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《Technical Note》

Development of Self-Actuated Shutdown System Using Curie Point Electromagnet

Tae-Ryong Kim* and Jin-Ho Park
Korea Atomic Energy Research Institute
150 Dukjin-dong Yusong-ku, Taejon 305-353, Korea
trkim@kepri.re.kr

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Abstract

An innovative concept for a passive reactor shutdown system, so called self-actuated shutdown system(SASS), is inevitably required for the inherent safety in liquid metal reactor, which is designed with the totally different concept from the usual reactor shutdown system in LWR.

SASS using Curie point electromagnet(CPEM) was selected as the passive reactor shutdown system for KALIMER (Korea Advanced Liquid MEtal Reactor). A mock-up of the SASS was designed, fabricated and tested. From the test it was confirmed that the mockup was self-actuated at the Curie point of the temperature sensing material used in the mockup. An articulated control rod was also fabricated and assembled with the CPEM to confirm that the control rod can be inserted into core even when the control rod guide tube is deformed due to earthquake. The operability of SASS in the actual sodium environment should be confirmed in the future. All the design and test data will be applied to the KALIMER design.

Key Words : self-actuated shutdown system, curie point electromagnet, liquid metal reactor

1. Introduction

Liquid metal reactor (LMR) has some inherent safety characteristics as follows [1];

① Low pressure
② Subcooling margin
③ Excellent heat transfer characteristics of the coolant
④ Low transient reactivity

Even though LMR is said to be in general safer than light water reactor(LWR) in virtue of the above inherent characteristics, the reliability of the reactor shutdown systems is particularly important to managing the core meltdown accident, since LMR is operated in the higher temperature and the fast neutron environment than LWR. Due to these environments, the structural design of the LMR is different from that of LWR, that is, thin shell is used in LMR to reduce the possibility of thermal shocks.

* : Korea Electric Power Research Institute at present

To enhance the reliability of the structures and to warrant the safe shutdown of the reactor for unprotected anticipated transient without scram(ATWS) events, an ultimate shutdown system is inevitably required in addition to the usual reactor shutdown systems for the inherent safety in LMR. Since the ultimate shutdown system is recommended to be designed in a passive concept, it is sometimes called a self-actuated shutdown system(SASS).

SASS is, by definition, a mechanism actuating in case of the accident condition to safely shutdown the reactor core by its physical characteristics without any triggering signal or external powers for actuating. On the other hand, SASS is not controlled by the external actuating circuits (sensors, logic circuits, etc) of the reactor protection system, but controlled by the change of its physical characteristics, just as the fuse in electric lines.

According to the physical properties used, several types of SASS have been developed. SASS utilizing the flow pressure of the coolant has been mostly developed in USA[2~5]. The shut-off rods floated on the pressure generated by the precisely designed orifice and bellows in the normal operating condition are dropped and inserted into core by the gravity of the rods when the pressure is diminished due to the loss of flow condition. Another type of SASS utilizing a Curie point electromagnet(CPEM) has been developed in several countries[6~11]. The principle of this type is to use the physical phenamenon that the saturated magnetic flux density in the electromagnet made of a ferromagnetic material for holding control/ shutoff rods is drastically decreased when the material is heated up to its Curie point. The actuating temperature of this SASS type is entirely dependent on the ferromagnetic material used, which is called temperature sensitive material(TSM). The shut-off rods held by the electromagnet with TSM are released when the coolant(sodium) temperature rises and the temperature of the TSM subsequently reaches the Curie point of the TSM during the abnormal condition of the reactor core (e.g. unprotected ATWS). Even though the electric power is continuously supplied to CPEM, the released shutoff rods are inserted into the reactor core by the gravity to safely shutdown the reactor core.

In spite that most SASS developed up to date were done with the functional test in laboratory, they have not been installed in actual reactors since most programs of fast breeder reactor development in the world have been cancelled or postponed.

SASS concept using CPEM was selected for KALIMER (Korea Advanced Liquid MEtal Reactor) which is under development as one of the national nuclear programs, based on the evaluation of its functionality, licensibility, cost, reliability, manufacturing, operability and maintenance. The mock-up test was also performed to confirm the operating principle and to verify the passive characteristics of SASS[12].

2. Design of SASS

2.1. Curie-Point Electro-Magnet(CPEM)

In design of the SASS, the most important parameter is the Curie point at which the control/shut-off rods in ultimate shutdown system are self-actuated. As the Curie point is one of the material properties, the selection of operating Curie point means the selection of the TSM. In this report, the operating Curie point was determined to be 600°C for the confirmation of the operating principle of SASS considering the core exit temperature of the coolant in KALIMER.

CPEM, the key component of the SASS, is composed of electromagnet core, coil and the

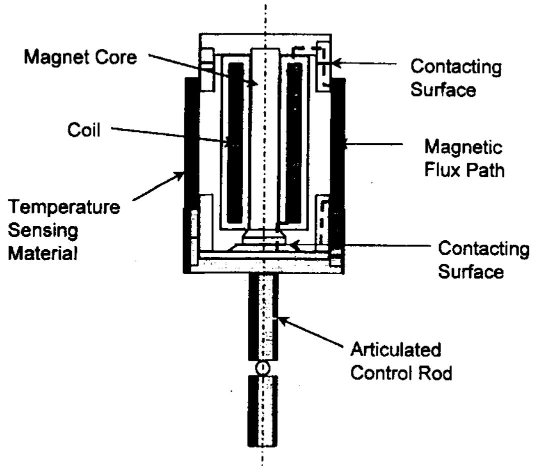

Fig. 1. Schematic Diagram of CPEM

Table 1. Materials Used in CPEM in the Test

Component	Material	Characteristics
TSM	High nickel alloy (62.5%Ni-Fe)	Curie point= 570℃ ~590℃ Tensile strength= 66,558 psi
Core	Pure iron	Curie point= 760℃ Melting point= 1532℃ Maximum permeability= 5,000 Tensile strength= 39,036 psi
Coil	Alumina dispersed copper alloy	Melting point= 1083℃ Thermal conductivity = 365w/(m · k) at 20℃
Insulation	Flexible Mica sheet	Breakdown voltage= 20kV

temperature sensitive material (TSM) as shown in Fig. 1.

2.1.1. Materials Used

A high nickel alloy(62.5%Ni-Fe) was selected as the TSM in this study based on the requirement of the Curie point and the availability of the material. The Curie point of the alloy was known to be 600 ℃ according to several literatures[6~9], but the purchased nickel alloy was reported to have the Curie point of 570℃ ~590℃ by the manufacturer.

The material used for the electromagnet core of CPEM is required to have the higher Curie point than that of TSM so as to maintain a strong ferromagnetism at the operating Curie point. By this requirement, a pure iron(Curie point: 770℃) was selected as the electromagnet core material.

The coil used in the electromagnet is also required to have good conductivity, stability and mechanical strength up to the operating Curie point. The alumina-dispersed copper alloy was selected as the coil element.

The insulation material used with the coil was selected to be a flexible Mica because of its high electrical resistivity (breakdown voltage: 20kV) and flexibility (thickness: 0.15mm) for easy fabrication.

The materials used in CPEM and their characteristics are summarized in Table 1.

2.1.2. Structure and Magnetic Flux Design

The structure and the magnetic flux of CPEM should be designed to maintain the electromagnetic force enough to hold the control/shutoff rods of ultimate shutdown system during the normal operation, and to make the TSM to be heated up to Curie point as soon as possible for an unprotected ATWS. Therefore it is recommended that the surface of TSM be designed to have fins for the good heat transfer between TSM and coolant. In this report, however, the TSM was designed to be a simple cylinder because the purpose of this study is to confirm the principle of CPEM.

The saturated magnetic flux density should be at least 0.5 Tesla to prevent the false actuation during the normal operation. It is also required that the hysteresis in the magnetism be negligibly

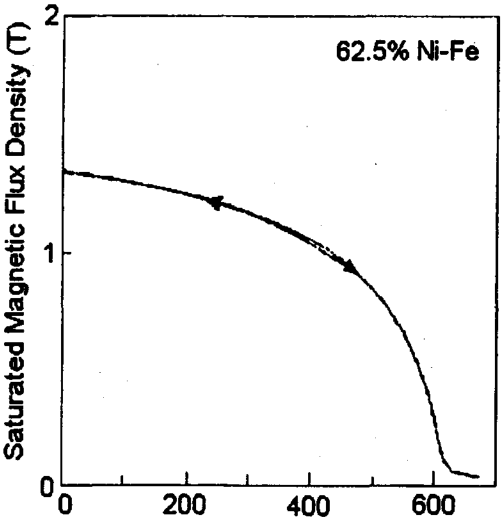

Fig. 2. Saturated Magnetic Flux Density of the TSM Used

small. The saturated magnetic flux density characteristic of the nickel alloy is shown in Fig. 2.

The coil with the insulation material was wound on a cylindrical bobbin and assembled with the magnet core. The cylindrical TSM was installed on the path of the magnetic flux outside of the magnet core, so that the electromagnetic force was decreased to drop the control/shut-off rods with TSM when the TSM was heated up to the operating Curie point. To measure the temperature of TSM, three(3) K-type thermocouples were installed on the surface of the TSM in the interval of 120° around the cylindrical TSM.

2.2. Articulated Control Rods Design

The control/shut-off rod mockup was also manufactured and assembled with the TSM. As mentioned earlier, LMR structure is designed to be a thin shell for the operating condition of low pressure and high temperature. The thin shell structure has an advantage against thermal shock but a disadvantage for earthquake. Therefore the possibility of distortion of the guide tubes for

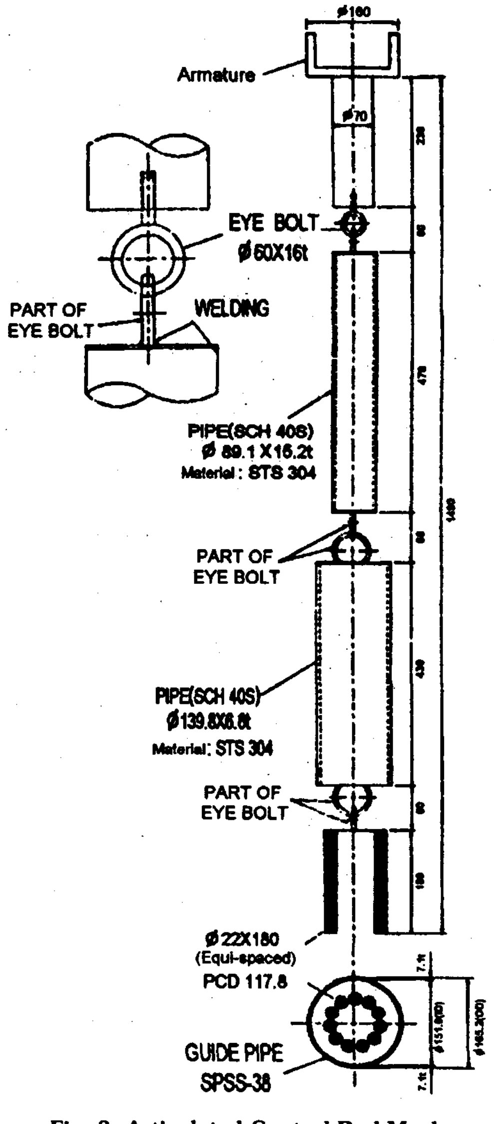

Fig. 3. Articulated Control Rod Mockup

control/ shut-off rods of ultimate shutdown system during the earthquake should be considered in the design of SASS.

The mockup was designed to have 3 articulated joints as shown in Fig. 3 so that the control/shut-off rods could be inserted into the reactor core to safely shutdown the reactor even when guide tubes for the control/shut-off rods were distorted due to the earthquake. Since the articulation was of a simple mechanical type (eye bolt), it was free from

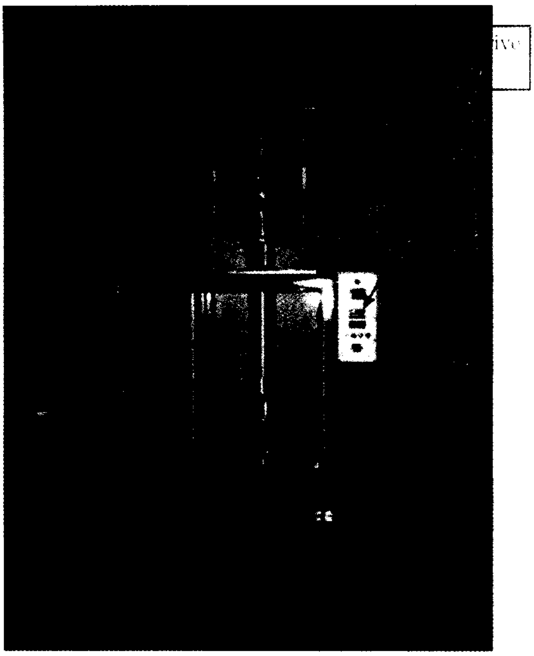

Fig. 4. SASS Test Rig

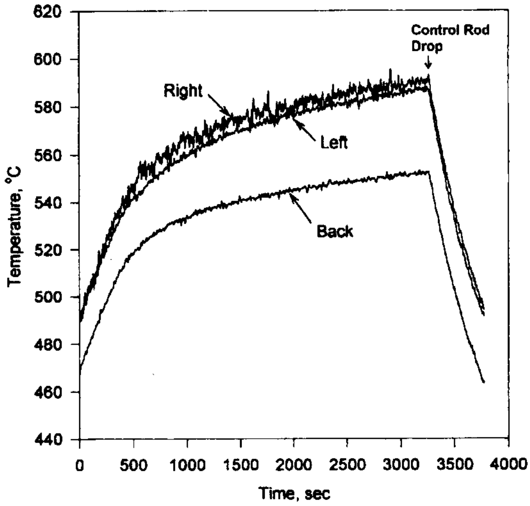

Fig. 5. Temperature Change on Surface of the TSM

any malfunction caused by the impurity in the coolant (sodium). The total length was 1.5m and the weight was about 70 kg which was expected to be the weight of actual control rod. The material used was the stainless steel for the test in water or sodium later.

2.3. Test Rig Design

A test rig is needed to heat up the TSM to at least its Curie point for the function test of the CPEM. A furnace (heating capacity: 8 KW) with a small chamber to heat up the CPEM only was manufactured for the test rig. A thermocouple (K-type) was installed to indicate the temperature inside the chamber. The furnace was also equipped with an inert gas supplier to prevent the oxidation of the CPEM. A guide tube with a shock absorber at the bottom was prepared below the furnace chamber for the drop of the control rod mockup. Sight glass was also prepared in the guide tube to visually confirm the drop of the control rod mockup.

Once the control rod with TSM is dropped by the gravity, the temperature of the TSM is lowered below the Curie point and the saturated magnetic flux density in the TSM is subsequently restored. A control rod drive mechanism using an air cylinder was designed to hold and raise the control rod up again. Fig. 4 shows the whole test rig. It was equipped with 4 casters for the easy mobility.

3. Test Results and Discussion

Function test of the SASS concept using CPEM was carried out. At first the nitrogen gas as the environmental gas was supplied to expel the air from the chamber of the furnace. Next the furnace was heated up to 650℃ in several steps and holded.

Fig. 5 shows the curves of temperature change in 3 thermocouples installed on the surface of the TSM. The point at which the temperature drops sharply in the figure is the actuating point of the SASS, that is, the control rod with the TSM is dropped outside of the heating chamber.

As shown in the figure, the temperature trends of two thermocouples are of the similar shape but that of the other one is lower than the former two. The reason seems that the thermocouple at the backside of TSM directly contacts the cold nitrogen supplied in the chamber. Therefore it might be reasonable to consider the averaged temperature, 590±5℃, of the right and left thermocouples as the Curie point.

When the TSM of CPEM was cooled and the saturated magnetic flux density was restored, the control rod was raised by the driving mechanism (air cylinder) and the test was repeated. The same result were obtained in the repeated tests.

4. Conclusion and Future Works

To confirm the operating principle of SASS using CPEM under development as one of the innovative concepts of KALIMER, a mockup was designed, fabricated and tested. From the test it was confirmed that the mockup was self-actuated at the Curie point (590±5℃) of the temperature sensing material used in the electromagnet. As the result was well reproduced in the repeated tests, it can be concluded that CPEM is a proper choice for the SASS, the passive ultimate shutdown system of KALIMER.

The actuating temperature of SASS for unprotected ATWS events is entirely dependent on the Curie point of the temperature sensitive material used. Therefore the development of the various temperature sensitive material is one of the important subjects in the future. Structure of the temperature sensitive material should be re-designed to have fins for the rapid response against the abnormal condition in the future. The response time should be also measured according to the various temperature transient. For practical validation of the articulated control rod system, a distorted guide tube would be used in the future test. The operability of SASS in the actual sodium environment should be also confirmed in the future.

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