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TECHNICAL REPORT

In-vessel Type Control Rod Drive Mechanism Using Magnetic Force Latching for a Very Small Reactor

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A highly reliable control rod drive mechanism driven by an electric motor installed inside the reactor vessel (INV-CRDM) for a very small reactor has been designed. The INV-CRDM contributes to the compactness and simplicity of the reactor system, and can eliminate the possibility of a rod ejection accident. In the design, a new type of latch mechanism using an electromagnetic force to directly connect both of the shafts, one of which was the motor driven shaft and the other the control rod driving shaft, was applied so as to make the INV-CRDM very compact. The cable supplying current remained stationary, even when both of the shafts was moving. The required functions of the latch mechanism are to maintain an adequate latching force for the control rod shaft to move within a stroke of 370 mm, and to release the shafts in a shorter time than 0.2 s after a scram signal is received. A functional test with a model that approximately simulated the design was conducted to test the latching force and de-latching at room temperature. The test showed that the latching force increased with the current of the magnet coil, as did the de-latch time. The post-test analysis with a finite element analysis code revealed that the clearance between the two shafts greatly affected the latching force. With the same analysis method, the design analysis of the latch mechanism at a high temperature condition of 300°C was conducted, and it was confirmed that the latch mechanism contained enough latching force.

KEYWORDS: in-vessel type control rod drive mechanism, latch mechanism, immovable magnet, very small reactor, electromagnetic force

I. Introduction

In general, the reactor power of a marine reactor or a very small reactor is controlled by the reactor control system using only the control rods, without a chemical shim, to avoid a complex chemical processing system.

An in-vessel type control rod drive mechanism (INV-CRDM), which is installed inside the reactor vessel, can help achieve a highly compact and simple reactor system, and eliminate the possibility of a rod ejection accident. The Japan Atomic Energy Research Institute (JAERI) has developed this type of CRDM,[1)] driven by an electric motor, for the advanced marine reactor MRX[2)] with a thermal output of 100 MW, which is mainly used for a nuclear-powered ship. The INV-CRDM of the MRX adopts several innovative components, such as a latch mechanism with separable ball nuts, a synchronous motor with the rotor of a permanent magnet, and ball bearings, all of which are capable of working in high temperatures and under high water pressure. The INV-CRDM of the MRX can be basically applied for large-scale PWRs or BWRs.

In addition to the MRX, the JAERI has also designed a concept for another small-scale reactor, a submersible compact reactor, the DRX[3)] with a thermal output of 0.75 MW, as the power source of a scientific research vessel for deep undersea operations. The DRX has a more compact INV-CRDM than the MRX. Although the driving motor and the ball bearings adopted in the MRX's INV-CRDM can be basically applied by reducing the sizes to fit in with the DRX, the outer diameter of the latch mechanism with the separable ball nuts cannot be reduced below 200 mm due to mechanical limitations, while the DRX requires the diameter to be less than 140 mm.

The JAERI has developed a very compact INV-CRDM for the DRX that contains a new type of latch mechanism. The required functions for the latch mechanism are to mechanically connect the driving motor shaft and the control rod driving shaft, and to instantly separate them in the event of scram, that is, the fast insertion of the control rod into the core. The latch mechanism of the DRX should be arranged in a small space, and must be able to operate in high temperature steam. To comply with this requirement, a new type of latch mechanism using an electromagnetic force to directly connect both of the shafts was applied for the first time, and resulted in the construction of a very compact type of latch mechanism.

The latch mechanisms using the electromagnetic force for the CRDMs have been adopted in JAERI's swimming-pool type research reactors, JRR-3 and JRR-4. The CRDMs of these reactors are placed in atmospheric air outside the reactor vessels, with the JRR-3's CRDM being set below the reactor vessel, and the JRR-4's CRDM being set above the reactor vessel. Space to arrange the CRDM in these reactors is not restricted as tightly as it is in the DRX.

These latch mechanisms on the research reactors move vertically upwards or downwards along with the driving shafts of the control rods. The cable supplying the electricity to the latch magnet, therefore, should be stretched or folded back according to the position of the latch mechanism. The cables and relevant device must possess the mechanical strength sufficient to withstand the repeated stress caused by mechanical expansion and contraction as the latch mechanism moves, throughout the long operation life of the reactor.

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The new type latch mechanism for the DRX does not require a moveable cable; although the contact surface of the motor-driven shaft and the control rod driving shaft moves within the control rod stroke within the same range as the control rod is able to vertically move, the latch magnet and the cable for it do not move. This type of latch magnet enables the system to be very simple, compact, and reliable. The key issue in the realization of a very compact INV-CRDM is to ensure that the design of this type of latch mechanism can meet the required function, which is to firmly connect both shafts within the stroke, and to separate them instantly in the scram.

In the present paper, the concept for a very compact in-vessel type CRDM is described, focusing on the latch mechanism. In addition, a basic functional test on the latching, and a magnetic field analysis performed on the latching force, are described.

II. Design Conditions

The design conditions for this very compact INV-CRDM for the DRX were set up as follows. We took the fact that the INV-CRDM was being installed in a submersible into account for this set-up:

(1) Compactness

The DRX adopts four sets of the INV-CRDM inside the core barrel. The cross-sectional size of each CRDM should be no more than 140 mm of a side length in square, and the stroke should be 370 mm.

(2) Driving Function

The position of the control rod that connects with the driving shaft should be controlled stably, smoothly, and accurately during normal operation. The speed of the driving shaft as it moves upwards and downwards should be 0–390 mm per minute, except for the scram. The latch mechanism should maintain the connection of the motor-driven shaft and the control rod driving shaft—latching—during the control of the reactor power by the control rod except the scram.

(3) Scramming Time

The DRX requires a short scramming time below 1.0 s, which counts from the occurrence of the scram signal to complete insertion of the control rod into the core. Since the time for the control rod to pass through the core is estimated to be 0.6 s and a time delay of the signal reached to the latch mechanism 0.2 s, the time in which the very compact INV-CRDM releases the control rod after receiving the scram signal, which is called the de-latch time, should be less than 0.2 s.

(4) Effect of Ship Position within the Water

A change in the position of the ship due to an accident, such as the capsizing of the ship, should be taken into account when considering the functioning of a marine reactor. For the DRX, the total scramming time required is less than five seconds in the event of an inclination of 90° by the ship, and the de-latch time is less than 0.5 s. Even for an overturn of 180°, the scram should be securely completed.

(5) Circumstances in which the INV-CRDM should be Operated

The very compact INV-CRDM should be operated in high temperature saturated steam (about 290°C), since it works in a primary loop.

(6) Lifetime for Exchange of the Very Compact INV-CRDM

The design of the DRX requires the very compact INV-CRDM to last for 20 years without having to be exchanged, and to be capable of scramming at least 1,000 times throughout that 20-year lifetime.

Fulfillment of the design conditions (1), (2) and (3) will be described in the following chapter. The design conditions of (4) and (6) are not discussed in the present paper, since they are almost the same as those of the MRX. Working condition (5) with regards to the latch mechanism is also discussed.

III. Concept of a Very Compact INV-CRDM using Magnetic Force Latching

A conceptual drawing of the very compact INV-CRDM is shown in **Fig. 1**. It consists of four sections; a power source section for driving the control rods, a section of force transformation from rotation to linear motion, a latch mechanism with shafts, together with a spring, and a control rod position detector.

The power source section (**Fig. 2**(a)) induces rotational torque by a driving motor, which is a built-in type synchronous motor with a permanent magnet for the rotor, the same type of motor as in the MRX.[1] The force transformation section (Fig. 2(b)) transfers the rotational torque of the driving motor to the rectilinear motion of the shaft by a ball-nut-screw, which is of a self-lubricating type which does not require oil. For rotation, there are thrust and the radial ball bearings, which can be operated in high temperature steam. Since a ball bearing capable of operating in high temperature water has already been developed,[1] its applicability to steam conditions has now been investigated at Japan Atomic Energy Research Institute (JAERI). The latch mechanism, the most typical feature in the present concept, attracts both the motor-driven shaft and the control rod driving shaft to connect or latch them for normal operation with an electromagnetic force, or stops attracting them to separate or de-latch them for the scram. While the motor-driven shaft is made of a solid cylinder, the control rod driving shaft is hollow axially in the center to allow water to fill the space that will be made when both shafts separate in the event of a scram. Below the latch mechanism, the spring is set so as to help a scram to occur quickly, at any position the ship might assume, even during a hypothetical overturn, according to the design condition (4). The control rod position detector uses a magnetostrictive wire type sensor on the principle of the Wiedeman effect, the same as the MRX's one,[1] and is arranged to be parallel to the motor-driven shaft in order to avoid the magnetic effect of the latch mechanism.

The main design parameters are presented in **Table 1**. The dimensions were decided on the basis of the DRX design. The maximum size of the very compact INV-CRDM satisfies the design conditions on compactness. The maximum required drawing force in latching is 0.5 kN, which includes the weight of the control rod driving shaft, the total weight of the control rod cluster, and the maximum spring force at the highest position of the control rod driving shaft within the range of shaft motion.

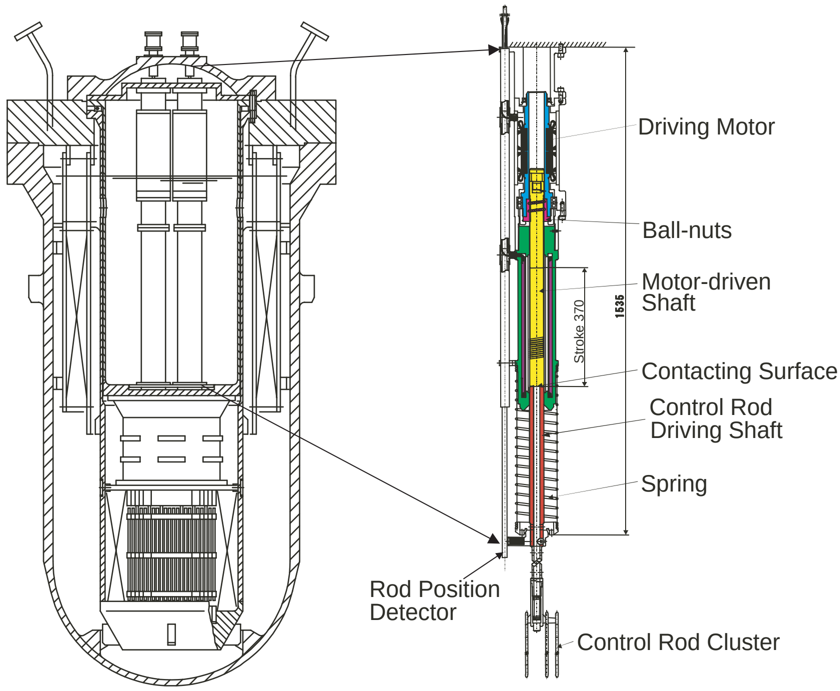
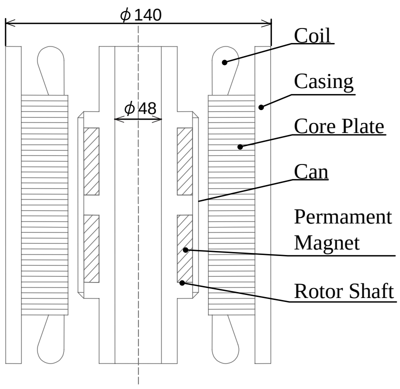
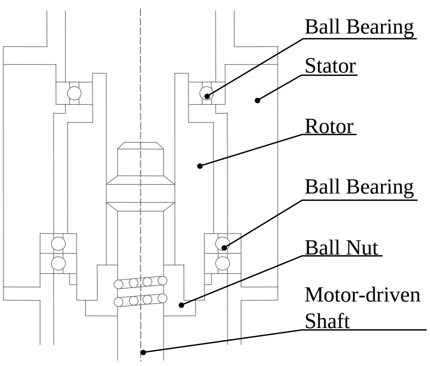


Fig. 1 Concept of a very compact INV-CRDM in a very small reactor



(a) Section of power source



(b) Section of force transformation

Fig. 2 Concept of power source and force transformation

The motion of the latch mechanism is illustrated in **Fig. 3**. The components of the latch mechanism are an electric magnet coil, a magnet enclosure for the magnetic field, and the shafts. These shafts are apart from each other during non-operation. Both the materials of the shafts and the magnetic enclosure—the yoke—are SUS-440, through which a magnetic flux can pass. When the electric magnet is energized, a magnetic flux passes through the magnet enclosure and these shafts, and both shafts are attracted by the magnetic force. After de-energizing the electric magnet, both shafts can be separated with the assistance of the self-weight and spring force.

Note that although both shafts contact substantially by energizing the magnet, a small distance between them, a clearance distance, should be maintained for fast separation during a scram. If they contact without any clearance, the time lag to separation after the de-energizing of the magnet will increase due to the residual magnet flux in the shaft. This time lag, called the de-latch time, in other words, the time it takes for the latch mechanism to release the control rod shaft after receiving the scram signal, is the same as the one in the reference,[1)] and should be smaller than 0.2 s as the design value for the normal ship position. In the present design, a clearance of 0.5 mm is maintained by chromium plating, which is a non-magnetic material. In the present paper, the contacting surface means the surface contacted substantially with the magnetic clearance.

After scram or once the magnet has been de-energized, both the shafts will be positioned apart from each other, and their maximum distance will be within the stroke. The shafts can be connected again by energizing the magnet after the

Table 1 Main design parameters of the INV-CRDM for a very small reactor by comparison with those of MRX and PWR

Items	Present design	For MRX	For PWR
Type	In-vessel type, motor driven	In-vessel type, motor driven	Out-vessel, Mag-jack driven
Operating conditions	In the primary loop (298°C, 8.4 MPa, steam)	In the primary loop (310°C, 12 MPa water)	Magnet coil in air (<180°C, 0.1 MPa)
Dimensions			
Outer diameter	140 mm (a length in square)	200 mm	274 mm
Stroke	370 mm	1,400 mm	3,620 mm
Maximum required drive force	0.5 kN (latching force)	2.2 kN	1.6 kN
Scramming force by	Weight and spring	Weight and spring	Weight

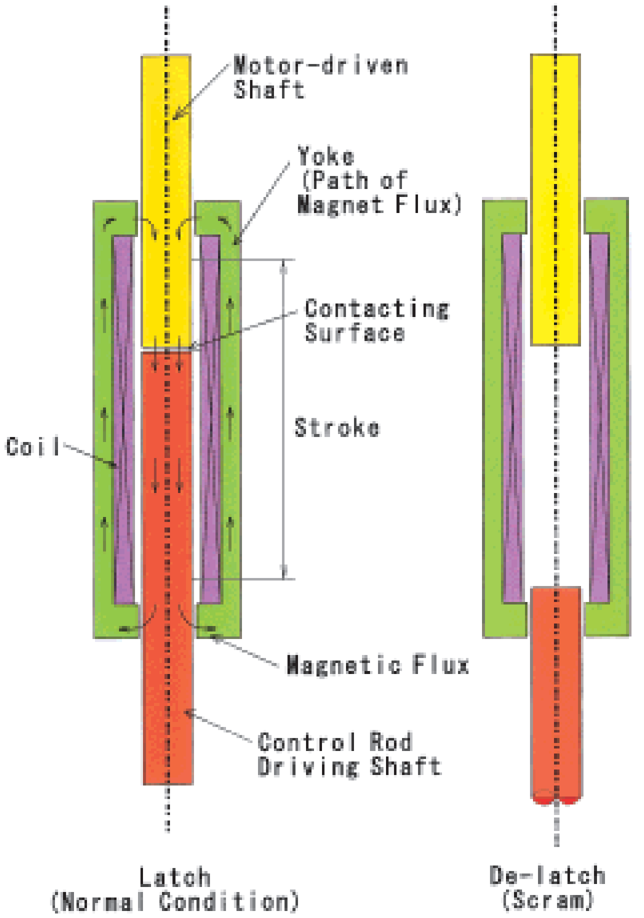


Fig. 3 Motion of latch mechanism

motor-driven shaft approaches, with the help of the drive motor to the control rod driving shaft.

The force (F) to attract the shafts, *i.e.*, the latching force, depends on the amount of magnetic flux (B) passing through the contacting surface and the cross section area (S) of the shaft, as expressed by the following equation:

$$F = 0.5 \times B^2 \times S/\mu_0, \tag{1}$$

where μ_0 is the space permeability. The magnetic flux is a function of the electrical current to the magnet coil, the material and configuration of the magnetic flux pathway, the surrounding temperature, and the clearance between both shafts. Although the magnetic flux increases with the electricity to the magnet, its increase is limited by magnetization saturation, and the saturated value B_s, which depends on the material and the surrounding temperature.

However, the total downward load (W) of the control rod driving shaft is expressed by a summation of the weight (W_0) of the control rod driving shaft within the stroke, the weight (W_1) of the rest of the control rod driving shaft and the control rod cluster, and the spring force (P):

$$\begin{aligned} W &= W_0 + W_1 + P \\ &= S \times L \times \rho + W_1 + P, \end{aligned} \tag{2}$$

where L is the stroke, and ρ is the density of the control rod driving shaft.

The force F should be greater than the load W for latching. This leads to the fact that if the stroke is too large, latching will be impossible for a given saturated magnetic flux B_s. Thus, the maximum stroke of this type of latch mechanism ($L_{\max}$) is limited by the value of B_s:

$$\begin{aligned} &F \geqq W \\ &0.5 \times B_s^2 \times S/\mu_0 \geqq S \times L_{\max} \times \rho + W_1 + P \\ &0.5 \times B_s^2/\{\mu_0 \times \rho(1+N)\} \geqq L_{\max}, \end{aligned} \tag{3}$$

where N $(= (W_1 + P)/W_0)$ is the ratio of the weight W_1 and the force P against W_0. The maximum stroke $L_{\max}$, which satisfy Eq. (3), becomes the greater for the larger B_s and the smaller ratio N. In the present design, the stroke L of 370 mm has a relatively large reserve against the $L_{\max}$ of about 1.8 m for $N = 6$ and $B_s = 1.6$ T.

In this discussion, however, the effect of clearance on the force is not taken into account. In practice, the function of the latch mechanism should maintain enough latching force and a lesser de-latch time under the limitation of $L_{\max}$. In general, when the latching force becomes greater, the de-latch time increases.

In the following chapter, the functional test performed is described. Although the test conditions are not always the same as the design conditions, this test confirmed the basic performance of the latch mechanism. A post-test analysis on the magnetic field was conducted to clarify the characteristics of the magnetic flux profile.

IV. Functional Test of Latch Mechanism

Tests of the latching and de-latching motion were conducted. The maximum magnet latching force (F_M) and the de-latch time (T_d) were measured at conditions of room temperature.

1. Test Assembly

The test assembly is presented in **Fig. 4**. The main parameters are presented in **Table 2**. The top of the upper shaft simulating the motor-driven shaft was hung in the test section by a crane through a load cell. The bottom of the lower shaft simulating the control rod driving shaft was connected with an air-cylinder through an extension rod. The air-cylinder was used to adjust the downward vertical load. Both shafts were made from SUS-410, through which a magnetic flux can pass, and were hollowed axially in the center for convenience in the test procedure. The stroke of the moving shaft was 400 mm. A magnet coil with a winding number of 580 turns was arranged outside the shafts.

In the test, a direct current was fed to the electric magnet up to a maximum of 6 A. A non-fuse circuit breaker NFB was used to instantaneously cut the electricity supply to the electric magnet for the scram test, by which the de-latch time was measured. Output signals such as the load cell and the current were recorded by a thermal-array recorder.

2. Test Results

As a preliminary test, the de-latch time was measured without inserting any plate between both shafts—no magnetic clearance—to confirm the effect of the residual magnetic flux on the de-latch time. In this situation with no magnetic clearance, the de-latch time was revealed to be very large, in the order of seconds, while it was very small in the same degree when the magnetic clearance was 0.3–0.7 mm. Therefore, a thin SUS-304 plate with a 0.7 mm thickness, which is a non-magnetic substance, was glued to the top of the lower shaft to make the clearance in the following test.

The forces F_M were measured by energizing the magnet after the position was fixed using the crane, and by pulling the lower shaft downwards with the air-cylinder. The forces F_M are shown in **Fig. 5** for the different positions with the parameter of the current.

The forces F_M are shown to increase with the current of the magnet coil. The profiles of F_M are relatively flat along the moving length of the contacting surface, although the F_M values at the top position are slightly greater than those at the bottom position. The reasons for the derivation from the flat profile of F_M are considered to be caused by the distortion of the shaft center, the scattering of sizes, such as the shaft diameters or gaps between the shaft and the yoke, the magnetic resistance, and the non-uniform winding of the magnet coil in fabrication. If the magnet coil were wound non-uniformly along the moving length of the shaft, the magnetic flux passing through the contacting surface would differ according to the position. In the process of coil assembly, it was possible

Table 2 Main parameters of the functional test

Items	Parameters
Test conditions	Room temperature, in air
Magnet	
·Outer dia. (Inner dia.)	118 mm (72.1 mm)
·Guide tube inner	41.2 mm
·Length	490 mm
·Coil winding	580 turns
·Material of yoke	Carbon steel
Shaft	
·Outer dia. (Inner dia.)	40 mm (22 mm)
·Length of each shaft	485 mm
·Material	SUS403
·Gap spacer	SUS304 (0.7 mm)

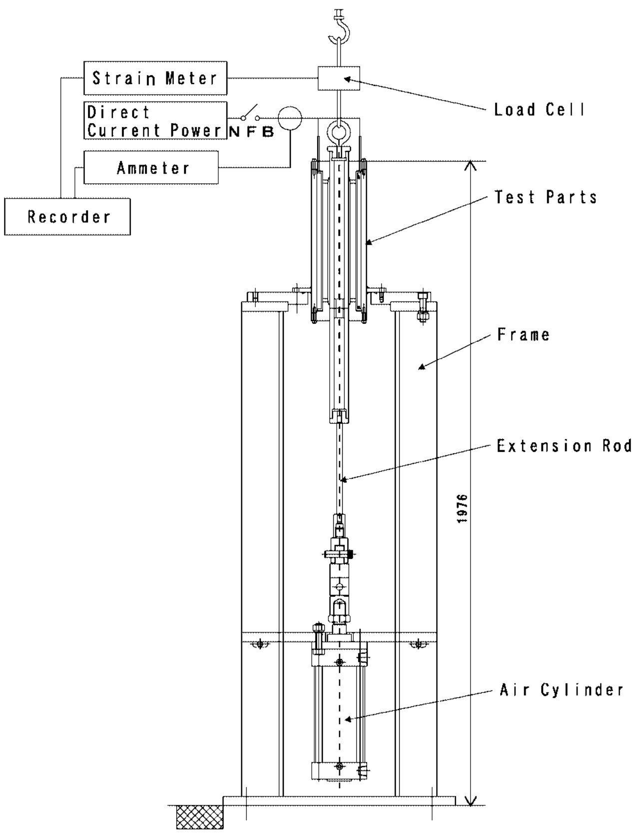


Fig. 4 Test assembly

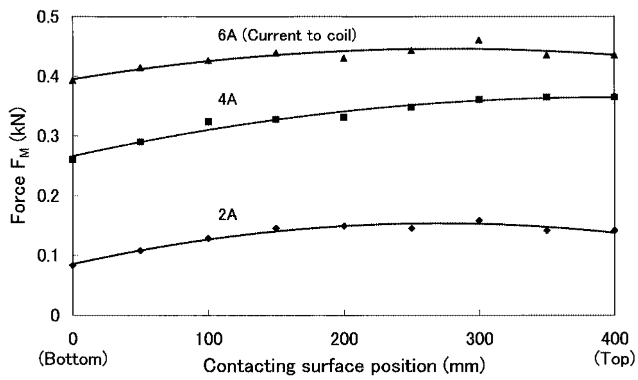


Fig. 5 Force F_M measured in the test at room temperature

for the coil to be partially wound.

Although hollow shafts were used in the present test, the solid shaft will be adopted for the upper shaft—the motor-driven shaft—in the DRX. The force F_M in the case of the solid rod can be increased 1.25 times over the present hollow rods, an increase which is based simply on the ratio of both cross-sectional areas. This result roughly indicates that the required force of 0.5 kN for the DRX can be attained with a minimum current of 6 A at room temperature conditions. Since the magnetic flux will decrease at a high temperature, a design-based analysis with the B-H curve, the relationship between the magnetic flux density and the magnetic coercive force H for high temperature, is necessary. In the present study, the B-H curves of the SUS-410 were measured at 300°C and at room temperature. The B-H curves of the SUS-410 are shown in **Fig. 6**, together with those of the carbon steel at room temperature. The measured curves show that the B of SUS-410 becomes smaller at a high temperature for the H over 250 Oe, and is smaller than that of carbon steel.

The measured de-latch time T_d is shown in **Fig. 7**. The current to the coil was 6 A, and the pulling force of the control rod driving shaft was 0.15 kN, which were conservative conditions for the de-latch time, since a larger current and a smaller pulling force make for a larger de-latch time. The measured de-latch times were all below 0.2 s, because of the help of the magnetic clearance between the shafts. The profile of T_d along the length was approximately flat, although it was larger at the middle position than at both ends, due to the residual magnetic flux after the demagnetization of the magnet coil. The test result shows the design condition (3) for the scramming time can also be satisfied, provided a proper clearance, taking into account the attracting force, is maintained.

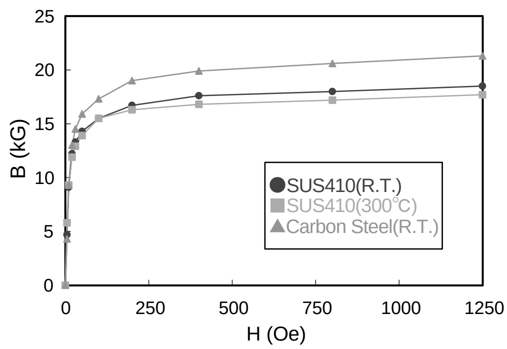


Fig. 6 Measured B-H curves of SUS-410 and carbon steel

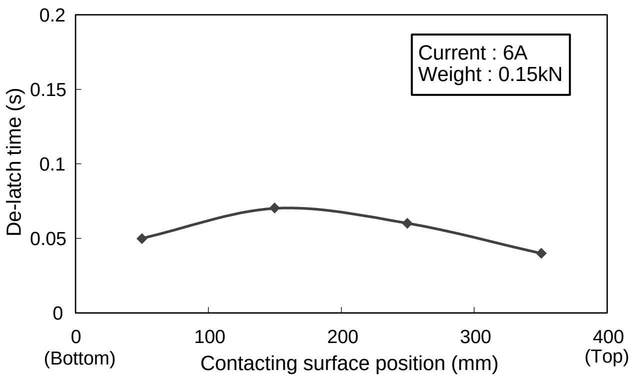


Fig. 7 De-latch time measured in the test at room temperature

V. Magnetic Field Analysis

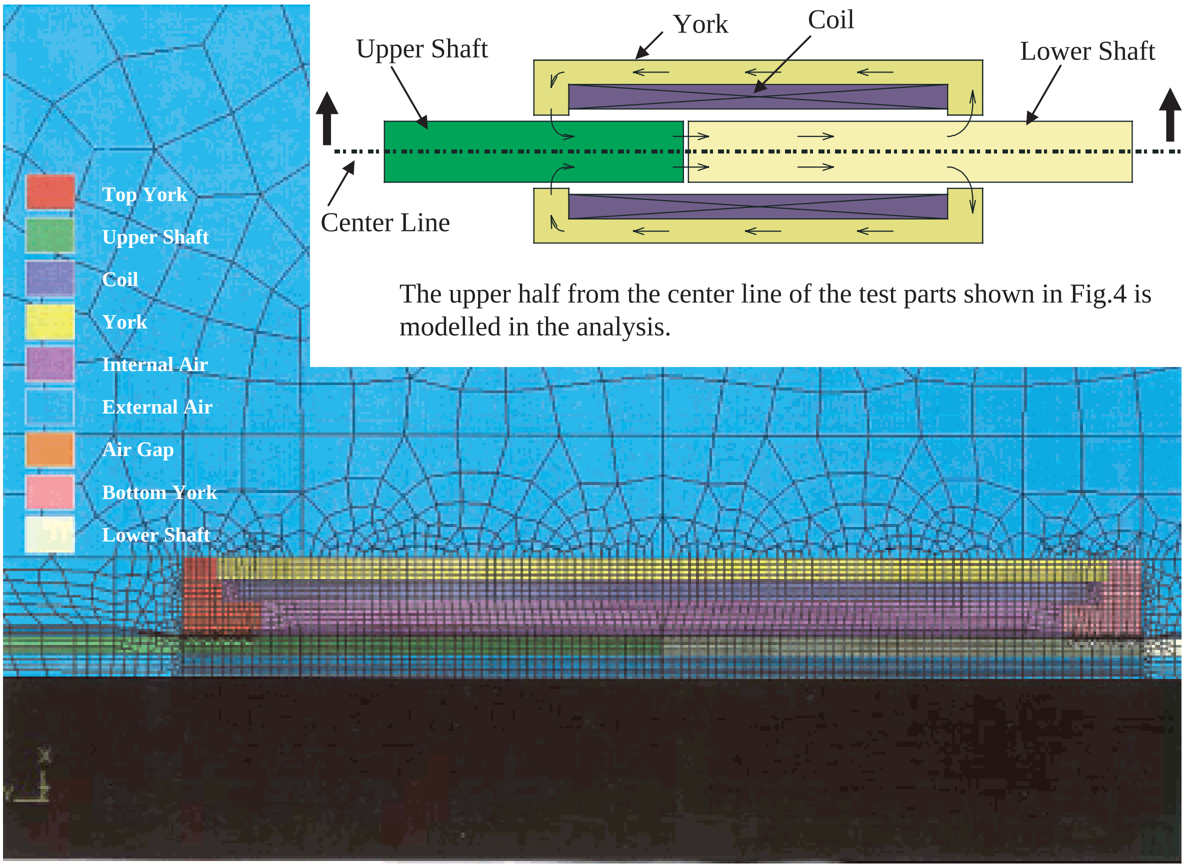
1. Post Test Analysis

The force F_M in the test was analyzed by a magnetic field code. The magnetic flux passing through the rod depends on the magnetic resistances such as a gap or area reduction, and its leakage from the shaft surface or at a branch, together with the ampere-turn profile of the magnet coil. The magnetic flux analysis was conducted to reveal the magnetic flux profile by focusing on the magnetic resistance and the leakage.

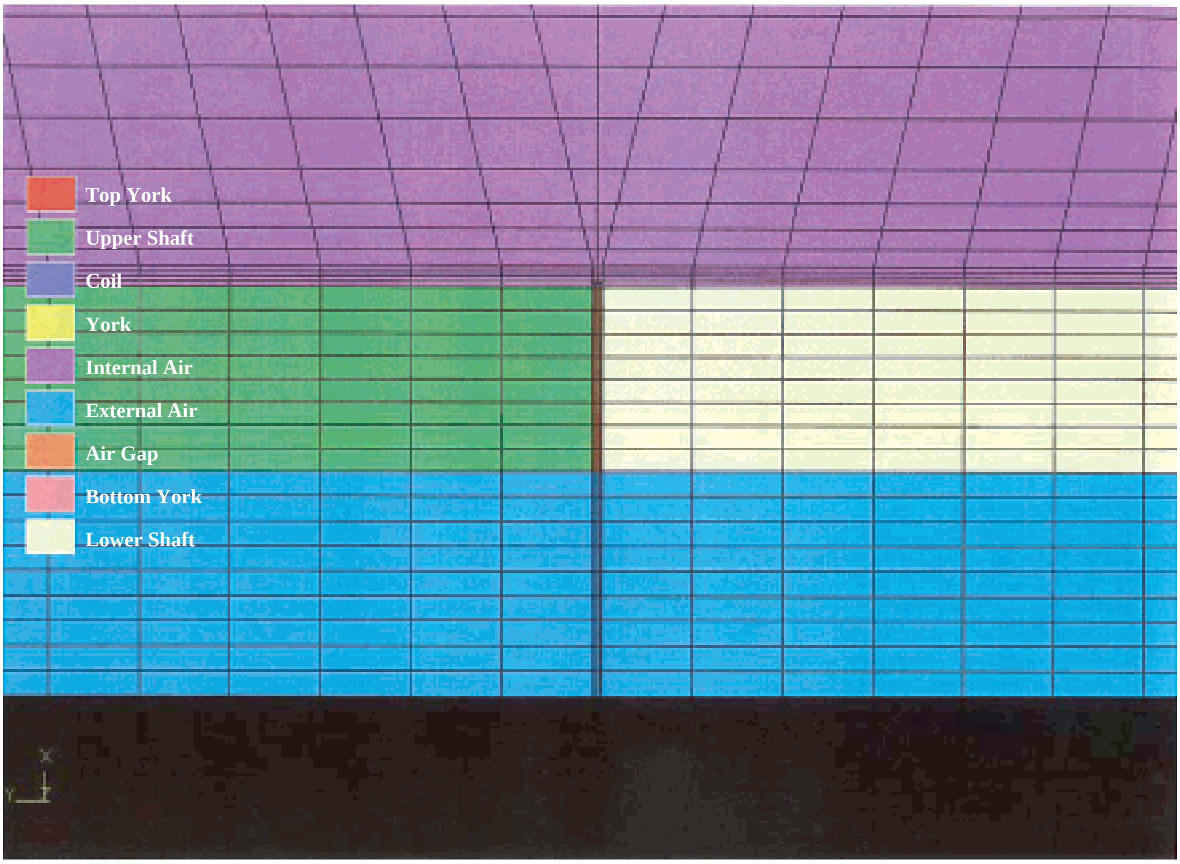
A finite element analysis code, MAGNA/FIM, was used with the axial symmetry two-dimensional vector potential method (A-ϕ method). The analysis model for the half of axial symmetry of the test section is shown in **Fig. 8**(a) for overall, (b) for details of the contacting part. The total numbers of the junction and element were 8,093 and 8,013, respectively. In the present analysis, the ampere-turn profile of the magnet coil was taken as uniform to clarify the effect of the magnetic resistance and leakage on the magnetic flux profile, and the infinite boundary was applied as a boundary condition. The force F_M was calculated by the Maxwell stress method, which is the surface integration of the magnetic flux.

The vector profile of the magnetic flux density for the condition of current 6 A is shown in **Fig. 9**(a) for the whole test section and in Fig. 9(b) for each part. The position of the contacting surface is set at the middle of the range. Analysis showed that most of the magnetic flux passed through the shaft inside. A small amount of the magnetic flux made a short path emerging from the shaft surface, some of which did not pass through the contacting cross-sectional area and were not attributed to the attraction force, the leakage of the magnetic flux. At the corners of both the top and the bottom positions, a little magnetic flux goes outside along the shafts, not towards the yoke, and this flux is also the leakage. Around the contacting surface, some leakage due to the gap was seen. The ratio of the magnetic flux passing effectively through the contacting surface area to the maximum magnetic flux in the path of the yoke was about 0.94 in this case. The magnetic flux density was larger at the smaller cross-section area, and *vice-versa*. The maximum magnetic flux density in the pathway was less than 1.5 T, which means that the magnetic flux does not reach to saturation on the base of the measured B-H curve.

The force F_M obtained by the analysis was compared with that of the test data. The comparison is shown in **Fig. 10** against the current, where the position of the contacting surface is just at the middle of the range. Both of the forces increased with the current. However, the analysis values were larger than the test ones. The reasons for this difference were considered to be because of the larger gap thickness in the test, more magnetic leakage, more resistance than expected, and the distortion of the shaft center in the test. The results of the parameter survey analysis on the gap thickness are presented in the same figure. It shows that gap thickness had a great effect on the force F_M, and the result of the gap thick-

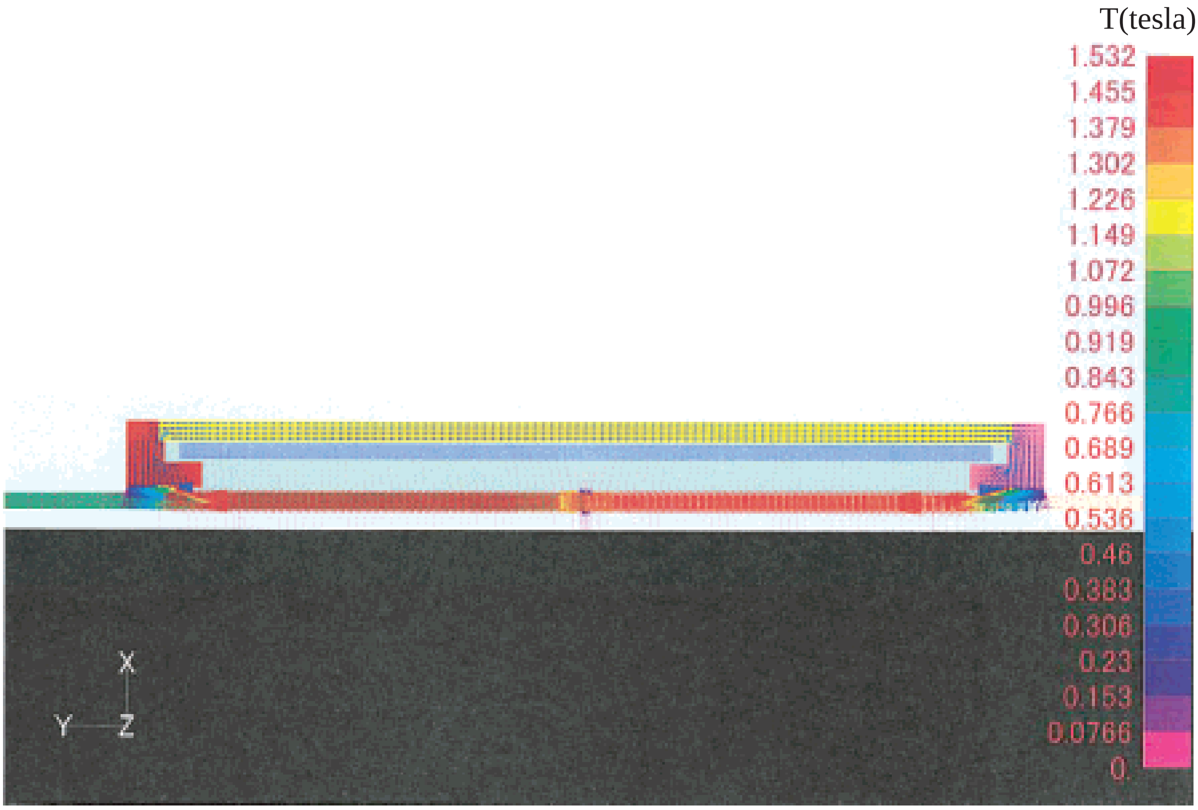


(a) Overall

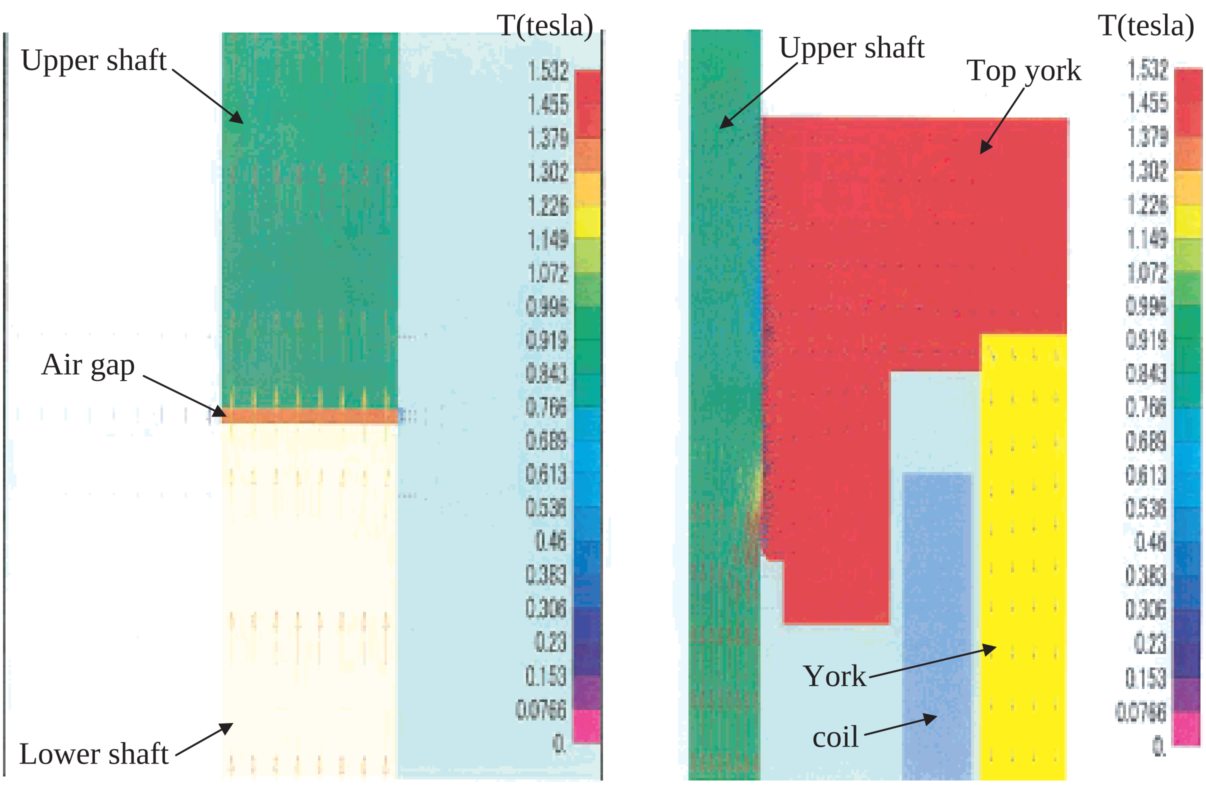


(b) Contacting part

Fig. 8 Model for post-test analysis



(a) Whole test section



(b) Parts in detail

Fig. 9 Vector of magnetic flux density of post-test analysis; current 6 A, the center position of the stroke ness 0.9 mm agreed well with the test data. Note that the gap was made in the test by gluing a thin plate (of a 0.7 mm thickness) of SUS-304 with a bonding agent to the top of the control rod shaft surface. Although it was uncertain how thick the bonding agent was, it can be said that the substantial gap thickness was close to 0.9 mm. Apart from the test, the clearance of the real sized latch mechanism can be accurately maintained by chromium plating by manufacturing prototype latch mechanisms.

The analysis values of F_M with a clearance of 0.9 mm are shown in **Fig. 11** for the whole range of the stroke by comparing with the test values. At the center and the bottom, the analysis values show good agreement with the test data. At the top position, the test data was greater than the analysis values, which was probably due to the magnet coil of the present test being wound denser at the upper part than at the lower part.

As a result, the profile of the magnetic flux in the pathway was revealed, and the forces F_M compared well between the analysis and the test, providing the substantial gap thickness was 0.9 mm, thicker than the plate, and the coil was wound thicker at the upper part.

2. Design Analysis of Latch Mechanism

The magnetic field analysis for the design based latch mechanism of the DRX shown in Fig. 1 was performed with the same analysis method as that of the post test analysis. The presentation of the analysis model similar to that of the post-test analysis is omitted to avoid overlapping. The differences of the geometry parameters between the test and design analyses were the stroke (400 mm, 370 mm), the substantial gap thickness (0.9 mm, 0.5 mm), the hollow shaft or the solid shaft for the motor driven shaft, and the coil winding number (580, 500 turns). The design based latch mechanism is to be operated under high temperature conditions of 290°C.

The ampere to the magnet is varied in three cases: 6 A, 8 A, and 10 A. The analysis result of the force F_M in the range of the stroke is shown in **Fig. 12**. The force F_M becomes smaller at the upper part than at the lower part, because the motor-driven shaft is solid, where the magnetic resistance or leakage is less than that of the hollowed shaft. The required force to latch is 300 N at the bottom position and 500 N at the top position. Even in the case of the current to the magnet 6 A, the design value is greater than the required force.

It can be confirmed by analysis that the force F_M of the design based latch mechanism conforms to the requirements

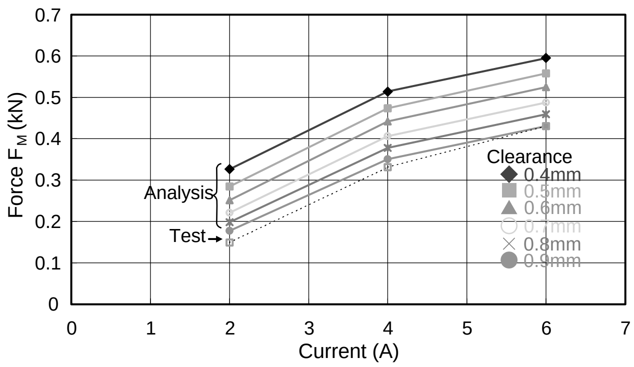


Fig. 10 Comparison of force F_M between the analysis and the test—at the center position of the stroke

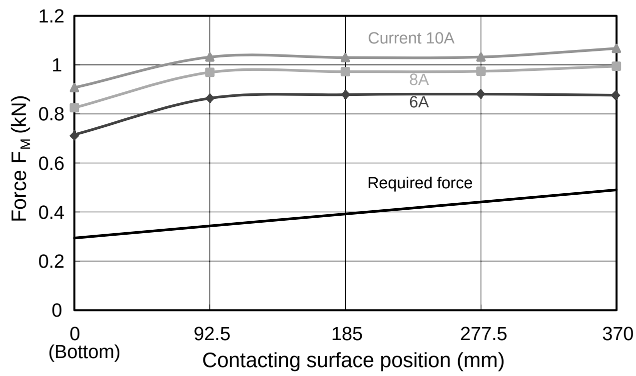


Fig. 12 Design analysis of latch mechanism on latching force

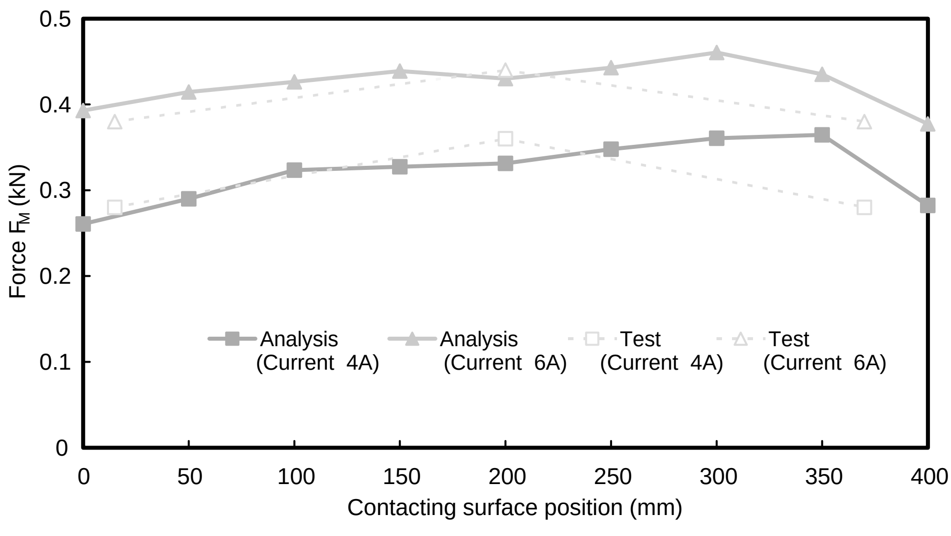


Fig. 11 Comparison of force F_M between the analysis and the test—Clearance 0.9 mm for the analysis

of the DRX in high temperature circumstances. The attracting force is independent whether water or steam.

Apart from the attracting force, the de-latch time should be confirmed as being less than 0.2 s by a test under high temperature circumstances, since it is difficult to analytically estimate the de-latch time. The clearance can be optimized on the force F_M and the de-latch time according to the full-scale test data, which will be included in a next stage study.

VI. Conclusion

A new type of latch mechanism which uses an electromagnetic force to directly connect both of the shafts, and which does not require a moving cable, was applied for the first time. With the functional test of the latch mechanism under room temperature and the magnetic field analyses, the following conclusions can be made:

(1) The entire size of the present INV-CRDM satisfies the design conditions of compactness by virtue of its simple latch mechanism.

(2) The maximum stroke $L_{\max}$ of this type of latch mechanism is generally expressed by Eq. (3), with the conditions of the latching force being greater than the total weight. In practice, the de-latch time should be taken into account in addition to the latching force under the limitation of the $L_{\max}$.

(3) The latching force was confirmed, by a functional test using a model at room temperature, to increase with the current of the magnet coil, and the de-latch time also to increase with the current. The clearance between the contacting shafts was revealed by a post-test analysis to dominate the latching force, which is also affected by magnetic leakage and by resistance through the pathway.

(4) At a high temperature of 300°C, the feasibility of the latching force of the present design was confirmed by the design analysis of the latch mechanism.

(5) The clearance affects both the latching force and the de-latch time. Since the de-latch time is difficult to evaluate analytically, a test using the full sized model under the same conditions as during reactor operation is necessary to optimize the attracting force and the de-latch time in a subsequent study.

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