Proceedings of the 17th International Conference on Nuclear Engineering
ICONE17
July 12-16, 2009, Brussels, Belgium

ICONE17-75851

# DESIGN AND DEVELOPMENT OF DIVERSE SAFETY ROD AND ITS DRIVE MECHANISM FOR PFBR

**R.Vijayashree, P.ChellaPandi, K.Natesan, S.Jalaldeen, S.C.Chetal, Baldev Raj**

Indira Gandhi Centre For Atomic Research, Department of Atomic Energy, Kalpakkam - 603 102, India
Ph.No. 91 44 -274 80 221, Fax No: 91 44 -274 80 104, rviji@igcar.gov.in

## ABSTRACT

Prototype Fast Breeder Reactor (PFBR) is U-$PuO_2$ fuelled sodium cooled Pool type Fast Reactor and it is currently under advanced stage of construction at Kalpakkam, India. The Fast Breeder Test Reactor (FBTR) which is the only fast reactor currently operational in India is having only one shutdown system. However the IAEA and Atomic Energy Regulatory Board (AERB) Guide Lines call for two independent fast acting diverse shutdown systems for the present generation reactors. Hence PFBR is equipped with two independent, fast acting and diverse shutdown systems. A shutdown system comprises of sensors, logic circuits, drive mechanisms and neutron absorbing rods. The two shutdown systems of PFBR are capable of bringing down the reactor to cold shutdown state independent of the other. The absorber rods of the second shutdown system of PFBR are called as Diverse Safety rods (DSR) and their drive mechanisms are called as Diverse Safety Rod Drive Mechanisms (DSRDM). DSR are normally parked above active core by DSRDM. On receiving scram signal, Electromagnet of DSRDM is de-energised and it facilitates fast shutdown of the reactor by dropping the DSR in to the active core. This paper presents chronological design and development of the prototype DSR and DSRDM starting from the design specifications. Salient design specifications for both DSRDM and DSR are listed initially. The conceptual & detailed design features are explained with the help of figures. Various important design options considered in the initial design stage, choice of final design along with brief explanation for the particular choice are also given for some of the important components. Details on material of construction are given at appropriate places. Details on various analysis such as large displacement analysis for buckling, bending analysis for determining reactive forces and friction in the mechanism, thermal stress analysis of electromagnet during scram, flow induced vibration analysis of DSRDM and DSR and hydraulic analysis for estimating the pressure drop and drop time of DSR are also given. Test plans for design verification, manufacturing and shop testing experience of prototype systems, and criteria for endurance testing in sodium for qualification of DSRDM and DSR for operation in reactor are also briefed.

## 1. Introduction

PFBR, India's first commercial fast breeder reactor employing fast fission is a challenging project from technological point of view to meet the energy security of the country. The safe operation of the nuclear reactor is crucial to avoid any radiation hazards. Therefore it is very important to precisely design the reactor and to ensure proper functioning of all the components during the reactor operation. FBTR, the only operational fast reactor in India is having a single shutdown system. However, in line with the safety guide lines for the present generation reactors, PFBR is equipped with two independent fast acting diverse shutdown systems [1, 2]. A shutdown system comprises of sensors, logic circuits, neutron absorbing rods and their drive mechanisms. Schematic arrangements of the absorber rods and drive mechanisms of both the shutdown systems of

PFBR are shown in Fig.1. Figure.2 shows the arrangement of absorber rods in the core of PFBR.

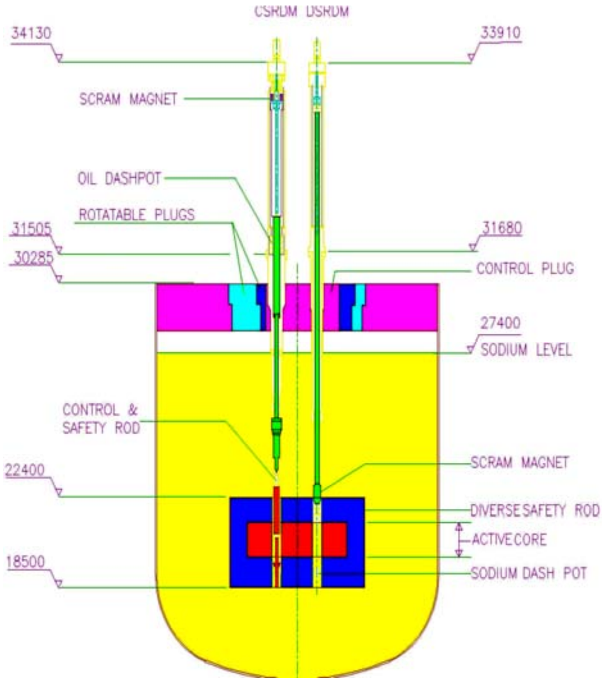


**Fig.1: Shutdown Mechanisms of PFBR**

| SYMBOL | TYPE OF SUBASSEMBLY | No. |
|---|---|---|
| | FUEL (INNER) | 85 |
| | FUEL (OUTER) | 96 |
| | CONTROL AND SAFETY ROD | 9 |
| | DIVERSE SAFETY ROD | 3 |
| | BLANKET | 117 |
| | SOURCE | 3 |
| | STEEL REFLECTOR | 132 |
| | PURGER | 6 |
| | $B_4C$ SHIELDING (INNER) | 124 |
| | STORAGE LOCATION | 147 |
| | STORAGE FOR SOURCE | 3 |
| | FAILED FUEL STORAGE LOCATION | 6 |
| | STEEL SHIELDING | 609 |
| | $B_4C$ SHIELDING (OUTER) | 417 |
| | TOTAL SUBASSEMBLIES | 1757 |

**Fig.2: Core plan of PFBR (Legend)**

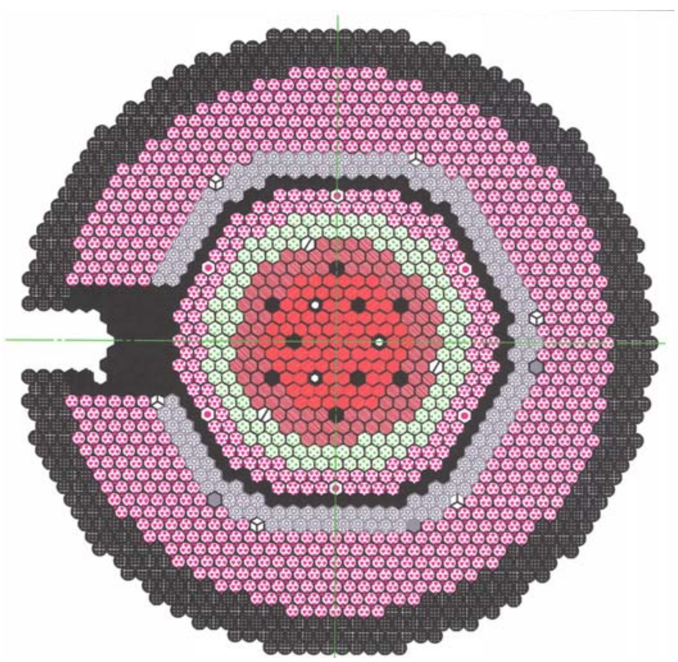

**Fig.2: Core plan of PFBR**

The nine absorber rods of the first shut down system are used for start-up, controlled shut down, control of reactor power and also for rapid shut down on receiving scram signal. The three absorber rods of the second shut down system are parked outside active core during normal operation and are used only for rapid shut down of reactor on abnormal conditions. This paper attempts to describe the design specifications, design and analysis of the DSR and DSRDM, manufacturing experience and criteria for qualification of the system for operation in reactor.

## 2. Function

The function of DSRDM is to facilitate shutdown of the reactor on abnormal conditions by rapid insertion (i.e., scram action) of DSR into the active core under gravitational force.

## 3. Design Specifications

The following are the salient specifications for the design of DSR and DSRDM

- There shall be only one speed, 4 mm/s, for raising and lowering the DSR.
- Free fall time of DSR during scram under normal operating condition shall be less than 1.0 s in flowing sodium, including response time of electromagnet.

- Leakage of argon from the mechanism into RCB shall be less than 1 x $10^{-8}$ Pa $m^3$/s.

- DSRDM shall be secured with control plug such that it is not ejected and maintains leak-resistant integrity during CDA.

- The performance of DSRDM along with DSR shall be assessed continuously by measurement of friction, leak-tightness and free fall time.

- DSRDM shall operate satisfactorily with the maximum misalignment of 30 mm between the axes of EM and head of DSR during start up of reactor.

- Normal operation of DSRDM shall be possible during and after OBE. Full insertion of DSR in the core during a SSE shall be possible.

- The design shall ensure that there is no permanent connection between DSR and DSRDM and shall allow plug rotation.

- Sufficient cooling shall be ensured for the DSR, so that the specified temperature limits for the clad, $B_4C$ and sodium are not exceeded.

- The hydraulic design shall ensure proper cooling in the case of accidental fall of one DSR into active core when reactor is under full power and hypothetically continues to operate at full power.

- There shall be sufficient margin available in the downward force to prevent inadvertent ejection of DSR when it is deposited in its sheath.

## 4. Description of DSR Sub-assembly

The overall configuration of DSR Sub-assembly (DSR-SA) is shown in Fig. 3. DSR-SA consists of mobile DSR and a stationary sheath. The stationary sheath is hexagonal in shape and it has externally similar configuration as that of any other core assembly. It is supported on grid plate and it is 4.46m long. It has self orientation feature and its head is suitable for handling by transfer arm machine. Its bottom end is open to the coolant plenum below grid plate. It is having leaf springs fitted at its foot to prevent its inadvertent lifting during the movement of DSR.

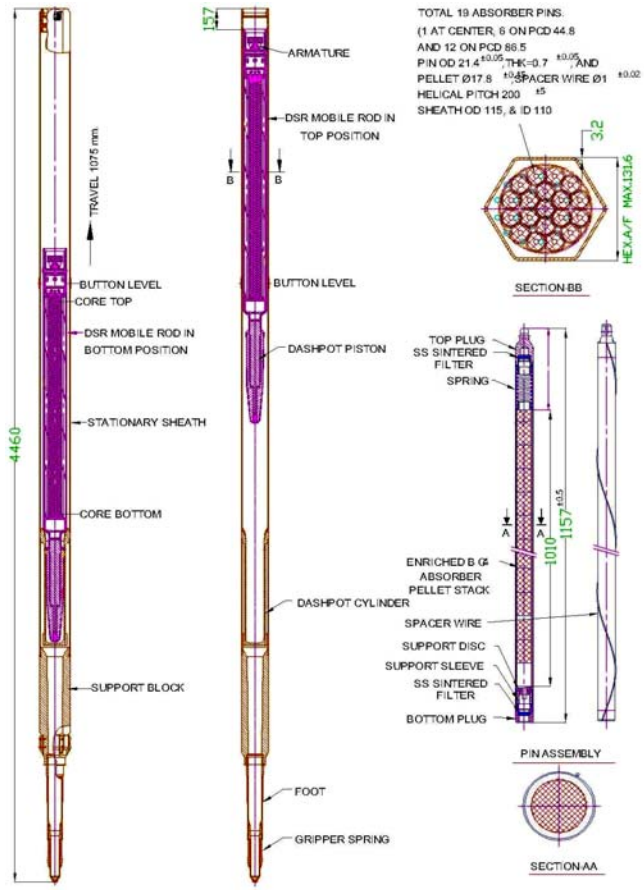


**Fig.3: DSR Subassembly**

Two extreme positions of DSR, viz., top and bottom positions are also shown in Fig. 3. There are 19 pins having $B_4C$ pellets enriched to 65% $B_{10}$ and stacked in D9 clad tubes. The pins are freely hanging from the top and are held by guide rails. They are arranged in circular pitch as a bundle. The guide rails are fixed inside a cylindrical sheath. At the bottom end of the cylindrical sheath, the dashpot piston made of 9 Cr - 1 Mo is attached. The piston is hard faced with nickel base alloy. The dashpot cylinder is located below the active core region and it is welded to the stationary hexagonal sheath. Two designs for dashpot piston one with labyrinths on outer surface and another with smooth conical surface having varying cone angles were designed and tested for achieving uniform deceleration for the DSR. The design with smooth conical surface was chosen as the final choice based on its ability to take misalignments between dashpot piston and cylinder. There is a swivel joint provided at the top end of mobile DSR. This provides required flexibility and degree of freedom for handling of DSR by Electromagnet (EM) of DSRDM.

## 5. Description of DSRDM

Schematic of DSRDM along with DSR and vertical section of DSRDM are shown in Fig.4. The mechanism mainly consists of two parts, viz., upper part and lower part. The lower part is partially immersed in hot pool sodium and the upper part is in RCB environment.

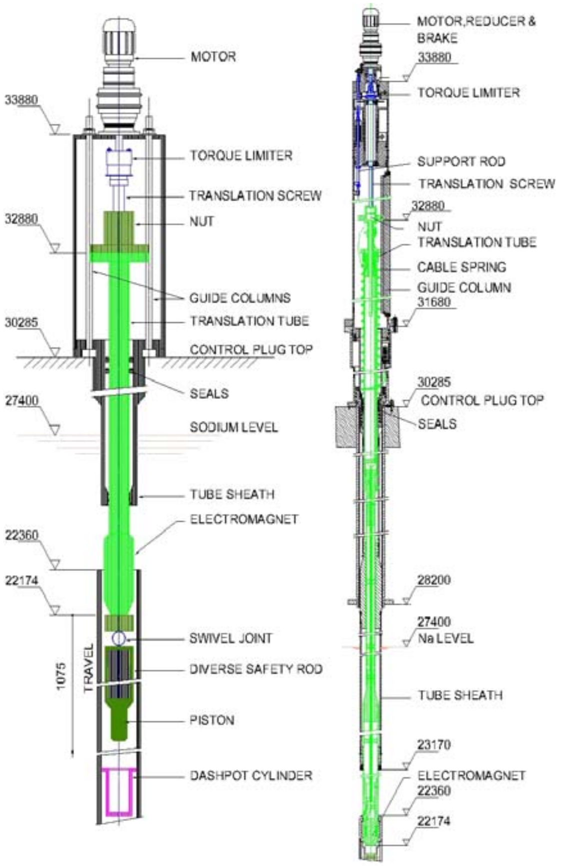


**Fig.4: Schematic & Vertical section of DSRSM**

The mobile assembly of DSRDM consists of upper, middle, lower translation tubes and an EM. EM at the lower end of the mobile assembly of DSRDM holds the head of DSR. DSR is parked above the active core during normal operation and is always within its stationary hexagonal sheath.

The mobile assembly is coupled with the nut of roller screw-nut mechanism. Motor drive sub-assembly rotates the screw in either direction to raise or lower the mobile assembly. Torque limiter and shear pins provided in the drive line ensure the safety of the mechanism against overload. When DSR is held by the EM, it translates up or down based on the direction of rotation of the motor.

On receiving the scram signal, the EM is de-energised and the DSR alone is released to fall under gravity. At the end of free fall travel of 825 mm, it is decelerated by a sodium dashpot for the remaining 250 mm travel.

### 5.1 Leak tightness

Lip type seals made of fluorocarbon are used as the primary leak tight barrier which prevent entry of cover gas of the reactor in to the upper part of the mechanism. The upper part is hermetically sealed with respect to Reactor containment building by the provision of 'O' rings at all the openings and is maintained at slight positive pressure with respect to cover gas. Rotary 'O' ring seals are provided at the interface between the geared motor and the mechanism.

### 5.2 Material

The 316 LN is the main material of construction for lower part of DSRDM. The Electromagnet is made of soft iron. Nickel base alloy is the choice for parts requiring hard facing and immersed in sodium. The parts of translation tube in sliding contact with other parts are hard chrome plated. The upper part is made of carbon steel or alloy steel. Nitrided 17/4-PH is the material used for splines.

### 5.3 Instrumentation

Rotary potentiometer is used for continuous position indication of mobile assembly and that of DSR when it is held by EM. Reed switches and proximity switches are used for discrete position indication of mobile assembly of DSRDM and also for the control of the mechanism. Load cells are provided for online friction measurement and also to detect the presence or absence of DSR hanging from the EM. The response time of Electromagnet is measured using the decay curve of the current when the EM is switched off. Mutual inductance type sodium leak detector is provided inside the EM to ensure its leak tightness as the response time depends on its leak tightness.

Various options for detecting the free fall time of DSR such as methods based on acoustics, eddy current and neutronics are under consideration and research is being done for the same.

## 6. Design and Analysis

The following paragraphs give brief summary of various analyses done to finalise the detailed design of the DSRDM and DSR.

### 6.1 Large displacement analysis for buckling

The mobile assembly of DSRDM consists of upper, middle and lower translation tubes. At the bottom end of lower translation tube, the EM is attached. Whenever the DSR is latched with EM, the mobile assembly of DSRDM is subjected to compressive force. At the same time due to misalignment between the DSRDM and DSR-SA, the mobile assembly is also subjected to lateral displacement. Large displacement analysis was done to determine the buckling strength of the DSRDM and to decide the allowable compressive load during the above mentioned latching operation. The axial load vs axial deflection is plotted from the analysis results (Fig.5). The initial slope of the load vs deflection curve with respect to vertical axis is calculated (line A). A line with twice the slope as that of initial slope is drawn on the load vs deflection curve (line B). The load at which the line crosses the deflection curve is taken as the critical buckling load. This is based on criterion of collapse load given in para NB- 3213.25 of ASME code [3]. Parametric study of the buckling strength with respect to sizes of translation tube and number of guides for translation tube was done to finalize the configuration of the translation tube and tube sheaths. The sizes of translation tube and tube sheaths are primarily guided by the buckling requirements.

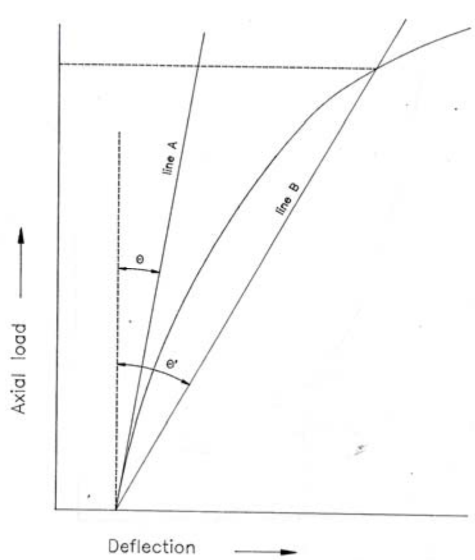


**Fig.5: Typical Load deflection curve**

(θ - Initial slope of load deflection curve,

$\theta' - \tan^{-1}(2\tan\theta)$)

### 6.2 Bending analysis

Though theoretically DSRDM is inline with the DSR, due to various causes such as manufacturing tolerances, slopes at support locations, differential thermal expansions and bowing of core subassemblies, maximum misalignment of 25 mm is expected between axes of DSRDM and DSR. The mobile assembly of DSRDM is guided by the handling head of DSR-SA and the total misalignment is taken only by the bending of DSRDM. The bending stiffness of DSRDM estimated from the linear static structural analysis is 8 N/mm. The reactive forces and consequent friction forces at guide points were also estimated. Sufficient clearance exists between tube sheath and translation tube to take care of relative deflection.

### 6.3 Transient Temperature fields surrounding EM during scram

The outlet temperature of sodium exiting from DSR-SA is 500 $^{o}$C and the EM of DSRDM is well within the stationary sheath of DSR during normal operation of the reactor. Figure.6 shows the transient evolution of SA flow, DSR and fuel SA sodium outlet temperatures during SCRAM. It is seen from the Fig. 6 that during the normal reactor operating condition, temperature of the sodium exiting from DSR subassembly is 773 K (500˚C). Immediately after SCRAM, the sodium temperature reduces to 690 K (417 ˚C) in 20 sec. Subsequently, the temperature rises by 10 K and finally reaches a steady state value of 670 K (397˚C). Fig.7 shows the temperature difference between inner and outer cores of EM near its bottom end. Maximum temperature difference of 20 $^{o}$C is expected between the inner and outer cores which are welded together for sealing purpose and the thermal stresses are within allowable limits for the event of scram. In the initial design of EM the outer core and inner core were welded at both bottom and top ends which was leading to very high thermal stresses. In the final design the inner core is left free at the top end to allow relative axial thermal expansion.

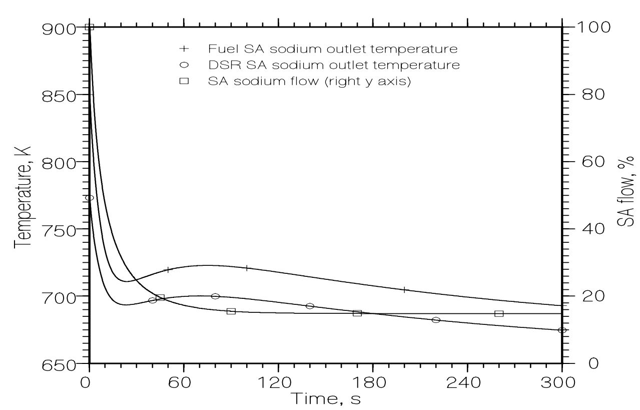


**Fig. 6: SA flow and temperature evolution during SCRAM**

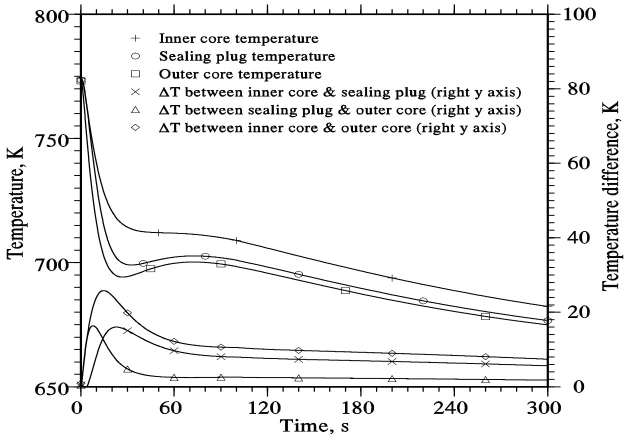


**Fig.7: Temperature evolution in the magnet assembly at the bottom end during SCRAM**

### 6.4 Flow induced vibration analysis

DSRDM and DSR are subjected to both parallel and cross flow velocities during normal operation in reactor. The DSRDM is subjected to cross flow velocities of 0.9 m/s and 1 m/s at the elevation 27400 and 22400. In addition there is a parallel flow of 2.3 m/s between the mechanism and its shroud. The parallel flow velocity between mobile DSR and its sheath is 0.57 m/s and parallel flow velocity through the mobile DSR is 0.31 m/s.

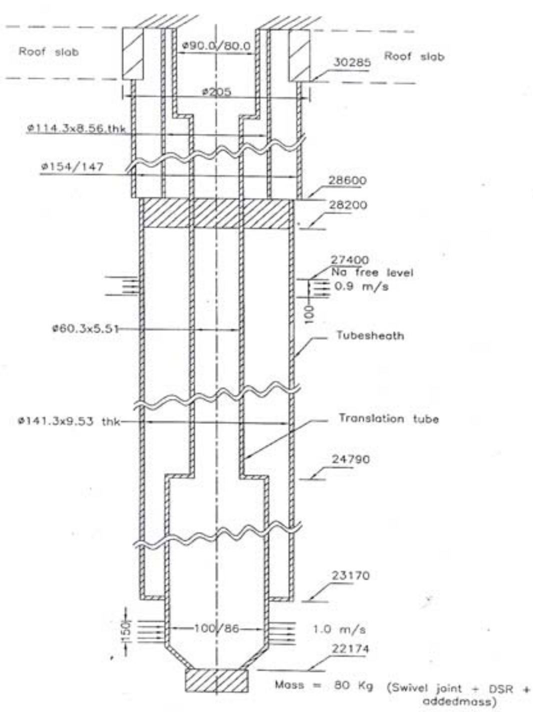


**Fig.8: Schematic diagram of DSRDM**

Fig.8 and Fig.9 show the schematic diagram and beam model employed for analysis of the system. A lumped mass of 80 kg added at the bottom end takes care of mass of mobile DSR along with the added mass due to the sodium between the DSR and hexagonal sheath. The first four natural frequencies of the system as per analysis are 0.62, 9.86, 20.45 and 37.28 Hz. The critical mechanism for Flow induced vibration is vortex shedding. In the full load operation it is ensured that the natural frequency ($f_n$) and vortex shedding frequency ($f_s$) meet the ASME guide lines [4] to avoid resonance (i.e $f_n/f_s < 0.7$ or $f_n/f^s > 1.3$).

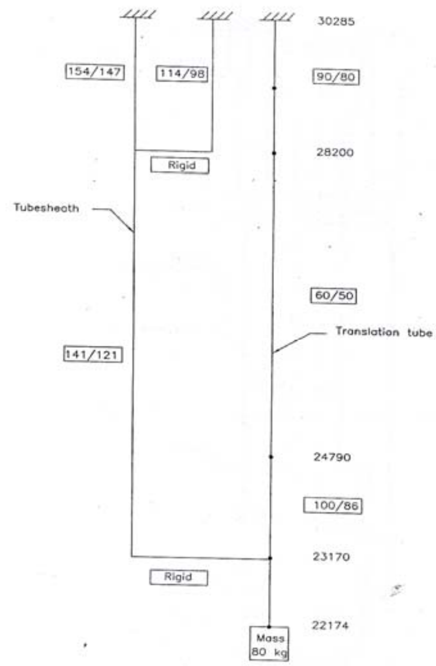


**Fig.9: Beam model of DSRDM**

### 6.5 Hydraulic Analysis for estimating the pressure drop and drop time of DSR

The heat generation in DSR-SA during full power operation of reactor when DSR is at the top and bottom positions is 0.38 MW (t) and 0.97 MW(t) respectively. The required flow through the DSR to ensure cooling under the hypothetical accidental fall of one of the DSR into the active core when reactor is at full power is 3 kg/s. The pressure difference between the top and bottom ends of DSR-SA causes upward flow of sodium into the DSR-SA. This upward flow while ensuring cooling also offers considerable resistance to the free fall of DSR. Hence design optimisation studies were done using a computer programme (developed in-house). The estimated total differential pressure is 4.75 x $10^4$ Pa for the required flow of 3 kg/s in the DSR deposited position. For this pressure difference the flow increases to 3.7 kg/s when the DSR is lifted to top position. When DSR is dropped with the above pressure difference, the DSR reaches the maximum velocity of 1.56 m/s during drop. The estimated free fall time is 825 ms. Fig. 10 shows the estimated displacement of DSR with respect to time.

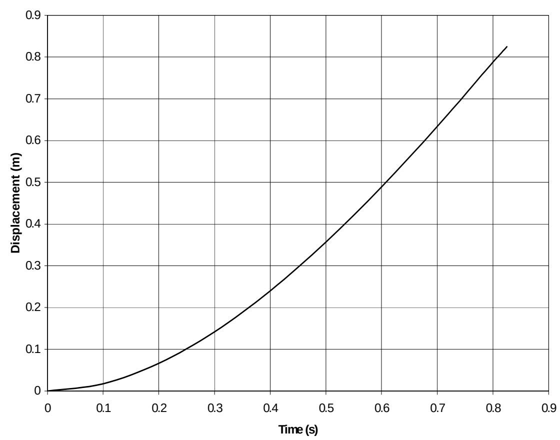


**Fig.10: DSR Dropping Characteristics**

## 7. Manufacturing Experience

The DSRDM and DSR are the most important components of the second shutdown system of PFBR. The reliable functioning of the system has to be ensured by design and development process. The EM working continuously at high temperature sodium environment and a dashpot using sodium as the working fluid and working at high temperature and high neutronic environment were the two critical subassemblies that have gone through many development cycles. The following paragraphs address some of the key developmental issues that have been tackled successfully.

### 7.1 Development of welding procedure for EM

The design specification for the electromagnet of DSRDM is very stringent because of the restrictions on the space availability and also because of the misalignment between DSRDM and DSR. The parting plane diameter is required to be limited to 60 mm. Design optimisation was done to maximise the holding force, to minimise the leakage flux and to avoid saturation of parts of inner and outer cores. The inner core of EM is slotted to reduce the eddy current and made leak tight by welding the bottom face of inner and outer cores with a nonmagnetic material. In the initial design a stainless steel insert was introduced between the inner and outer cores and welded. However the design was improved by buttering the faces with inconel 82 filler wire and then welding them together. By this modification the weld design was improved to butt weld from fillet weld and it was also possible to ensure the integrity by ultrasonic testing [5].

### 7.2 Manufacturing and shop testing experience of prototype DSRDM

The prototype of DSRDM was manufactured within 17 months from the starting of the manufacturing which was well ahead of the planned schedule of 24 months for its manufacture. Well defined manufacturing specification, detailed process plans indicating the intermediate stage inspections for all the items, written and approved procedures for various processes such as welding, chrome plating etc, subassemblies testing procedures and detailed assembly procedures were prepared. The above mentioned highly methodical way of working strictly adhering to ISO standards led to the above mentioned success of the manufacturing process. However there were few hitches before the system could be completely assembled and shop tested for its performance. The rotary ‘O’ ring seals were not allowing the rotation of the intermediate shaft. Improving the perpendicularity tolerance between the mounting face of the motor and its shaft solved the problem. The transportation of assembled upper part resulted in failure of load cells and improving the packing procedure avoided the recurrence of this incident.

## 8.0 Qualification of the system of DSR and DSRDM

Extensive test plans were drawn right at the initial design stage itself for qualifying the various subassemblies before integration of them with the prototypes of DSRDM and DSR. Subsequent paragraphs discuss the overall test plans and also the criteria adopted for deciding the number cycles for endurance testing.

### 8.1 Test Plans

There are three phases of testing for the completion of prototype development namely individual component testing, integrated functional testing in room temperature and endurance testing at high temperature in sodium. Table-1 gives the list of experiments that were planned in the very early stage of design itself. A companion paper in this conference gives the details of the test setups and also results of testing that are completed till now [6].

### 8.2 Criteria for endurance testing in sodium

The overall test plans for the development of the system was discussed in previous paragraph. This paragraph addresses exclusively the basis adopted for deciding the number of test cycles for endurance testing.

**Table 1: List of Experiment for DSRDM & DSR**

| S.No | Name of the experiment | Objective |
|---|---|---|
| 1 | Testing of Electromagnet of DSRDM in air, furnace and in sodium | To measure load Carrying capacity with respect to current at various temperatures and response time. To verify the endurance against thermal shocks. |
| 2 | Testing of dashpot of DSR in water | Functional testing and to measure deceleration and dynamic pressure with respect to time. |
| 3 | Testing of DSR in water loop | To measure the pressure drops in various positions of mobile DSR.<br>To measure the free fall time vs flow.<br>To measure the flow split between mobile DSR & bypass flow in the annulus between mobile DSR & stationary sheath.<br>To measure the hydraulic lifting force.<br>To verify the performance against flow induced vibrations. |
| 4 | Testing of specimens for Self welding possibility between armature & EM of DSRDM | To prove that there is no self-welding risk between the armature and Electromagnet for the chosen combination of materials under the given stress and temperatures in sodium. |
| 5 | Testing of prototype DSRDM & DSR in air/water and in sodium | Integral testing of the system for Functional verification at various temperatures & Endurance testing |
| 6 | Testing of prototype DSRDM and DSR under seismic conditions | To ensure the insert ability and to measure the drop time |
| 7 | In sodium tribological studies | To estimate the friction coefficients of combination of materials in sliding contact and to determine the wear. |

Since the damage occurring in DSRDM and DSR is mainly due to fatigue cycles during scram actions, it was proposed to use ASME [7] guide lines to deicide the number of test cycles. Maximum operating temperature and the expected misalignment are the two important parameters that are simulated during endurance testing. As per ASME requirement when size, surface finish, stress and temperature are maintained, a factor of 4.6 is recommended on number of test cycles with respect to the specified number of cycles. The Table-2 details out the specified number of service cycles for DSRDM and DSR, service temperature, number of test cycles and the test temperature for translation cycles –Type I & II and also for SCRAM cycles.

One scram cycle consists of the following operations

- Holding of DSR
- Raising up to 1075 mm position
- Release of DSR
- Lowering to 0 mm position

One translation cycle – Type 1 consists of the following operations

- Holding of DSR
- Raising up to 1075 mm position
- Lowering to 100 mm position
- Release of DSR
- Lowering to 0 mm position

During the translation cycles it was proposed to lower the DSR to 100 mm position and then release it, instead of depositing it in its sheath, this was to get clear signal on release of DSR when EM is de-energised.

One Translation cycle – Type 2 consists of the following operations

- Lowering of EM from 1450 mm up to 1075 mm
- Raising up from 1075 mm position up to 1450 mm.

These cycles were to confirm the entry of EM inside the DSR sheath with misalignment.

## 9.0 Conclusion

The design and developmental activities for DSRDM and DSR, which are one of the most important subsystems of PFBR has been explained. The activities have yielded encouraging results and have enhanced the confidence that operation of DSRDM and DSR in reactor would be trouble free and the indented functions would be fully met.

**Table-2: Number of service & Test Cycles**

| Operation in Plant | Number of service cycles in | | Maximum Service Temperature (K) felt by | | | | Test cycles | | Test temperature (K) |
|---|---|---|---|---|---|---|---|---|---|
| | | | DSRDM during | | DSR during | | | | |
| | DSRDM | DSR | Raising | Lowering | Raising | Lowering or Dropping | Name | Number | |
| Scram | 752 | 38 | 670 | 670 | 670 | 773 | Scram | 175 | 773 |
| | | | | | | | Translation - Type 1 | 3285 | 670 |
| Planned shutdown | 109 | 6 | 670 | 817 | 670 | 773 | Translation - Type 1 | 502 | 817 |
| Surve -illance | 60 | 3 | 473 | 473 | 473 | 473 | Scram | 14 | 473 |
| | | | | | | | Translation - Type 1 | 262 | 473 |
| Raising for plug rotation | 60 | - | 473 | 473 | - | - | Translation - Type 2 | 276 | 473 |


## ACKNOWLEDGEMENTS

The contribution made by Shri.V.Rajan Babu in the way of lively technical discussions and valuable suggestions through out the design process is acknowledged. The contributions of Shri.D.Rangasamy in electrical & instrumentation design are acknowledged. The contributions made by S/shri B.K.Javalae, P.A.Sasidharan and Jai sankar in the preparation of assembly and detailed drawings of the systems under consideration and also the various test setups are acknowledged. The contributions of M/s MTAR towards the manufacture of prototype DSRDM are also acknowledged.


## NOMENCLATURE

AERB : Atomic Energy Regulatory Board

ASME : American Society of Mechanical Engineers

CDA : Core disruptive Accident

DSR : Diverse Safety rod

DSRDM: Diverse Safety Rod Drive Mechanism

DSR-SA: Diverse Safety rod Subassembly

EM : Electromagnet

FBTR : Fast Breeder Test Reactor

IAEA : International Atomic Energy Agency

OBE : Operation Base Earth Quake

PFBR : Prototype Fast Breeder Reactor

SSE : Safe Shutdown Earth Quake

## REFERENCES


[1] Rajan Babu, V., et al., 1995, ”Design Philosophy of PFBR Shutdown Systems”, Proc. of Technical Committee Meeting, IAEA-TECHDOC-884, Obninsk, pp. 81-88.

[2] Rajan Babu, V., et al., 1995, ”Design of Shutdown Systems for PFBR”, Ibid, pp. 89-96.

[3] ASME, Section III, Div. 1, NB-3213.25, 1998.

[4] ASME, Section III, Div. 1, Appendix-N, 2001.

[5] Dey, H.C., Shankar, V., Vijayashree, R., Sivaraman, P., Banerjee, A., 2007, ”Development of Joining Procedure for Pole Pieces of the Electromagnet of the Diverse Safety Rod in a Fast Breeder Reactor”, International Journal of Nuclear Energy Science and Technology, **3(1)** pp. 76–87.

[6] Vijayashree, R., et al., 2009, “Testing and Qualification of Diverse Safety Rod Drive Mechanism for PFBR”, Report No. ICONE 17-75853

[7] ASME, Section III, Div. 1, Appendices, Para II-1500, 2004.