CONTROL ROD DRIVE MECHANISM FOR NUCLEAR REACTOR

[0001] This application claims the benefit of U.S. Provisional Application No. 61/185,887 filed June 10, 2009. U.S. Provisional Application No. 61/185,887 filed June 10, 2009 is incorporated herein by reference in its entirety.

BACKGROUND

[0002] In a pressurized water reactor (PWR) or other type of nuclear reactor, movable control rods are used to control the nuclear reaction. The control rods include a neutron absorbing material, and are arranged to be inserted into the reactor core. In general, the further the control rods are inserted into the core, the more neutrons are absorbed and the more the nuclear reaction rate is slowed. Precise control of the amount of insertion, and accurate measurement of same, is useful in order to precisely control the reactivity. The control rods drive mechanism (CRDM) provides this control.

[0003] In an emergency, the control rods can be fully inserted in order to quickly quench the nuclear reaction. In such a "scram", it is useful to have an alternative fast mechanism for inserting the control rods. Additionally or alternatively, it is known to have dedicated control rods that are either fully inserted (thus turning the nuclear reaction "off") or fully withdrawn (thus making the reactor operational). In such systems, the "on/off" rods are sometimes referred to as "shutdown rods" while the continuously adjustable control rods are sometimes referred to as "gray rods".

[0004] Given these considerations, it is known to construct a CRDM employing a lead screw that is engaged by a separable roller-nut assembly. During normal operation, the roller-nut assembly is clamped onto the lead screw by an affirmative magnetic force acting against biasing springs. By turning the roller nut the lead screw, and hence the attached control rods, are moved in precisely controllable fashion toward or away from the reactor core. In a scram, the electrical current is cut thus

cutting the magnetic force, the biasing springs open the separable roller nut, and the gray rod including the lead screw scrams. An example of such a configuration is disclosed, for example, in Domingo Ricardo Giorsetti, "Analysis of the Technological Differences Between Stationary & Maritime Nuclear Power Plants", M.S.N.E. Thesis, Massachusetts Institute of Technology (MIT) Department of Nuclear Engineering (1977) which is incorporated herein by reference in its entirety.

[0005] For an integral pressurized water reactor (integral PWR), it is known to mount the CRDM externally and to couple with the control rods inside the pressure vessel by suitable feedthroughs. To reduce the extent of feedthroughs, it has also been proposed to integrate the CRDM within the pressure vessel. See, for example, Ishizaka et al., "Development of a Built-In Type Control Rod Drive Mechanism (CRDM) For Advanced Marine Reactor X (MRX)", Proceedings of the International Conference on Design and Safety of Advanced Nuclear Power Reactors (ANP '92), October 25-29, 1992 (Tokyo Japan) published by the Atomic Energy Society of Japan in October 1992, which is incorporated herein by reference in its entirety.

[0006] Existing CRDM designs have certain disadvantages. These disadvantages are enhanced when an internal CRDM design is chosen in which the complex electro-mechanical CDRM is internal to the high pressure and high temperature environment within the pressure vessel. Placement of the CRDM internally within the pressure vessel also imposes difficult structural challenges.

[0007] The separable roller-nut creates a complex linkage with the lead screw that can adversely impact gray rod insertion precision during normal operation. Reattachment of the roller-nut to the lead screw can be complex, and it may not be immediately apparent when contact is reestablished, thus introducing a positional offset after recovery from the scram event. Scramming the lead screw also has the potential to cause irrecoverable damage to the threading or structural integrity of the lead screw. Still further, wear over time can be a problem for the complex separable roller-nut.

[0008] Another consideration is reliability. Because rod scramming is a safety-critical feature, it must operate reliably, even in a loss of coolant accident (LOCA) or other failure mode that may include interruption of electrical power, large pressure changes, or so forth.

[0009] The control rod position detector is also typically a complex device. In some systems, an external position detector is employed, which requires feedthroughs across the pressure vessel wall. For the internal CRDM of the MRX reactor, a complex position detector was designed in which a transducer generates a torsional strain pulse that passes through a magnetoresistive waveguide, and magnetic field interactions are measured to adduce the rod position. In general, an internal position detector operating on an electrical resistance basis is prone to error due to temperature-induced changes in material resistivity.

BRIEF SUMMARY

[0010] In one aspect of the disclosure, a control rod mechanism for use in a nuclear reactor, the control rod mechanism comprises: a control rod configured for insertion in a reactor core to absorb neutrons; a connecting rod connected with the control rod; a drive mechanism including a lead screw engaged with a motor-driven nut such that rotating the nut causes linear translation of the lead screw; and a latch operatively connecting the connecting rod to move together with the lead screw, the latch opening responsive to a loss or removal of electrical power to detach the connecting rod from the lead screw.

[0011] In another aspect of the disclosure, a control rod control method comprises moving a control rod linearly using a lead screw and, responsive to a scram, detaching the control rod from the lead screw whereby the control rod scrams but the lead screw does not scram.

[0012] In another aspect of the disclosure, a nuclear reactor comprises: a reactor core; a pressure vessel including a lower vessel section containing the reactor core, an upper vessel section disposed above the reactor core and above the lower vessel

section, and a mid-flange located above a reactor core and disposed between the lower vessel section and the upper vessel section; and an internal control rod drive mechanism (CRDM) supported by the mid flange.

[0013] In another aspect of the disclosure, a control rod drive mechanism (CRDM) for use in a nuclear reactor comprises: a connecting rod connected with at least one control rod; a lead screw; a drive mechanism configured to linearly translate the lead screw; an electromagnet coil assembly; and a latching assembly that latches the connecting rod to the lead screw responsive to energizing the electromagnet coil assembly and unlatches the connecting rod from the lead screw responsive to deenergizing the electromagnet coil assembly.

BRIEF DESCRIPTION OF THE DRAWINGS

[0014] The invention may take form in various components and arrangements of components, and in various process operations and arrangements of process operations. The drawings are only for purposes of illustrating preferred embodiments and are not to be construed as limiting the invention.

[0015] FIGURE 1 diagrammatically shows an illustrative nuclear reactor vessel of the pressurized water reactor (PWR) type.

[0016] FIGURE 2 diagrammatically shows the upper internals section of the illustrative nuclear reactor vessel of FIGURE 1.

[0017] FIGURES 3-5 diagrammatically show aspects of a shutdown control rod system employing hydraulic lift.

[0018] FIGURES 6-15 diagrammatically show aspects of a control rod system with electromagnetic gray rod functionality and a magnetic latch system for scram functionality.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

[0019] With reference to FIGURE 1, an illustrative nuclear reactor vessel of the pressurized water reactor (PWR) type is diagrammatically depicted. An illustrated primary vessel **10** contains a reactor core **12**, internal helical steam generators **14**, and internal control rods **20**. The illustrative reactor vessel includes four major components, namely: 1) a lower vessel **22**, 2) upper internals **24**, 3) an upper vessel **26** and 4) an upper vessel head **28**. A mid-flange **29** is disposed between the lower and upper vessel sections **22**, **26**. Other vessel configurations are also contemplated. Note that FIGURE 1 is diagrammatic and does not include details such as pressure vessel penetrations for flow of secondary coolant into and out of the steam generators, electrical penetrations for electrical components, and so forth.

[0020] The lower vessel **22** of the illustrative reactor vessel **10** of FIGURE 1 contains the reactor core **12**, which can have substantially any suitable configuration. One suitable configuration includes a stainless steel core former structure that contains the fuel assemblies and is replaceable in order to refuel the reactor, and which is supported by the lower vessel. The illustrative upper vessel **26** houses the steam generators **14** for this illustrative PWR which has an internal steam generator design (sometimes referred to as an integral PWR design). In FIGURE 1, the steam generator **14** is diagrammatically shown. A cylindrical inner shell or upper flow shroud **30** separates a central riser region **32** from an annular down-comer region **34** in which the helical steam generators **14** are located. The illustrative steam generator **14** is a helical coil design, although other designs are contemplated. Primary reactor coolant flows across the outside of tubes of the steam generator **14** and secondary coolant flows inside the tubes of the steam generator **14**. In a typical circulation pattern the primary coolant is heated by the reactor core **12** and rises through the central riser region **32** to exit the top of the shroud **30** whereupon the primary coolant flows back down via the down-comer region **34** and across the steam generators **14**. Such primary coolant flow may be driven by natural convection, by internal or external primary coolant pumps (not illustrated), or by a combination of pump-assisted natural convection. Although an integral PWR design is illustrated, it is also contemplated for the reactor vessel to have an external steam generator (not

illustrated), in which case pressure vessel penetrations allow for transfer of primary coolant to and from the external steam generator. The illustrative upper vessel head **28** is a separate component. It is also contemplated for the vessel head to be integral with the upper vessel **26**, in which case the steam generator **14** and upper shroud **30** are optionally supported by lugs on the inside of the vessel head.

[0021] The illustrative embodiment is an integral PWR in that it includes the internal steam generators **14**, which in general may have various geometric configurations such as helical, vertical, slanted, or so forth. For the purpose of redundancy, it is generally advantageous to have more than one steam generator, whose pipes or tubes are typically interleaved within the downcomer region **34** to facilitate thermal uniformity; however, it is contemplated to include only a single steam generator. Although the illustrative steam generators **14** are shown disposed or wrapped proximate to the shroud **30**, in general the steam generators may fill a substantial volume of the down-comer region **34**, and in some embodiments the steam generators may substantially fill the annular volume between the outer surface of the shroud **30** and the inside surface of the pressure vessel **10**. It is also contemplated for the internal steam generators or portions thereof to be disposed in whole or in part in the riser region **32**,above the shroud **30**, or elsewhere within the pressure vessel **10**. On the other hand, in some embodiments the PWR may not be an integral PWR, that is, in some embodiments the illustrated internal steam generators may be omitted in favor of one or more external steam generators. Still further, the illustrative PWR is an example, and in other embodiments a boiling water reactor (BWR) or other reactor design may be employed, with either internal or external steam generators.

[0022] With reference to FIGURE 2, the upper internals section **24** in greater detail. In the illustrative design the upper internals section **24** provides support for control rod drives or drive mechanisms **40**, **42** and control rod guide frames **44** and is also the structure through which control rod drive power and control instrumentation signals pass. This allows the upper vessel **26** and integral steam generator **14** to be removed independently of the control rod drives and associated structure. However, a more integrated design is also contemplated, such as using a common section for both the CRDM support and the integral steam generator support.

[0023] With particular reference to the illustrative embodiment of FIGURE 2, the upper internals structure **24** includes an upper internals basket **46**, a CRDM support structure **48**, control rod guide frames **44**, and the control rod drive mechanisms **40**, **42** themselves. The upper internals basket **46** is suitably a welded structure that includes the mid-flange **29** and the support structure for the control rod guide frames **44**. In one suitable embodiment, the control rod guide frames **44** are separate 304L stainless steel welded structures that are bolted in place, the mid-flange **29** is a SA508 Gr 4N Cl 2 carbon steel forging, and the balance of the structure is 304L stainless steel. The CRDM support structure **48** includes support lattices for the control rod drives **40**, **42** and guide structure for the in-core instruments. All of these are suitably 304L stainless steel. The CRDM support structure **48** is bolted to the upper internals basket **46**. These are merely illustrative materials and construction, and other configurations and/or reactor-compatible materials are also contemplated.

[0024] The illustrative example of FIGURE 2 employs two types of control rod drives **40**, **42**: a hydraulic control rod drive type **42** that operates the shutdown rods which are either fully withdrawn or fully inserted into the core; and an electrical control rod drive type **40** that operates the gray rods which are inserted various amounts throughout the life of the core to control the nuclear reaction rate during normal reactor operation. The gray rods are also configured to scram, that is, to be rapidly inserted into the reactor core **12**, during certain emergency conditions. In other embodiments, it is contemplated to omit the shutdown rods entirely in which case the gray rods also provide shutdown operation.

[0025] With continuing reference to FIGURE 2 and with further reference to FIGURES 3-5, aspects of the shutdown rods are illustrated. The shutdown rods are suitably arranged in clusters mounted on spiders or the like that are all operated in single bank and are all moved by a single shutdown rod drive **42**. FIGURES 3-5 show only the single shutdown rod drive **42**, but not the spiders and individual shutdown rods. This configuration is cognizant of the fact that the shutdown rods are used in a binary "on/off" manner, and are either all wholly inserted into the reactor core **12** in order to shut down the reaction, or are all wholly withdrawn from the reactor core **12** in order to allow normal reactor operation.

[0026] With particular reference to FIGURE 3, the shutdown rod drive **42** includes a cylinder housing **50**, a cylinder cap **52**, a cylinder base plate **54**, and a connecting rod **56** providing connection to the shutdown rod lattice (not shown). The illustrative shutdown rod drive **42** of FIGURES 3-5 is a hydraulically actuated drive using reactor coolant inventory clean-up return fluid from high pressure injection pumps at approximately 500 °F (260 °C) and 1600 psi to hold the shutdown rod bank out of the reactor core **12**.

[0027] With particular reference to FIGURE 4, a sectional view of the piston region with the rod in the withdrawn position is shown. In an enlarged portion of FIGURE 4 a vent port **60** of the cylinder cap **52** is shown, together with a lift piston **62**, piston rings **64** (which in some embodiments are metallic), a scram buffer **66**, and a buffer cocking spring **68**. The withdrawn position shown in FIGURE 4 corresponds to the shutdown control drive cylinder **42** being pressurized.

[0028] With particular reference to FIGURE 5, a sectional view of the piston region with the rod in the inserted position is shown. An enlarged portion of FIGURE 5 shows the lift piston **62**, the piston rings **64**, the scram buffer or scram buffer piston **66**, a rod guide bushing **70**, and rod sealing rings **72** (which in some embodiments are metallic). The cylinder base plate **54** is seen in the enlarged portion to include a pressure port or inlet port **74**. The inserted position shown in FIGURE 5 corresponds to the shutdown control drive cylinder **42** being unpressurized.

[0029] In some embodiments, the coolant is allowed to bleed past the piston and shaft seals **64**, **72** and becomes part of the inventory returned to the reactor vessel **10**. The shutdown rod drive cylinder **42** is mounted above the reactor core **12**. A hydraulic line (not shown) to actuate the cylinder **42** is routed through the flange **29** and instrument lines are routed through pressure tight conduit to common connectors that are also optionally used for the gray rod drives **40**. The extension rods that connect the control rod spiders to the shutdown rod lattice are optionally designed so that they will slide through the lattice so that a single stuck cluster will not prevent the other sets of control rods from dropping. Additionally, the extension rods are designed to be disengaged from the control rod spider so that the shutdown rods remain in the

core when the upper internals **24** are removed. Disengagement and reengagement is done using remote tooling at during refueling operations.

[0030] During normal reactor operation, the shutdown rods are suspended completely out of the reactor core (that is, in the withdrawn position) by pressurization of the shutdown rod hydraulic cylinder **42**. For example, in one suitable embodiment coolant inventory clean-up return fluid from the high pressure injection pumps is supplied at 500°F (260 °C) and 1600 psi to the underside of the lift cylinder piston **62**, via the inlet port **74** of the cylinder base **54**. In this example, the fluid present in the cylinder **50** above the piston **62** is supplied from the reactor vessel **10** through the cylinder cap vent port **60**, and is therefore at the reactor vessel conditions of 600 °F (315 °C) and 1500 psi, resulting in a net 100 psi pressure differential across the piston **62**. Piston sizing is selected such that the developed pressure differential is sufficient to support the specified load of the shutdown rods and supporting spiders and other associated components and lift the shutdown rod bank through the cylinder stroke to the top stop of the piston **62**.

[0031] In the event of a vessel-pressurized scram, the shutdown rod bank is abruptly released by ceasing the supply of pressurized coolant to the bottom side of the lift piston **62** and venting the supply line to atmospheric pressure. In the aforementioned example the vessel pressure at the top surface of the lift piston **62** is expected to create an initial 1500 psig pressure differential across the lift piston, which acts along with the influence of gravity to propel the translating assembly (including the lift piston **62**, scram buffer piston **66**, cocking spring **68**, connecting rod **56**, and shutdown rod lattice (not shown) downward toward the full insertion position illustrated in FIGURE 5. During the descent of the translating assembly, the force of the buffer cocking spring **68** holds the buffer piston **66** out of the bore of the lift piston **62**, preserving a fluid-filled buffer cavity between the two pistons **62**, **66**. When the bottom surface of the buffer piston **66** impacts the fixed base plate **54** of the cylinder assembly, the continued travel of the lift piston **62** expels the trapped fluid through controlled flow restrictions, thereby dissipating the kinetic energy of the translating assembly. Additionally, kinetic energy is dissipated through elastic deformation of the translating assembly components, especially the long, relatively slender, connecting

rod **56**. Other kinetic energy dissipation mechanisms are also contemplated. When the fluid is expelled from the cavity, the lift piston **62** impacts the buffer piston **66**, bringing the translating assembly to rest.

[0032] With continuing reference to FIGURES 1 and 2 and with further reference to FIGURES 6-14, an illustrative embodiment of the gray rods and associated drive mechanisms **40** is described. As seen in FIGURE 6, in the illustrative embodiment there are two different gray rod configurations (Type 1 and Type 2). The gray rods **80** are arranged as gray rod clusters, which in turn are yoked together in groups of two or four and supported by connecting rods **82** as shown in FIGURE 6. The configuration Type 1 also includes a counterweight **84** in place of one connecting rod/cluster unit. More particularly, a yoke **86** connects two connecting rods **82** and the counterweight **84** to form a configuration of Type 1. A yoke **88** connects three connecting rods **84** to form a configuration of Type 2. The gray rod drives **40** are mounted above the reactor core **12**. FIGURE 7 shows a plan view of the locations of the gray rod drives **40** and of the shutdown rods lift cylinder **50**, respective to the CRDM support structure **48**. The shutdown rods lift cylinder **50** is centrally located. Four outboard gray rod drives **40**, each moving two rod configurations of Type 1 including yokes **86**, move simultaneously. Two inboard drives **40**, each moving four rod configurations of Type 2 including yokes **88**, move simultaneously. These different sets of drives **40** optionally move together or independently. Power and signal connections are suitably routed through a pressure tight conduit or in-core instrumentation guide **90** to connectors on the mid-flange **29** (not shown in FIGURE 7).

[0033] As with the shutdown rods, the extension rods that connect the control rod spiders to the rod lattice are optionally designed so that they will slide through the lattice so that a single stuck cluster will not prevent the other sets of control rods from dropping. Additionally, the extension rods are optionally designed to be disengaged from the control rod spider so that the gray rods can remain in the core when the upper internals are removed or be removed while the upper internals are on their support stand. Two suitable design styles for the gray rod control mechanism include the "magnetic jack" type and the "power screw" type. Of these, the power screw type is expected to provide more precise position control for the gray rod clusters, and

accordingly the illustrated embodiment employs the power screw type control mechanism.

[0034] With reference to FIGURE 8, in one illustrated embodiment the gray rod control mechanism **40** employs a ball nut lifting rod configuration. FIGURE 8 shows both the fully inserted state (left-side drawing) and fully withdrawn state (right-side drawing). The drawings of FIGURE 8 show the yoke **88** of the Type 2 configuration; for the Type 1 arrangement the yoke **88** is replaced by the yoke **86**. In the embodiment shown in FIGURE 8, a bottom stop/buffer assembly **100** is mounted on a reactor support **101**, optionally with additional lateral support provided for the electromagnet coil assembly. Lower and upper support tubes **102**, **104**, which mount to the top of the bottom stop **100**, provide the guidance for the lead screw/torque taker assembly. A ball nut/motor assembly **106** mounts on top of the upper support tube **104** and an electromagnet coil assembly **108** mounts to the top of the motor. Within the electromagnet coil assembly **108** resides a lifting rod-to-lead screw latching assembly **110** that (when latched) supports a lifting/connection rod assembly **112** (seen extended in the inserted state, i.e. left-side drawing).

[0035] A position indicator assembly is mounted to the support tubes **102**, **104** between the ball nut/motor assembly **106** and the bottom stop assembly **100**. In some embodiments, the position indicator is a string potentiometer suitably mounted below the latching assembly **110**, although other mounting locations are contemplated. The illustrated string potentiometer includes a tensioned spool **120** mounted on the support tube **102** and a "string" or cable or the like **122** having an end attached to the lifting/connection rod assembly **112** such that the string or cable **122** is drawn off the spool **120** against the tension as the lifting/connection rod assembly **112** (and, hence the attached gray rod clusters) move toward the reactor core **12** (not shown in FIGURE 8). When the motion is reversed, the tension in the tensioned spool **120** causes the string or cable **122** to roll back onto the spool **120**. A rotational sensor **124** measures the rotation of the tensioned spool **120** using an encoder that counts passage of fiducial markers or another rotational metric. The mounting of the string potentiometer can be otherwise than that illustrated, so long as the tensioned spool **120** is mounted at a location that does not move with the gray rods and the string or

cable **122** is secured to move with the gray rods. It is also contemplated to integrate the rotational sensor **124** with the tensioned spool **120**. The string potentiometer provides an electrical output signal consistent with the location of the connecting rod or other component **112** that moves with the gray control rod, thus providing positional information for the gray control rods within the reactor core **12**. The electrical position indication signal is conveyed out of the reactor vessel **10** through an electrical feedthrough (not shown), which can be made small and/or integrated with other electrical feedthroughs. The position indicator device is configured and calibrated for operation at reactor vessel temperature and radiation level.

[0036] With continuing reference to FIGURE 8 and with further reference to FIGURES 9-14, in the illustrated embodiment the translating assembly of the gray rod CRDM **40** includes three elements: a lead screw/torque taker assembly; a lifting rod/connecting rod assembly; and a latching system that operatively connects the lifting rod with the lead screw. FIGURE 9 shows the lead screw/torque taker assembly in perspective (left side) and sectional (right side) views. A motor assembly includes a stator housing **130** housing a stator **132** and a rotor **134**. An upper stator end plate **136** and a radial bearing **138** with adjustable spacer **140** complete an upper portion of the motor assembly, while a lower housing **142** and a thrust bearing **144** complete a lower portion of the motor assembly. A lower ball-nut assembly **150** disposed within the lower housing **142** is threaded to the rotor **134**, and an upper ball nut assembly **152** is also threaded to the rotor **134**. Both ball-nut assemblies **150**, **152** are coupled in threaded fashion with a lead screw **160** (shown in part in FIGURE 9). FIGURE 9 further shows portions of the lifting rod **112** and the upper support tube **104**.

[0037] With reference to FIGURE 10, the latching system is illustrated, including the lifting rod-to-lead screw latching assembly **110** and a portion of the electromagnet coil assembly **108**. Also shown in FIGURE 10 are an end **111** of the lifting rod **112** and a proximate end of the lead screw **160** terminating at or in the latching assembly **110**. Latches **170** directly connect the top end **111** of the lifting rod **112** to the lead screw **160** for normal operation, and disconnect the lifting rod **112** during scram (see FIGURE 11). The bottom of the lifting rod **112** is threaded to the top of the

connecting rod **82** (optionally by the intermediary yoke **86** or intermediary yoke **88**) thereby creating a continuous lifting rod/connecting rod assembly. The bottom of the connecting rod **82** couples directly to the control rod spiders thereby attaching the control rods to the mechanism. Optionally, a magnet **113** is disposed proximate to the top **111** of the lifting rod **112** to provide a magnetic signal for a magnetically-based position indicator (see FIGURE 21). FIGURE 10 also shows a portion of the motor including portions of the motor housing **130**, stator **132**, and rotor **134**, which is shown in full in FIGURE 9.

[0038] The latches **170** are housed in a latch housing **172** that includes a spring guide for a latch spring **174**. Additional components of the illustrated latching system embodiment include an electromagnet housing **176** housing electromagnets **177** forming an electromagnet coil stack, and permanent magnets **178** on the latches **170**. The lead screw **160** is threaded into a latching system base **179** of the latch housing **172**. The latches **170** are arranged to pivot about pivot locations **180** to provide a failsafe scram due to downward rod load.

[0039] In this embodiment, the lead screw **160** is continuously supported by a ball nut motor assembly (best seen in FIGURE 9) which allows for very fine control of lead screw position and consequently very fine control of the position of the control rod assembly. In the illustrated embodiment, the motor (e.g., stator **132**, rotor **134**) is a synchronous motor in which the rotor **134** is a permanent magnet. This design has advantages such as compactness and simplicity; however, other motor configurations are also contemplated.

[0040] The lead screw **160** does not scram. Instead, during a scram the top end of the lifting rod **112** of the lifting rod/connection rod assembly is disconnected from the lead screw **160** by the magnetically activated latching system (see FIGURE 11). When power is cut to the electromagnets **177** the failsafe latching system releases the lifting/connection rod assembly (and thus the control rod assembly) from the lead screw **160** thereby initiating a scram. A bottom stop and buffering system (not illustrated, but suitably similar to the bottom stop and buffering system of the illustrative shutdown rods described herein with reference to FIGURES 4 and 5) is

incorporated into the base/buffer assembly to dissipate the kinetic energy at the end of the scram stroke and to set the rod bottom elevation. A torque taker (not shown) is attached to the lead screw **160** to react the motor torque thereby providing translation of the lead screw/control rod assembly.

[0041] The normal state, that is, the state prior to scram, is shown in FIGURES 9 and 10. FIGURE 9 illustrates the ball nut motor assembly and FIGURE 10 shows the latching system engaged for normal operation. As seen in FIGURE 10, the permanent magnets **178** on the latches **170** are magnetically attracted toward the powered electromagnets **177** thus pivoting the latches **170** about the pivot locations **180** and engaging the latches **170** with a mating region of the lifting rod **112**. Thus, the latches **170** are secured with the lifting rod **112** in the normal state shown in FIGURE 10. Further, the latching system base **179** is threaded to or otherwise secured with the lead screw **160**. Accordingly, in the normal state of FIGURE 10 the lifting rod **112** is secured with the lead screw **160** via the latching system, and so as the ball nut motor assembly shown in FIGURE 9 translates the lead screw **160** the lifting rod **112** is translated with the lead screw **160**.

[0042] Scram is described with reference to FIGURE 11, which shows the lifting rod **112**, and consequently the control rod assembly, during a scram. To initiate scram the power to the electromagnets **177** is cut, that is, turned off. This removes the attractive force on the permanent magnets **178** on the latches **170**, and the latch spring **174** extends to pivot the latches **170** about the pivot locations **180** and away from the mating region of the lifting rod **112**. This disengages the latches **170** from the lifting rod **112**, and the lifting/connection rod assembly (and thus the control rod assembly) falls toward the reactor **12**. The lead screw **160** is seen in FIGURE 11 still at the previous withdrawal height (that is, the lead screw **160** is not scrammed), but power to the electromagnet coils **177** has been cut so that the magnetic field from the coils is removed.

[0043] As further shown in FIGURE 11, the pivoting of the latches **170** about the pivot locations **180** is stopped by impingement at a location **181** with the spring guide of the latch housing **172**.

[0044] With continuing reference to FIGURE 11 and further reference to FIGURES 12 and 13, to re-engage the mechanism after a scram, the lead screw **160** is driven to the fully inserted position via the ball nut motor (see again FIGURE 9). A lead screw on-bottom sensor is used to confirm lead screw full insertion. With particular reference to FIGURE 12, as the lead screw **160** nears the fully inserted position an angled camming surface **182** on the top **111** of the lifting rod **112**, which is scrammed to the bottom, will cam the latches **170** to their near full out position. With particular reference to FIGURE 13, when power is restored to the electromagnets **177**, the latches **170** will fully re-engage with the mating region of the lifting rod **112** so that the lifting/connection rod assembly is once again connected to the lead screw **160**. Normal operation can then resume as per FIGURE 10. To reiterate, FIGURE 12 shows the lead screw **160** being driven back down to the fully inserted position in preparation for re-engagement of the lifting rod **112**. Power to the electromagnet coils **177** is still cut and the latches **160** are still disengaged. The angled camming surfaces **182** on the top **111** of the lifting rod **112** are camming the latches **170** back into partial engagement with the top **111** of the lifting rod **112**. FIGURE 13 shows the lead screw **160** still on bottom but with the power restored to the electromagnet coils **177**. The restored magnet field has now re-engaged the latches **170** with the mating region of the lifting rod **112**.

[0045] FIGURE 9 diagrammatically shows a suitable embodiment of the ball nut/motor assembly **106**, including lower and upper ball nut assemblies **150**, **152**. In general, substantially any type of motor can be used, suitably configured for operation in the pressure vessel environment.

[0046] With reference to FIGURES 14 and 15, an illustrative embodiment is shown which employs a brushless DC electronically controlled (BLDC) motor **184** with lower ball nut assembly **185**. The assembly **184**, **185** is an illustrative embodiment of the ball nut/motor assembly **106**. With particular reference to FIGURE 14, the illustrative BLDC motor **184** includes a wound stator core assembly **186** disposed between a stator outer shell **187** and a stator inner shell **188** and secured by a stator upper housing **189** and stator lower housing **190**. A permanent magnet rotor **191** includes permanent magnets **192**. The BLDC motor **184** produces torque from

interaction of magnetic flux of the rotor magnets **192** and the current carrying stator conductors of the stator core assembly **186**. The lower ball nut assembly **185** is analogous to the lower ball-nut assembly **150** of FIGURE 9; however, in the illustrative assembly of FIGURE 14 there is no upper ball-nut assembly corresponding to the upper ball nut assembly **152** of FIGURE 9. The assembly of FIGURE 14 also includes a radial bearing **193**, a thrust bearing **194** secured by a thrust bearing lock nut **195**, and a motor top cap **196**. An insulated and environmentally robust electrical connection to the motor is provided by a lead wire gland **197**. For example, some suitable insulated lead wire glands are available from Conax® Technologies (Buffalo, New York, USA). With particular reference to FIGURE 15, the BLDC motor **184** and lower ball-nut assembly **185** are illustrated in the context of the control rod drive mechanism (CRDM) of FIGURES 10-13. The illustrative CRDM of FIGURE 15 also includes the previously described electromagnet coil stack assembly **177**, lifting rod-to-lead screw latching assembly **110**, lead screw **160**, and lifting rod **112**. The ball-nut assembly **185** engages the lead screw **160** so that, as the motor **184** rotates the permanent magnet rotor **191** and the secured ball-nut assembly **185**, the lead screw **160** is driven linearly.

[0047] With returning reference to FIGURES 1 and 2, an advantage of the disclosed reactor design is that the middle section includes the internals support flange or "mid-flange" **29**. This section can be made relatively thin, and provides support for the control rod drive mechanism and guides for the in-core instrumentation. This section provides electrical and hydraulic inputs for the control rod drive mechanisms (CRDMs). A reactor coolant drain penetration (not illustrated) is optionally also incorporated in this section. This drain line, if incorporated, is optionally isolated by an internal valve whenever the reactor is pressurized to limit or eliminate its potential as a loss of coolant accident (LOCA) site.

[0048] The illustrated upper internals **24** including the CRDM do not include illustrated thermal insulation. However, it is contemplated to insulate these components using an insulation system capable of withstanding a design temperature of at least about 650 °F (343 °C). By using the insulation system, external cooling water will not be required although may optionally also be used. For example, cooling

water can be supplied to the electrical devices to reduce the severity of the heat duty imposed by the operating environment. The insulation system facilitates locating the electrical CRDM within the pressure vessel, which reduces the overall height of the reactor vessel **10**, significantly reduces the number of penetrations into the reactor vessel **10**, and enables a complete reactor module to be shipped as a single unit. Another advantage is reduction of the overall height of the containment structure (not shown). Although the use of insulation is believed to be advantageous, other contemplated solutions include the use of water cooling and/or selecting materials capable of withstanding the high operating temperature without insulation.

[0049] The illustrative reactor embodiment is an integral pressurized water reactor (PWR) configuration. However, one or more of the disclosed techniques, apparatuses, or so forth are also expected to be suitably used in other types of nuclear reactor vessels, such as boiling water reactors (BWRs) that can advantageously incorporate internal CRDM assemblies, efficient control rod position sensors, and so forth.

[0050] The preferred embodiments have been illustrated and described. Obviously, modifications and alterations will occur to others upon reading and understanding the preceding detailed description. It is intended that the invention be construed as including all such modifications and alterations insofar as they come within the scope of the appended claims or the equivalents thereof.

CLAIMS:

1. A control rod mechanism for use in a nuclear reactor, the control rod mechanism comprising:

a control rod configured for insertion in a reactor core to absorb neutrons;

a connecting rod connected with the control rod;

a drive mechanism including a lead screw engaged with a motor-driven nut such that rotating the nut causes linear translation of the lead screw; and

a latch operatively connecting the connecting rod to move together with the lead screw, the latch opening responsive to a loss or removal of electrical power to detach the connecting rod from the lead screw.

2. The control rod mechanism as set forth in claim 1, wherein the control rod comprises a plurality of control rods connected with the connecting rod via a spider assembly.

3. The control rod mechanism as set forth in claim 1, further comprising:

an electromagnet magnetically controlling the latch, wherein loss or removal of electrical power to the electromagnet causes the latch to open to detach the connecting rod from the lead screw.

4. The control rod mechanism as set forth in claim 3, wherein the electromagnet is at least coextensive with a linear translation stroke over which the latch can be linearly translated by the drive mechanism.

5. The control rod mechanism as set forth in claim 3, wherein the latch includes permanent magnets that are attracted to the electromagnet when electrical power is supplied to the electromagnet.

6. The control rod mechanism as set forth in claim 3, wherein the latch is mechanically biased open and electrical power to the electromagnet operates to magnetically close the latch.

7. The control rod mechanism as set forth in claim 6, wherein the latch is mechanically biased open by a spring.

8. The control rod mechanism as set forth in claim 3, wherein the electromagnet does not move with the lead screw when the drive mechanism causes linear translation of the lead screw.

9. The control rod mechanism as set forth in claim 8, further comprising:

an electromagnet housing that housing the electromagnet, the latch also being disposed inside the electromagnet housing.

10. A control rod control method comprising:

moving a control rod linearly using a lead screw; and

responsive to a scram, detaching the control rod from the lead screw whereby the control rod scrams but the lead screw does not scram.

11. The control rod control method as set forth in claim 10, wherein the detaching comprises:

disengaging a latch securing the control rod with the lead screw.

12. The control rod control method as set forth in claim 11, wherein the disengaging a latch comprises:

removing electrical power from an electromagnet that magnetically closes the latch.

13. The control rod control method as set forth in claim 11, wherein the control rod is secured with the lead screw by a connecting rod having a lower end connected with the control rod and an upper end latched with the lead screw, and the detaching comprises:

unlatching the upper end of the connecting rod from the lead screw.

14. A nuclear reactor comprising:

a reactor core;

a pressure vessel including a lower vessel section containing the reactor core, an upper vessel section disposed above the reactor core and above the lower vessel section, and a mid-flange located above a reactor core and disposed between the lower vessel section and the upper vessel section; and

an internal control rod drive mechanism (CRDM) supported by the mid-flange.

15. The nuclear reactor as set forth in claim **14**, further comprising:

an integral steam generator disposed in the pressure vessel above the mid-flange.

16. The nuclear reactor as set forth in claim **14**, further comprising:

an internals basket assembly supporting the CRDM and secured to the mid-flange.

17. The nuclear reactor as set forth in claim **14**, further comprising:

control rod guide frames supported by the mid-flange.

18. The nuclear reactor as set forth in claim **14**, further comprising:

a hydraulic shutdown control rod drive mechanism supported by the mid-flange.

19. The nuclear reactor as set forth in claim **14**, wherein the internal CRDM including motors of the internal CRDM are disposed inside the pressure vessel, and the mid-flange provides electrical and hydraulic inputs to the internal CRDM.

20. The nuclear reactor as set forth in claim **14**, wherein the internal CRDM comprises:

a connecting rod connected with a control rod;

a lead screw;

a drive mechanism providing linear translation of the lead screw; and

a latch having (i) a latched state in which the connecting rod is latched to the lead screw such that the connecting rod moves together with the lead screw when the lead screw is linearly translated by the drive mechanism and an (ii) unlatched state in which the connecting rod is not latched to the lead screw.

21. A control rod drive mechanism (CRDM) for use in a nuclear reactor, the CRDM comprising:

a connecting rod connected with at least one control rod;

a lead screw;

a drive mechanism configured to linearly translate the lead screw;

an electromagnet coil assembly; and

a latching assembly that latches the connecting rod to the lead screw responsive to energizing the electromagnet coil assembly and unlatches the connecting rod from the lead screw responsive to deenergizing the electromagnet coil assembly.

22. The CRDM as set forth in claim **21**, wherein the latching assembly is secured with and linearly translates with the lead screw.

23. The CRDM as set forth in claim **22**, wherein the electromagnet coil assembly does not move with the lead screw.

24. The CRDM as set forth in claim **23**, wherein the electromagnet coil assembly is at least coextensive with a linear translation stroke over which the drive mechanism is configured to linearly translate the lead screw.

25. The CRDM as set forth in claim **21**, wherein the latching assembly is mechanically biased to be unlatched and includes magnets that experience a force responsive to energizing the electromagnet coil assembly that overcomes the mechanical bias to cause the latching assembly to latch.

26. The CRDM as set forth in claim **21**, wherein the latching assembly is disposed in the electromagnet coil assembly.