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MANAGING THE AGING OF BWR CONTROL ROD DRIVE SYSTEMS*

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ABSTRACT

This Phase I Nuclear Plant Aging Research (NPAR) study examines the aging phenomena associated with BWR control rod drive mechanisms (CRDMs) and assesses the merits of various methods of "managing" this aging. Information for this study was acquired from (1) the results of a special CRDM aging questionnaire distributed to each U.S. BWR utility, (2) a first-of-its-kind workshop held to discuss CRDM aging and maintenance concerns, (3) an analysis of the Nuclear Plant Reliability Data System (NPRDS) failure cases attributed to the control rod drive (CRD) system, and (4) personal information exchange with nuclear industry CRDM maintenance experts. The report documenting the findings of this research, NUREG-5699, will be published this year.

Nearly 23% of the NPRDS CRD system component failure reports were attributed to the CRDM. The CRDM components most often requiring replacement due to aging are the Graphitar seals. The predominant causes of aging for these seals are mechanical wear and thermal embrittlement. More than 59% of the NPRDS CRD system failure reports were attributed to components that comprise the hydraulic control unit (HCU). The predominant HCU components experiencing the effects of service wear and aging are valve seals, discs, seats, stems, packing, and diaphragms.

INTRODUCTION

Control rod drive mechanisms (CRDMs) are located at the bottom of boiling water reactor (BWR) pressure vessels, and they position the neutron absorbing control rod assemblies (CRAs) within the reactor core to provide reactivity control during startup and shutdown of the reactor, flux shaping at power, and emergency shutdown (scram). The CRD system consists of the CRDMs, the hydraulic control units (HCUs), and various valves, pumps, and headers that supply, move, and retain the system's operating fluid.

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The CRDM is a double-acting, mechanically latched, hydraulic cylinder that uses reactor quality water as its operating medium. Each CRDM has a companion HCU that contains numerous valves which regulate the operating flows and pressures delivered to the device. A CRA is attached to each CRDM at the spud, and movement is accomplished by admitting pressurized water into the appropriate part of the CRDM (Fig. 1). The drive mechanism is capable of inserting or withdrawing a CRA at a slow, controlled rate in order to vary reactor power, or can provide scram insertion to accomplish rapid shutdown of the reactor within a few seconds.

General Electric has manufactured six different models of CRDMs and four basic models of HCUs which are in service at BWRs throughout the United States. Improved scram times and enhanced operational performance have been the basis for many of the design differences occurring among the various models of both the CRDM and the HCU. Some aging-related degradation reported in the BWR-2, -3, -4, and -5 design CRDMs has been substantially reduced by material improvements and design features inherent to the BWR-6 models. Other types of reported component degradation are subject to plant operational parameters, such as water chemistry, and vary in frequency of occurrence with each different BWR unit.

Normal CRDM maintenance involves the overall cleaning and replacement of a relatively standard set of components with new or spare parts. If necessary, any part of the the CRDM can be replaced during rebuilding activities. Several utilities have established maintenance goals that require the refurbishment of all the CRDMs in a BWR unit every 10 years. However, historical data suggest that the maintenance interval varies for CRDMs with respect to their location in the core: centrally located drives are rebuilt more often than drives located along the periphery. The cause for dissimilar maintenance intervals is uncertain, but, due to lower vessel head geometry, the centrally located drives have more surface area exposed to the inside of the reactor than peripheral drives and may experience higher temperatures along this exposed length (Fig. 2).

Selection criteria for CRDM changeout does vary between plants. To monitor service wear and degradation, most utilities routinely trend individual CRDM withdrawal stall flows and operating temperatures. In addition, plant technical specifications require scheduled scram time testing and weekly-to-monthly CRDM "exercise" tests to ensure operability. In general, CRDM components degrade slowly as they age, and most aging problems do not occur suddenly but over a time interval of at least several years.

When a CRDM's performance indicators (e.g., stall flows, operating temperatures, and scram timing) begin to decline, it is scheduled for maintenance, usually during the next plant refueling outage. In recent years, advancements in maintenance tooling, changeout and rebuilding training, CRDM handling devices, and improvements in worker comfort have significantly decreased the human error contribution to CRDM aging as well as reducing ALARA exposures. The following sections highlight the predominant modes of CRD system degradation and specific steps taken by utilities to mitigate component aging and curtail maintenance related doses. Final research results will be published in NUREG/CR-5699, Vol. 1, entitled "Aging and Service Wear of Control Rod Drive Mechanisms for BWR Nuclear Plant

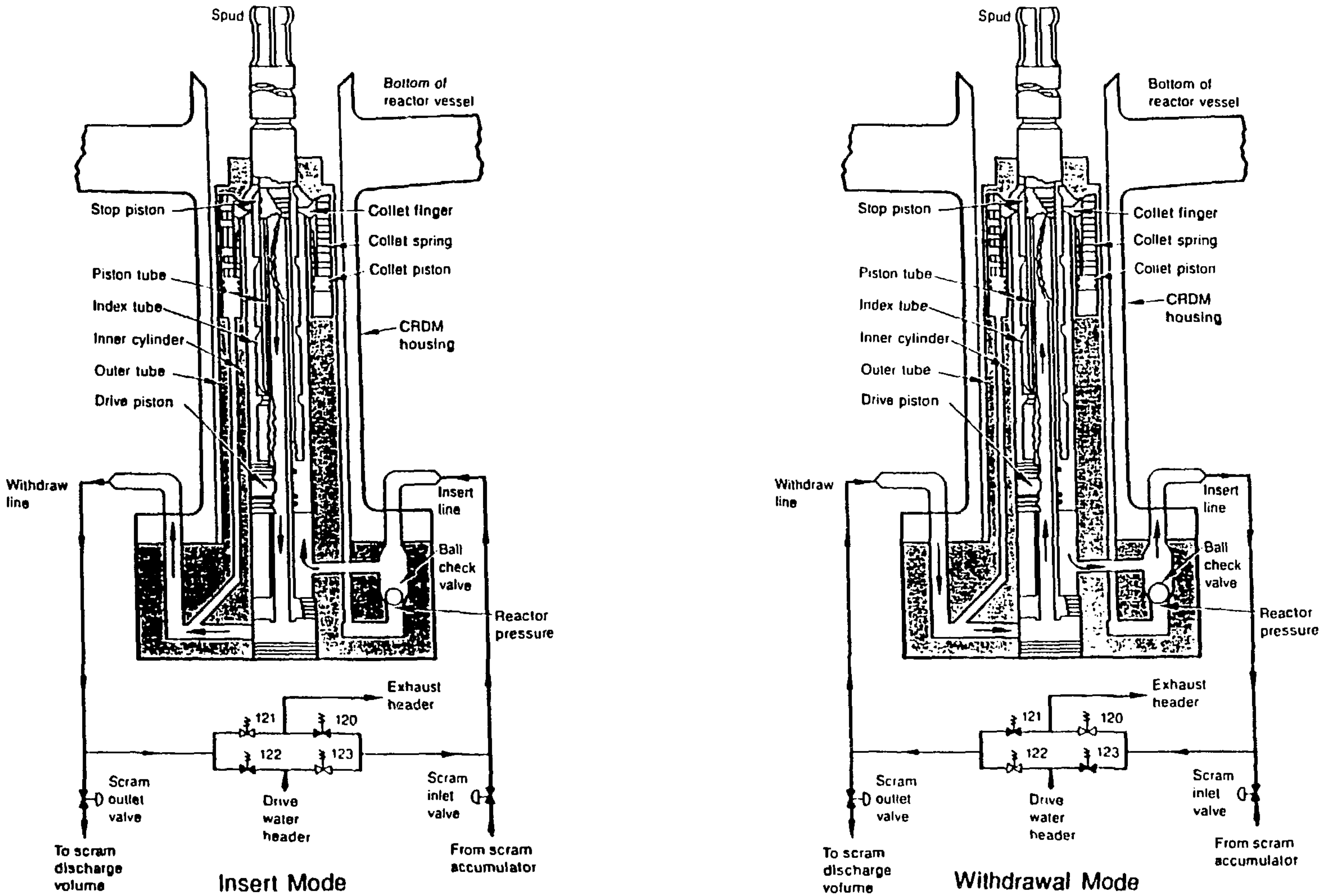

Figure 1. CRDM operation: insert and withdrawal modes.[1]

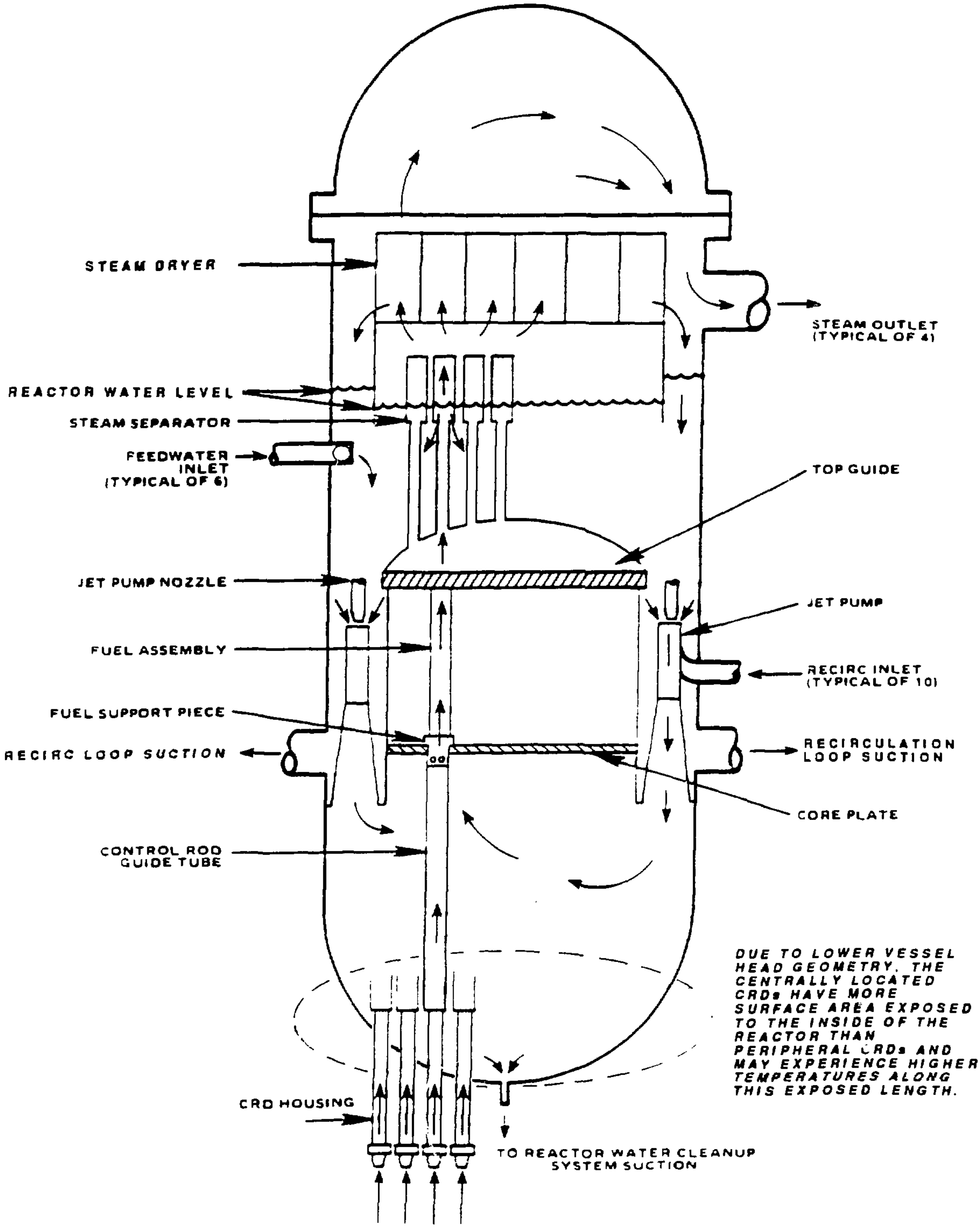

Figure 2. CRDM locations with respect to BWR lower vessel head geometry.

CRDM Degradation: Causes and Corrective Actions

As a whole, the 21 nuclear plants that responded to the CRDM aging workshop** questionnaire reported a good performance history for the BWR control rod drive mechanisms. NPRDS data analysis confirms this observation, with 72% of the failure reports being discovered by scheduled testing or routine observation, 24% by control room personnel, and only 2% as a result of a failed service demand (the remaining 2% of the NPRDS reports did not identify a discovery method in the failure narrative). The term "failure" applied in these NPRDS case histories refers to a component malfunction that may range in consequence from relatively insignificant (e.g., a small valve stem leak) to a complete operational failure (e.g., the valve did not perform on demand).

Workshop participants were also asked to share their observations regarding the primary causes of CRDM aging. In addition to normal service wear, the reported causes of CRDM degradation are Graphitar seal embrittlement, fatigue fracture, and thermal degradation, collet housing cracking, nitrided surface corrosion, human errors made during drive changeout and rebuilding activities, and, to a lesser extent, plastic deformation due to improper storage methods.

Debris, Corrosion, IGSCC, and Water Chemistry

Primary system cooling water containing "crud" (dirt particles, debris, corrosion products, and foreign materials that are found in varying amounts in the coolant) is ingested into the CRDM and responsible for the degradation of several components. Corrosion usually occurs first on CRDM components having nitrided surfaces: the index tube, piston tube, guide cap, and collet assembly. Debris becomes entrapped in the CRDM during normal operations, and its presence scars metal surfaces and defaces the Graphitar seals. As crud accumulates in the CRDM, the device's coolant flow rate may decrease and cause drive temperatures to increase, thus contributing to the thermal degradation of the seals. After a scram, coolant flow rates may increase and CRDM temperatures decrease because some of the crud has been "shaken out" of the drive. In addition, entrapped crud in between the Graphitar seal sets and their seating surfaces (on the drive and stop pistons) creates uneven force distributions during scram impacts that can cause seals to improperly function and break.

To reduce the amount of crud that can become entrapped in the CRDM, some utilities are vacuuming the bottom of the reactor vessel inside the guide tubes during refueling operations. In addition, the pre-BWR-6 design CRDMs had problems with the cooling water orifices becoming plugged with crud, which caused increased operating temperatures. Many utilities have retrofitted the older CRDMs with upgrade kits that modified the design of the cooling water orifice to mitigate this potential problem.

** *Managing the Aging of BWR CRDMs,* a workshop hosted for utility and commercial CRD system personnel by the Oak Ridge National Laboratory, January 29-31, Clearwater, Florida.

Nitrided surface corrosion has also been aggravated by poor storage methods. Occasionally, CRDMs are stored wet in air for more than 30 days before they can be rebuilt, usually due to strained outage schedules. The nitrided surfaces of the CRDMs begin to corrode, and the drive becomes excessively hard to disassemble for rebuilding. CRDM components can be inadvertently damaged during a difficult disassembly process from mishandling. One utility is currently employing a long-term storage technique which places its "dirty" CRDMs in an aqueous solution of triethanolamine, a corrosion inhibitor, so that rebuilding can be delayed for up to 24 months. Some advantages for using this type of storage technique are (1) it allows for radioactive decay, (2) it permits maintenance to be performed off the critical path, and (3) it enables drives to be rebuilt within 30 days of their actual need. According to attendees at the workshop, this method of storage has been used several times before without any noticeable component deterioration.

Significant numbers of CRDMs have been retired from service due to collet housing cracking. This intergranular stress corrosion cracking (IGSCC) phenomenon has been found in the model A, B, and C drives that were originally installed in BWR-2, -3, -4, and -5 plants. One utility reported in the questionnaire that 46% of the cylinder, tube, and flange assemblies in its CRDMs had to be replaced because of this type of degradation. Later CRDM designs (models D, E, and F) that were supplied in BWR-6 plants changed this component's material from a 304 to a CF3 (cast 304L) stainless steel. These improved models have not experienced this problem. Utilities observing collet housing cracking in their drives have either replaced affected CRDMs with the later model drives or improved the earlier models with upgrade kits from the vendor.

In the past decade, water chemistry in the primary system has been modified in at least nine BWR facilities by hydrogen injection. This practice is intended to reduce the potential for primary system corrosion and IGSCC, but was not implemented to address problems with CRDM collet housing cracking. To reduce the probability of IGSCC of the CRDM collet housing, the CRD system should use high purity deaerated water (characterized by lower oxygen content and conductivity) during reactor operations, which is normally available from the condensate treatment system instead of the condensate storage tank.

Effects of Fatigue and Mishandling

Fatigue and/or mishandling is suspected to be the cause of certain effects observed in the spud, the CRDM component that engages the control rod assembly blade via the uncoupling rod. There have been reports of the "fingers" of this Inconel X-750 component being easily bent after a prolonged service history (> 15 years) in the reactor vessel. CRDM rebuilding technicians have described the effect as the fingers "losing their memory," and have used screwdrivers to pry and bend the fingers back into a proper concentricity (a practice which is not recommended). Although no professional metallurgical examinations have been conducted on a malformed spud, the cause of the bent fingers is speculated to be (1) fatigue caused by mechanical loads imposed by repeated scrams, (2) deformation resulting from mishandling during CRDM installation, or (3) deformation from CRA installation while the CRDM is partially inserted. This type of spud damage (as shown in Figure 3) can present a myriad of coupling and uncoupling difficulties with the CRA. The spud, like all CRDM components, should be exchanged with a new spare part during rebuilding activities if it is damaged.

Nitrided Surface Degradation

In some CRDMs having a continuous service history greater than 15 years, degradation of the nitriding has been observed to the extent that, in one particular example, the unusually rough surface of an index tube could be easily scored with a piece of wood.[2] Although no formal metallurgical investigations have been conducted to determine the nature of this effect, it could be the result of a combination of causes: prolonged radiation exposure, poor water chemistry, high operational temperatures, and variations in the case hardening from the nitriding process. It should be noted that no operational problems were reported for one CRDM with a longitudinally "striped" index tube (as shown in Figure 4), but the component was not reused in the rebuilt device because its continued serviceability was considered questionable.

Graphitar Seal Wear and Breakage

Replacement of the Graphitar seals is a standard requirement during CRDM rebuilding activities. An intact and correctly seated seal allows differential hydraulic pressures (upon withdrawal, insert, and scram signals) to position the drive. As these seals degrade and become less effective, i.e., become broken, scarred, or chipped due to numerous scram impacts, undergo normal surface wear, or experience thermal degradation [caused by drive temperatures greater than 177° C (350° F)], the CRDM's stall flows increase and greater hydraulic pressures are required to maneuver the drive. There were 275 NPRDS failure reports that cited Graphitar seal wear as the cause of deteriorating CRDM performance. The predominant location of the seal failures was on the stop piston. CRDM withdrawal stall flows over 316 cm^3/s (5.0 gpm) (not attributable to the valving configuration on the HCU) are considered indicative of deteriorated seals that need to be replaced. Both General Electric and the Toshiba Corporation have developed improved Graphitar seals designed to be more durable and have a longer service life than those currently used in domestic BWR CRDMs. General Electric's new BWR-6 CRDMs are already equipped with these improved seals, and an improved replacement seal kit for BWR-2, -3, -4, -5, and -6 model CRDMs became available to utilities in February 1992.

Inner Filter Disengagement

Each CRDM has an inner and outer filter which serves to collect debris from reactor water that might otherwise damage the CRDM. The inner filter has been attributed with 90 failure reports in the NPRDS. Installation and maintenance errors were cited in 35 cases. Inner filters that are incorrectly installed during CRDM rebuilding can become loose during drive operation and cause the CRA to uncouple itself from the CRDM's spud. Uncoupling is a symptom observed in 27 of these reports. The inner filter is mechanically attached to the stop piston by means of a spring clip (Fig. 5). When

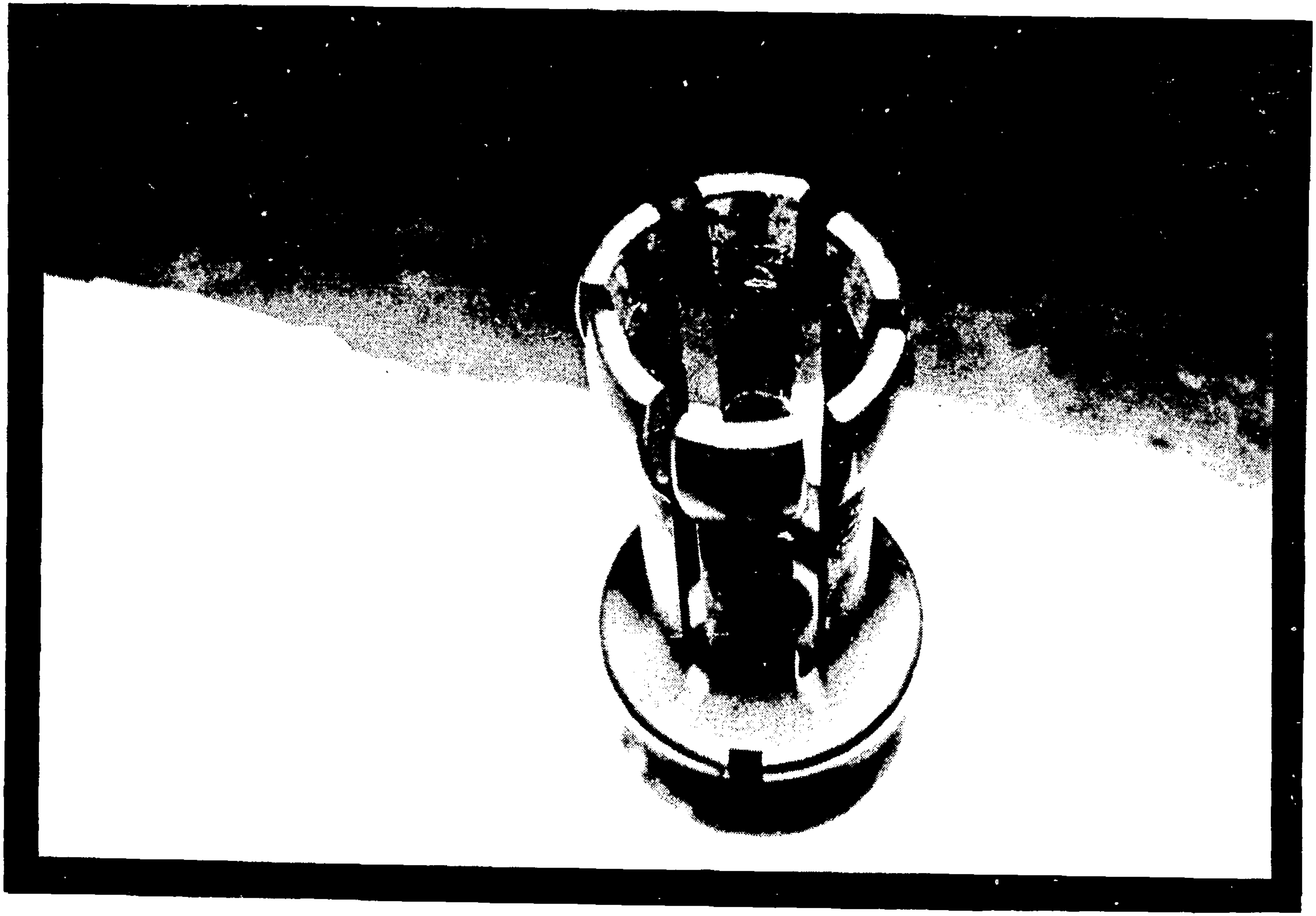

Figure 3. Bent CRDM spud fingers (notice lack of concentricity).

Figure 4. CRDM index tube surface degradation (notice striping left by collet fingers).

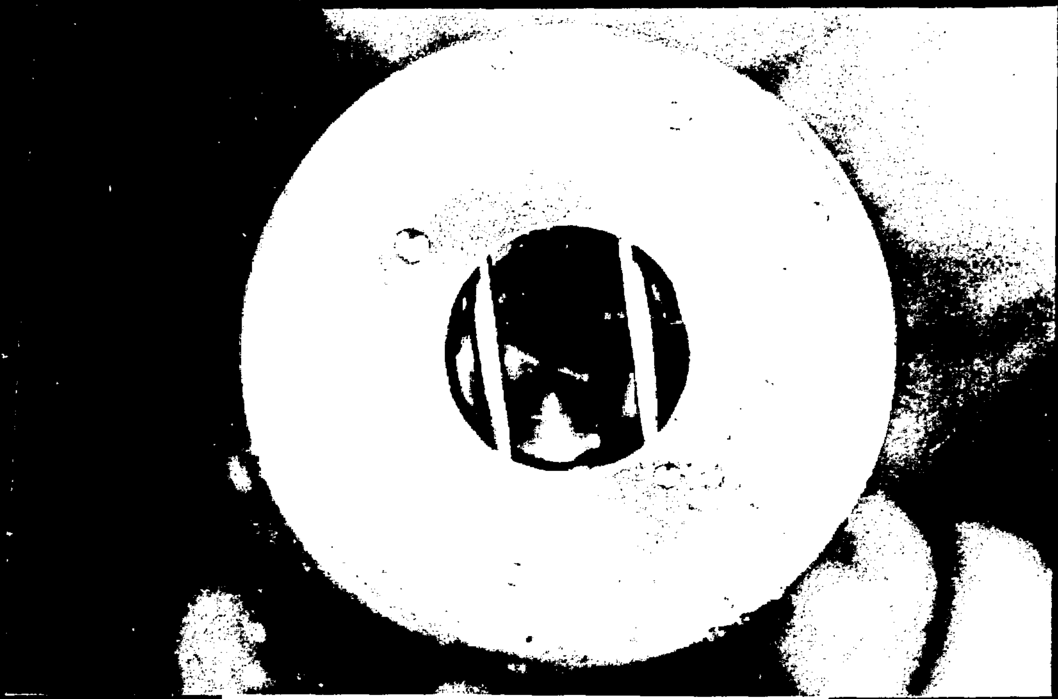

Figure 5. CRDM inner filter spring clip.

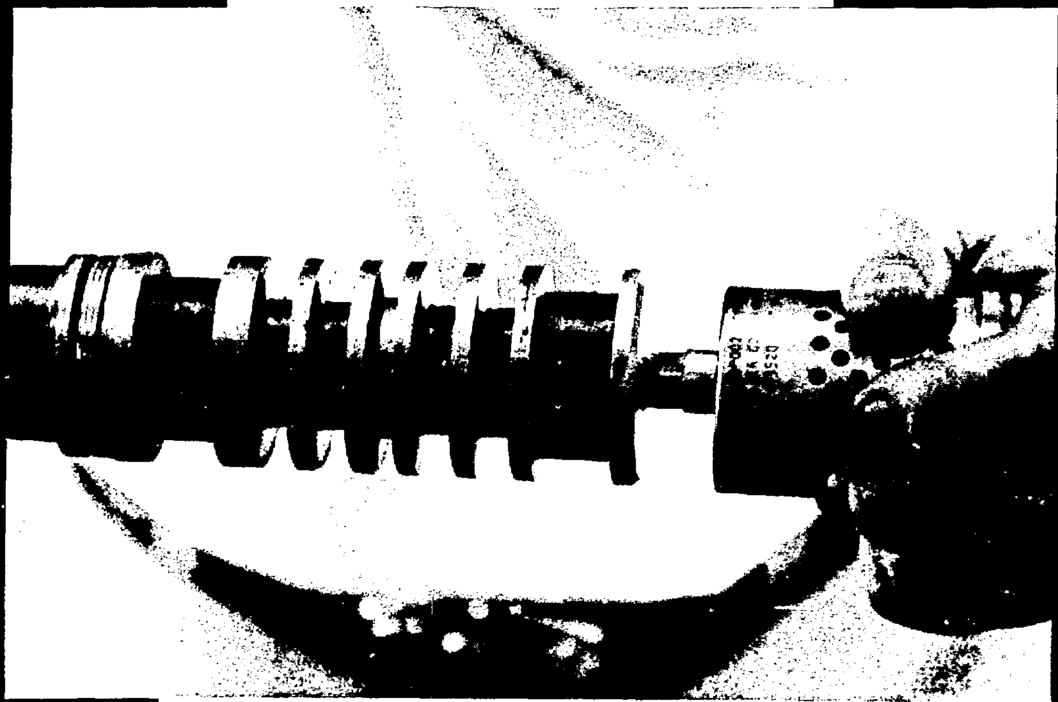

Figure 6. Attachment of inner filter to stop piston.

assembled, the inner filter engages the piston connector knob and is retained by locking flats that capture its spring clip after the filter is pushed onto the piston knob and rotated about 90° (Fig. 6). To test the proper installation of the inner filter, General Electric recommends using a filter assembly tool to pull the inner filter away from the stop piston with a force of about 89 to 133 N (20 to 30 pounds). After engagement has been verified, the tool is removed from the CRDM, sometimes with an unintentional jiggling or twisting motion. When this is done, the filter becomes improperly oriented and can easily be disengaged. Even if the filter is not fully rotated 90°, the filter may be inadvertently rotated more during CRDM rebuilding and handling activities.

During the initial withdrawal venting of entrapped air for a reinstalled CRDM, the CRDM is inserted to a notch position less than 06 and then fully withdrawn back to position 48. If the inner filter was not truly engaged during the rebuilding process, it could bind against the inner surface of the CRDM index tube during CRDM withdrawal. In this scenario, the inner filter can become disconnected, cocked, and suspended. During the applied withdraw signal, the uncoupling rod could jam against the side or top of the inner filter. When the CRDM is fully withdrawn at position 48, the misconfiguration of the internal components can result in the CRDM uncoupling with the CRA.

The Toshiba Corporation has instituted a modification in its inner filter's base configuration in order to provide an improved design that would prevent uncoupling trouble due to misassembly. To date, there have been no design enhancements made in the attachment configuration of inner filters used in CRDMs operating in US BWRs that would circumvent this type of disengagement.

Uncoupling Rod Misinstallation

Uncoupling has also been the result of the CRDM's uncoupling rod being misinstalled into the one of the spud's flow holes instead of the center holes and becoming vertically misaligned. This arrangement allows the bottom end of the uncoupling rod to contact the upper flange of the inner filter, lifting the control rod lock plug sufficiently to cause uncoupling. An uncoupling rod incorrectly installed in this manner can also prevent the CRDM from being withdrawn to back-seated position 48. If the uncoupling rod jams inside the spud flow hole from non-vertical orientation, it can stop the downward movement of the index tube before it reaches position 48. General Electric introduced a new uncoupling rod design in 1989 that was developed to prevent incorrect installation. The improved rod is available for BWR/2 through BWR/6 model CRDMs.[3]

Improper CRDM Storage Methods

The 4.7m, 204 kg (15.5 ft, 450 lb) CRDM can be a challenge to store. Inadequate storage support has been blamed for a few observed cases of CRDM "sagging", which were confirmed by performing runout measurements along the length of the drive. Utilities store CRDMs in shielded vaults, on specially built racks, and sometimes in their original shipping crates. CRDM components can be damaged by laying drives on the floor with only the collet housing and the flange end supporting the weight as shown in Figure 7. CRDMs should not be stacked on top of each other, separated by wooden blocks, which, in

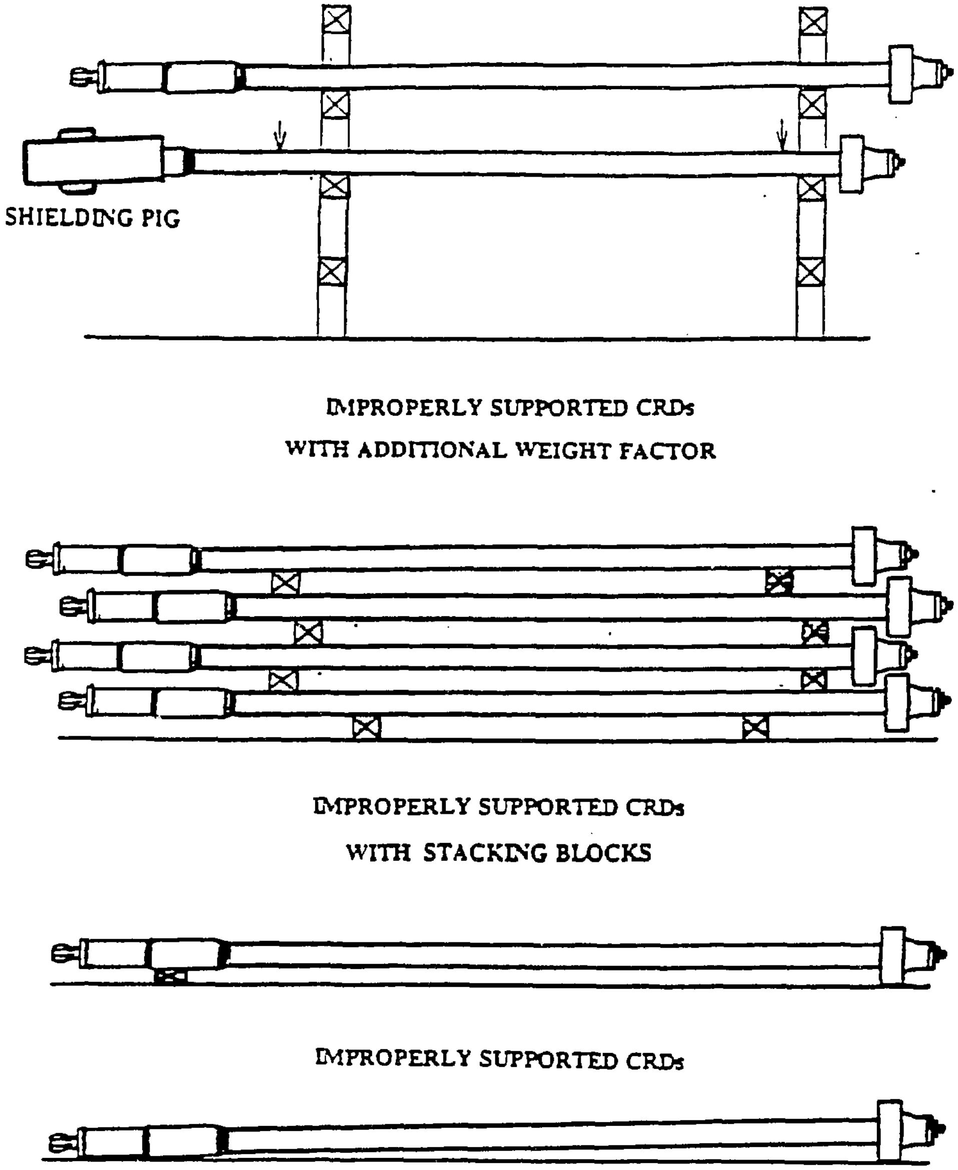

Figure 7. Improper CRDM storage scenarios.[2]

essence, transmits the weight of the stack to the lowest drive. Heavy, lead shielding "pigs" are sometimes left hanging on the spud end of "hot" drives for long periods of time, which places a moment on the collet housing. As shown in Figure 8, CRDMs should be stored in racks or vaults with a minimum of 2 points of support located 61 cm (24 in) from the flange end and 137 cm (54 in) from the spud end.

HCU Degradation: Causes and Corrective Actions

The NPRDS analysis yielded specific information on HCU degradation. Over 59% of the CRD system failures are attributable to the HCU. The HCU components requiring the most maintenance and replacement (as reported in the NPRDS) are identified in Figure 9. The following information discusses the HCU components requiring the most maintenance and the causes of their aging.

Accumulator Nitrogen Charging Cartridge Valve (HCU part no. 111)

There were 526 NPRDS failure reports on this particular valve. The leading reported cause of failure was attributed to worn valve packing (189 cases -- 36%). Normal valve wear or aging was "runner-up" in the cause category (164 cases -- 31%), and a worn valve stem ranked third among failure causes (71 cases -- 14%). Additional reported failure causes were multiple-cause valve aging (cites the failures of several valve parts), valve seat aging, and worn valve seals.

The cartridge valve is located at the bottom of the HCU on the instrumentation block. This component is frequently referred to as the "star valve" because of the shape of the hand crank on the stem. Many of the failures of the "U-cup" packing may be attributed to incorrect installation. General Electric manufactures a four-part packing installation tool that was specifically designed to replace the U-cup packing in this valve. If the packing tool is not used when repacking the valve, it is easy to damage the packing on the valve stem threads during installation and create a new leak. It has also been reported that utility maintenance personnel occasionally adjust the star valve with their foot, rather than bending over and using their hand. This practice could easily bend the narrow valve stem in addition to damaging the packing.

Scram Water Accumulator (HCU part no. 125)

The NPRDS has recorded 189 failure reports of this component with 119 of them requiring replacement units. In the pre-BWR-6 models, the chromium plating liner of this carbon steel tank is porous enough to allow water to seep in and cause corrosion of the carbon steel. General Electric issued a service information letter regarding the interior surfaces of these accumulators and determined that high-chloride, low pH water conditions would produce blistering and pitting of the plating throughout the cylinder. It was further reported that loose flakes of this plating may leave the accumulator and collect on the Teflon seat of the inlet scram valve and cause some leakage. If this occurs, it can result in control rod insertion. In addition, the tank's corrosion flakes can etch Teflon from the scram valve seat and subsequently become entrapped in the cooling water orifice of the companion CRDM. General Electric and the Toshiba Corporation have

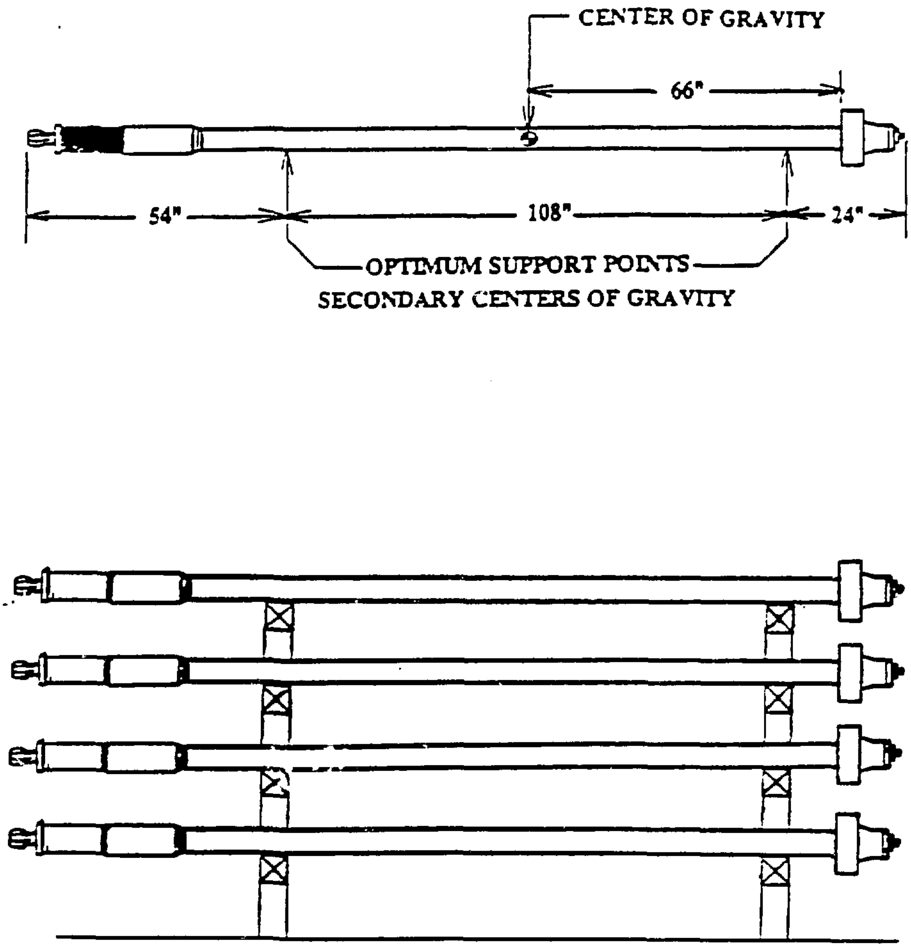

Figure 8. Acceptable CRDM storage arrangement. [2]

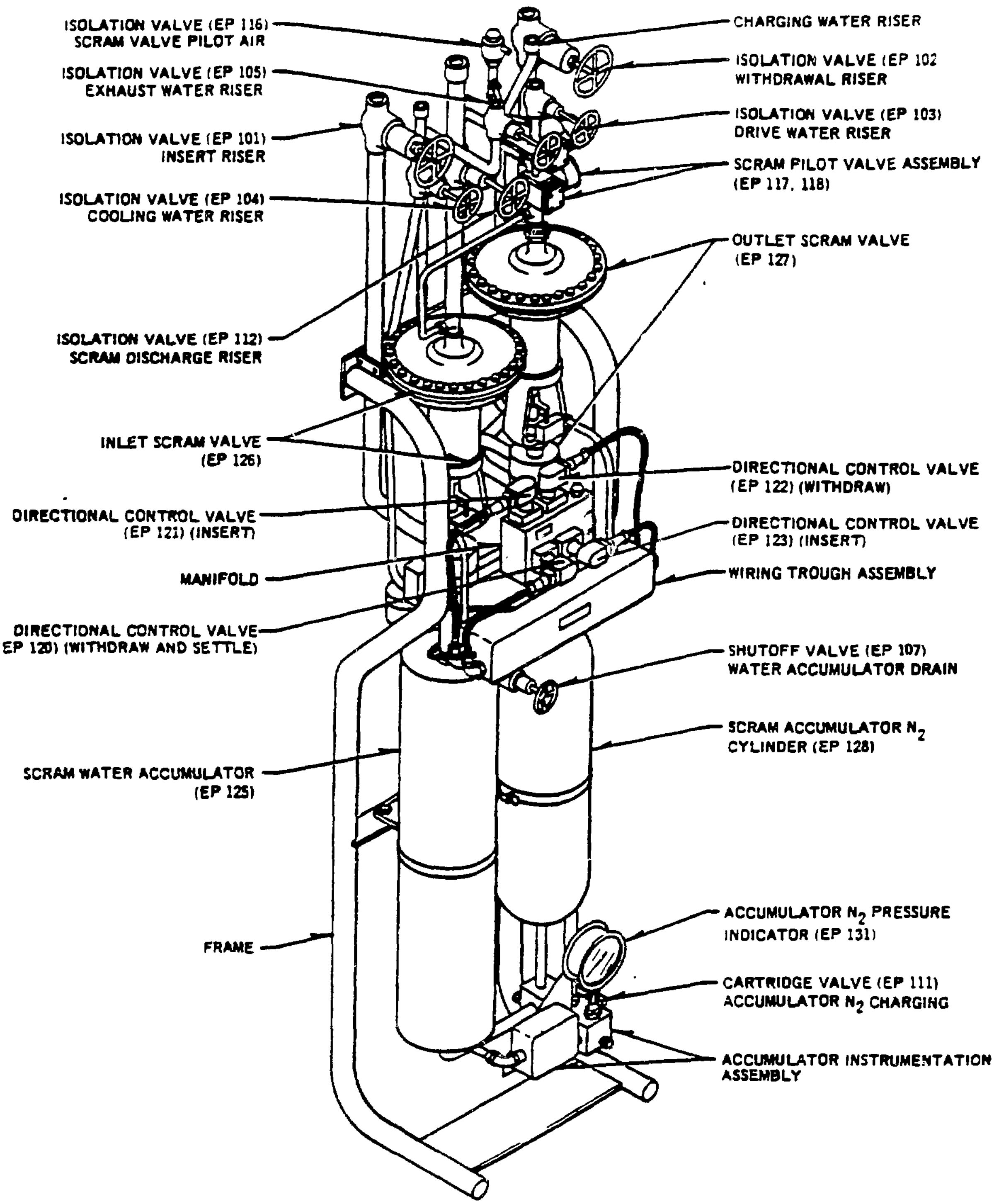

Figure 9. A BWR hydraulic control unit (HCU) and its components. [6]

developed stainless steel replacement units for this component. The predominant symptom of accumulator degradation reported in the NPRDS is a high water level alarm for the accumulator.

Inlet and Outlet Scram Valves (HCU part nos. 126 and 127)

There were 129 failure reports on the inlet scram valve (No. 126). The primary causes of degradation identified in the NPRDS were aging of the valve seat, multiple valve parts aging, worn valve packing, and worn valve diaphragms. Almost 65% of these reported failures have required valve rebuilding or replacement. As previously discussed, flakes of plating from a corroded accumulator can collect and erode the Teflon seat of this valve. In addition, the diaphragms of this valve are made from Buna-N reinforced with nylon. In a service infor-mation letter issued on this valve, General Electric recommends the lifetime (elapsed time between diaphragm cure and installation plus time in service) of this component to be 15 years for BWR/2s through BWR/5s and 12 years for BWR/6s. A supplemental service information letter from General Electric also stated that the nylon fibers around the diaphragm center hole on the Hammel-Dahl scram valve diaphragms could be damaged by the valve stem thread during diaphragm installation if the stem nut is tightened with the spring force applied under the diaphragm button. A subsequent redesign of the diaphragm has eliminated the protrusion of nylon fibers from the center hole. The outlet scram valve (No. 127) had 77 failure reports that cited incorrect operation, worn seats, worn diaphragms, and worn stems and packing. More than 85% of the outlet scram valve failures reported in the NRPDS have required rebuilding or replacement to restore service.

Scram Pilot Valve Assemblies and Solenoids (HCU part nos. 117 and 118)

There were 71 and 69 failure reports on the Nos. 117 and 118 valves, respectively. The causes of failure observed most frequently for this valve were a worn diaphragm, aged solenoid components (such as a coil "short" or a "blown" fuse), and normal valve wear or aging. The scram pilot valve solenoids had 241 reports of failure (185 by one plant) that cited the primary causes of failure as a worn seat (or disc). General Electric issued a service information letter indicating that cracking of the Buna-N rubber discs had been observed at a BWR plant causing delays in CRDM scram times. The cracking and deterioration of the Buna-N disc material was accelerated by long-term exposure to the heat of the normally energized solenoid coil and by oil and water contaminants in the utility's instrument air supply.[4] Since there is a continuous heat source from these normally energized solenoids, utilities could periodically monitor and trend surface temperatures to detect coil degradation, which was cited as the secondary cause of failure for these valves (increasing temperatures can indicate imminent coil failure)[5]. Industrial pyrometers could be used to obtain these data. General Electric also recommended in a service information letter that all BWR utilities establish a preventive maintenance program to replace all core assemblies, diaphragms, and associated parts in all CRD scram pilot valves, backup scram valves, and scram discharge volume test valves at periodic intervals since the Buna-N parts in these valves have a combined 7-year shelf and in-service life that elapses from the packaging date on the rebuild kit. The symptoms of scram pilot valve and solenoid degradation include slow scram times, leaking air, and abnormal solenoid noise (chattering, rattling, or ac hum).

Balance-of-CRD-System Component Failures

If failure report cited in the NPRDS was not attributed to a component associated with either the HCU or the CRDM, this analysis effort classified it as a balance-of-CRD system (BOCRDS) component failure. Only 18% of the failures reported in the NPRDS were attributed to components comprising this category. The following paragraphs discuss those component categories which had the higher numbers of failure reports.

CRD System Pumps and Pump Components

The CRD system pumps and pump components had 117 failure reports in the NPRDS. Worn bearings, seals, piping and parts erosion, looseness, and normal wear or aging are the most prevalent problems identified in this data base. Over 98% of the pump failures were discovered by testing or routine maintenance. Several U.S. utilities (both BWR and PWR) have instituted monthly-to-quarterly vibration signature analysis programs on various types of rotating machinery in their stations as part of their overall maintenance and ALARA reduction efforts. Bearing anomalies, misalignment, unbalance, looseness, and soft foundations are readily analyzed and diagnosed using fast Fourier transform (FFT) analysis. Other programs augment their diagnostics by utilizing oil analysis to examine metallic parts degradation. Although there have been a few CRD pumps completely changed out, pump components have normally been replaced on an "as-needed basis" to restore service, and occasionally, entirely rebuilt.

Miscellaneous Scram Discharge Volume Valves

There were 44 failure reports on valves associated with the scram discharge volume. In 25% of these cases, the valve actuator or operator was simply out of adjustment. Over 27% of the reports cited entrapped debris causing component failure. One station reported corrosion and entrapped debris on the scram discharge volume vent valve due to a failure in procedures to regularly cycle the valve. To mitigate buildup of debris, procedures were enhanced to require quarterly timing and results trending of valve actuation. Another station reported a failure of the scram discharge volume drain valve caused by an accumulation of dirt and corrosion on the seat surface. The failure narrative reported that the maintenance staff felt this may have been caused by a prolonged shutdown. Scram discharge volume system component failures have also been attributed to contaminated instrument air used to operate system solenoid valves[4]. The majority of the scram discharge volume valve failures (80%) have required valve rebuilding or replacement.

HCU and BOCRDS Electrical Components

This section groups the results of the electrical component failures for the HCU and CRD system, including any electrical components associated with the CRD pumps. The group includes the reported failures of electrical relays, switches, controllers, transmitters, power supplies, circuit breakers, and fuses. There were 207 failures altogether comprising 65 reports attributed to the HCU and 142 associated with the BOCRDS. There were no electrical component reports on the CRDM. The predominant causes of failure in these areas were cited as electrical component aging and the device being out of calibration (includes setpoint drift). As might be expected, the component was restored to service either via adjustment or complete replacement.

CRD System Instrumentation

There were 79 reports of failed gauges and instrumentation in the entire CRD system. As in the case of electrical components, the predominant causes of failure identified in the NPRDS were electronic component aging and out-of-calibration. Over 91% of these failures were corrected by an adjustment and the remainder required a like-for-like replacement.

Selection Criteria for CRDM Changeout and Rebuilding

There is much debate regarding the criteria applied by utilities to select CRDMs for changeout and rebuilding. Although there are many contributing factors that may vary the rate and effects of CRDM aging, the historical recommended maintenance interval of a CRDM has been ten years. With this figure in mind, many utilities have designed CRDM changeout schedules to reflect a 100 percent rebuild of all CRDMs in the reactor every ten years. Other utilities, that are rigorously and routinely monitoring and trending stall flow rates, operating temperatures, and acquiring friction traces of their CRDMs, feel they can confidently assess the operability of their CRDMs without scheduling drives for maintenance based solely on elapsed service time. The workshop reviewed the CRDM changeout history for 20 BWR units. The data suggests that centrally located drives undergo more maintenance than peripheral drives. Attendees at the workshop stated that not all the CRDMs that had been changed out exhibited operational problems, and that, frequently, operational problems had been erroneously attributed to CRDMs that should have really been directed at components on the companion HCU.

The selection of CRDMs to be rebuilt can be initiated by classifying drives into two groups: *Priority 1 CRDMs*, those drives which must be exchanged or rebuilt, and *Priority 2 CRDMs*, those drives which should be exchanged or rebuilt, and incorporated into the outage schedule if at all possible. Attendees at the workshop agreed on the following operational characteristics that would place suspect CRDMs into the two categories described in Table 1 and Table 2:

Table 1 - Characteristics of Priority 1 CRDMs -- Must be Exchanged or Rebuilt

1. Excessive scram times - violation of plant technical specifications.

2. CRDM does not fully insert during a scram.

3. CRDM has a history of uncoupling.

4. CRDM will not go into position 48 (fully withdrawn).

5. CRDM consistently has a withdrawal stall flow greater than 316 cm^3/s (5.0 gpm).

Table 2 - Characteristics of Priority 2 CRDMs -- Should be Exchanged or Rebuilt

1. Consistently high temperatures throughout length of travel [>177° C (350° F)].

2. Unacceptable withdrawal or insertion times that are unrelated to the HCU.

3. Repeated episodes of "double-notching" when moving, or CRDMs that continually require increased drive pressures to move (unrelated to the HCU).

4. CRDMs with high or abnormal friction traces not attributable to misalignment with fuel assemblies.

Attendees at the workshop also stated that when CRDMs began to display operational problems, several of the anomalies listed in Tables 1 and 2 would usually be manifested concurrently. For that reason, many utilities choose to rebuild CRDMs if they display *any* of the operational characteristics mentioned in these categories, and might also include those drives that have a continuous service time of ten years. Most CRDM aging problems, usually have a long lead time and do not suddenly occur without exhibiting characteristic warning signals.

ALARA Reduction During CRDM Changeout and Rebuilding

Workshop attendees commented that CRDM changeout and rebuilding is one of the highest dose, most physically demanding, and complicated maintenance activities routinely accomplished by BWR utilities. In the 30 years since the BWR design concept for commercial nuclear power production was first successfully demonstrated, there have been many enhancements in the maintenance techniques used to pull and refurbish CRDMs. However, some utilities have not taken advantage of new tooling and continue to use outdated maintenance equipment, which still adequately performs the task, yet inevitably results in higher doses delivered to the nuclear worker. According to questionnaire responses and nuclear commercial services input, substantial ALARA reduction can be realized by focusing improvements in three key areas associated with CRDM maintenance work: CRDM handling and exchange tools, worker comfort and environment, and worker training.

CRDM Handling and Exchange Tools

There are currently five different companies offering pneumatically or hydraulically operated devices which can be placed in existing BWR undervessel work platforms to assist CRDM personnel with changeout activities. They replace conventional, electrically driven winch systems supplied with the plants and require only two technicians for equipment operation.

More than half of the sites responding to the questionnaire stated that they had either purchased or contracted the use of this type of device in their CRDM changeout work, and also verified that it had significantly improved the performance of CRDM maintenance. Most further stated that this type of device had reduced job-related exposures, with two plants reporting overall exposure reductions of 38 and 56 percent.

CRDM Worker Comfort and Environment

The CRDM Aging Questionnaire asked utilities to indicate which conditions during CRDM changeout had the most influence toward improper CRDM maintenance. High temperatures were recognized by 65 percent of those participants as having the biggest negative impact on worker performance. In addition, high radiation levels (creating, in some cases, a false sense of urgency in workers not accustomed to this type of work), extremely cramped working conditions (a person works "hunched over" for long periods of time during changeout operations), poor vision (obstructed from instrumentation cabling and hampered by insufficient lighting), and inadequate communication were prevalent conditions that further complicate an already complex task. Other job location factors contributing to mishandling errors were disorientation, remoteness, cumbersome protection clothing, and visual impairment during CRDM "rainshowers" [the normal 126 to 189 cm^3/s (2 to 3 gpm) leak of reactor water when drives are removed from the vessel].

There are several utilities which have invested much time and money into developing improved maintenance conditions for CRDM changeout work. Some plants have revised and streamlined procedures, while others are testing new designs of radiation protection clothing, portable air conditioning apparatus, installing temporary lighting, and developing specialized tools for these tasks. The overall consensus of the workshop attendees was that any utility which sought ways to improve worker comfort during these activities would realize benefits not only in ALARA reduction but also in fewer maintenance errors.

CRDM Worker Training

CRDM worker training, particularly with undervessel mockups, improves crew performance and helps expedite tight outage schedules. "Full-rad dress" rehearsals are particularly valuable in acquainting technicians with working under restrained conditions. Both the CRDM changeout and rebuild crews should receive specialized training to correctly perform these tasks. More than half of the participants responding to the questionnaire either trained their own crews on mockup assemblies or employed contractors that had completed similar training. Many of the utilities provide three to five days of training to crews involved in changeout and rebuilding activities. In some cases, shortened "refresher" courses are provided to those personnel with previous experience. Several utilities stated that the training also involved individual testing. All of those utilities providing training or using specialized crews verified that these activities yielded improvements in job performance. Other benefits mentioned were reductions in radiation doses, increased worker safety, improved worker attitude, and fewer rebuild errors.

Other modifications made by utilities to reduce radiation exposures acquired during CRDM changeout and rebuilding activities include:

1. Inner and outer filters were discarded as waste rather than cleaned.

2. Shielded inner and outer filter removal tools were used.

3. Flush tanks were used during CRDM rebuilding activities.

4. Installed ALARA shielding achieved reductions at several sites that historically have "hot" drives.

5. Shielded storage racks and/or customized concrete vaults have been built into CRDM rebuilding rooms.

6. Remote cameras installed under the vessel and in the rebuild room have helped to better coordinate activities, save time, and reduce exposures.

Conclusions

As a whole, BWR control rod drive mechanisms have a good service record at U. S. nuclear plants. The BWR-6 design CRDMs have incorporated modifications that have eliminated problems experienced by the earlier models. The primary causes of CRDM aging are embrittle-ment, fatigue fracture and thermal degradation of the Graphitar seals, nitrided surface corrosion, mishandling and rebuilding errors occurring during CRDM maintenance and, to a lesser extent, improper storage support. According to NRPDS failure reports, the majority of maintenance for the CRD system occurs on the HCU. The HCU components reporting the most failures are the scram water accumulator, the accumulator nitrogen charging cartridge valve, the inlet and outlet scram valves, and their scram pilot valve assemblies and solenoids.

CRDM changeout and rebuilding activities occur at all BWR nuclear plants, but with varying amounts of worker exposures and time expended on the removal and refurbishment of drives. Many utilities are seeking ways to improve their overall CRDM maintenance processes. Some plants are aggressively pursuing ways to reduce radiation exposures acquired during CRDM maintenance by installing state-of-the-art tooling, improving worker comfort, and increasing maintenance training.

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