applied in this study.

The masses of the parts attached to the cylinder also produce dynamic loads during seismic conditions. The mass of each internal part is generated with its geometry and density.

7.2 Load Combinations

The design and seismic load combination described above is considered as a representative service condition because all other service conditions are assumed to be enveloped by these two conditions through the conservative approach with the uncertainties in the system design step.

8. Results

Using the final pinch load derived by design and seismic load combination in Section 5 and 2-dimensional nonlinear contact finite analysis as shown in Fig. 5, the maximum Trasca stress of 538.5 MPa on each clamping contact region is calculated as shown in Fig. 6 with no relationship with the component material. The stress at the clamping region is a highly localized stress on the bearing (stiffener) surface of the damper cylinder. Although the stress has secondary stress characteristics (classified as a primary membrane plus bending stress), the stress is well below the corresponding limit for the load combination. The stress away from the clamping contact region is well within the allowable limit for membrane stress.

5. Conclusions

A stress analysis of the hydraulic cylinder for the SSDM used in JRTR has been performed through the conservative approach with the uncertainties in the system design step.

The crank's pinch load with no slip between the bearing (stiffener) plate of hydraulic cylinder and base plate of mount bracket during SSE has been calculated by considering the design and seismic load combination.

The stress by the load combination satisfies the Class 3 criteria given Table NG-3325 of Section III of the ASME Code. The maximum stresses are at the clamp contact region in the cylinder.

REFERENCES

[1] S. Kim et al., Reactor Shutdown Mechanism by Top-mounted Hydraulic System, Trans. of the KNS Autumn Meeting, 2012.
[2] K.R. Kim, Y.G. Cho, An experimental study on the factors for the performance of a shutoff unit in the half-core test loop of HANARO, Trans. of the KNS Autumn Meeting, 2005.