AGING ASSESSMENT OF BWR CONTROL ROD DRIVE SYSTEMS*

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ABSTRACT

This Phase I NPAR study examines the aging phenomena associated with boiling water reactor (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 Nuclear Plant Reliability Data System (NPRDS) failure cases attributed to the CRD system, and (4) personal information exchange with industry experts.

An eight-page questionnaire was prepared by the Oak Ridge National Laboratory (ORNL) and distributed to all domestic BWR plants. The survey solicited site-specific data on CRDM degradation and failure experience, maintenance and aging interactions, and current testing procedures. To obtain firsthand information on CRDM aging histories, a workshop was sponsored by ORNL to discuss CRDM performance and the overall questionnaire results with utility participants. The three-day meeting on CRDM aging and maintenance was attended by 26 utility personnel from 21 BWR plants and 14 vendor and commercial representatives. These attendees provided invaluable information needed for understanding degradation mechanisms and maintenance constraints associated with BWR CRDMs.

As part of this study, nearly 3500 NPRDS failure reports have been analyzed to examine the prevailing failure trends for CRD system components. An investigation was conducted to summarize the occurrence frequency of these component failures, discovery methods, reported failure causes, their respective symptoms, and actions taken by utilities to restore component and system service.

The results of this research have identified the predominant CRDM failure modes and causes. In addition, recommendations are presented that identify specific actions utilities can implement to mitigate CRDM aging. An evaluation has also been made of certain maintenance practices and tooling which have enabled some utilities to reduce ALARA exposures received from routine CRDM replacement and rebuilding activities.

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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.

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 could be attributed to the fact that peripheral drives (which have a limited power shaping contribution) do not experience the higher core fluxes or undergo as many "feet of travel" as centrally located CRDMs.

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 operational problems do not occur suddenly but over a time interval of at least several months.

When a CRDM's performance does not meet plant requirements, 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 are to be published in NUREG/CR-5699, Vol. 1, entitled "Aging and Service Wear of Control Rod Drive Mechanisms for BWR Nuclear Plants."

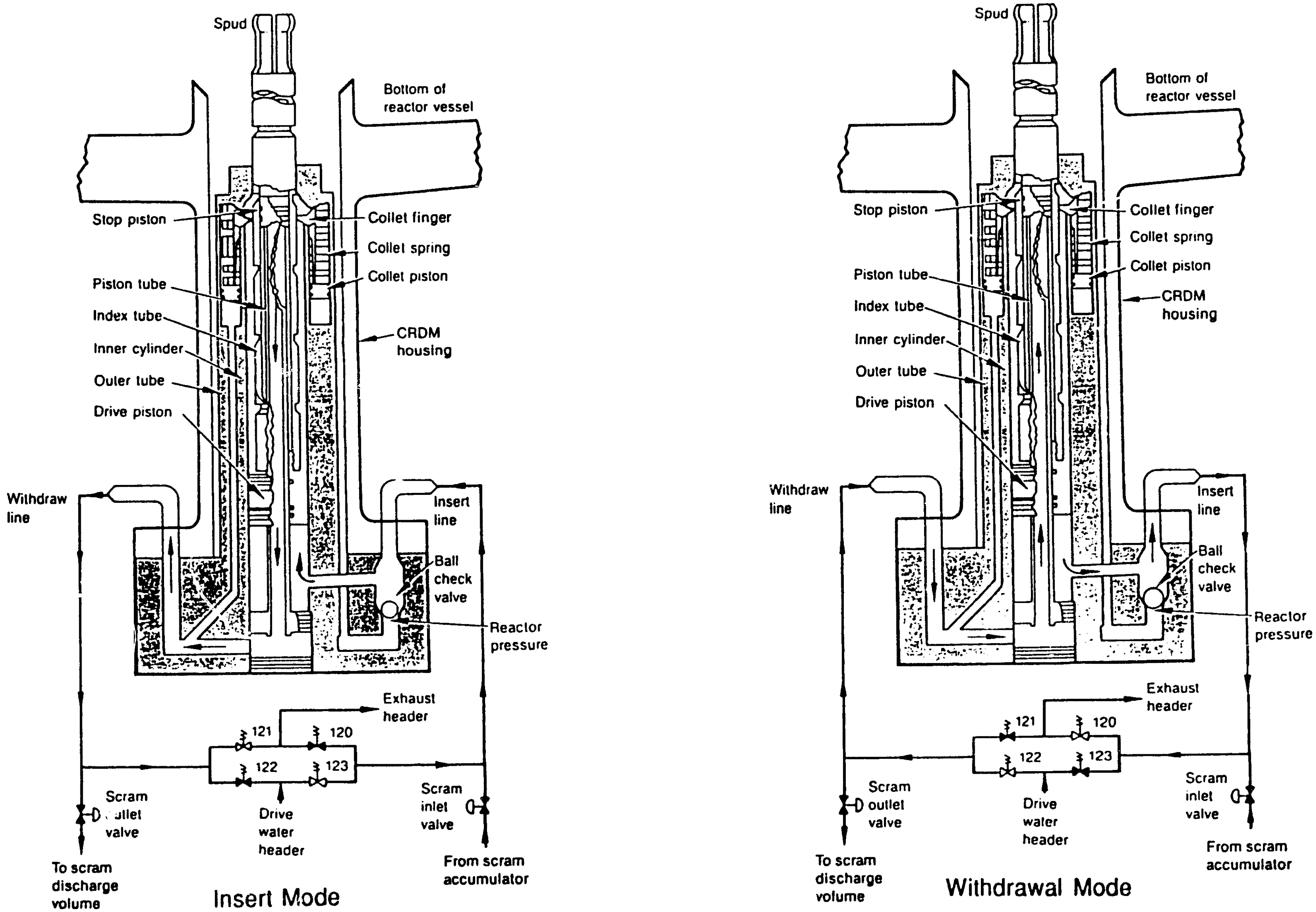

Figure 1. CRDM operation: insert and withdrawal modes.[1]

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 that did not perform its design function and does not necessarily imply the occurrence of an operational event.

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.

Water Chemistry, Corrosion, and IGSCC

Poor plant water chemistry has been a primary contributor to corrosion and "crud" formation (dirt particles, debris, and foreign materials that are found in varying amounts in the coolant). 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 the Graphitar seal seating surfaces (on the drive and stop pistons) creates uneven force distributions that can cause seal breakage during scrams.

To reduce the amount of crud that can become entrapped in the CRDM, some utilities are vacuuming the bottom of the reactor vessel in and around 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. Water chemistry has also been modified by the addition of hydrogen in at least nine BWR facilities to reduce the potential for corrosion in the primary coolant system. However, one workshop attendee reported that their plant management was considering discontinuing this practice because an increase in system radioactivity levels had been observed since its incorporation.

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 they can be rebuilt during the next outage, just prior to installation. Since there will be radioactive decay during the twelve to eighteen months of storage, it is hoped that the doses obtained from rebuilding these CRDMs will be lower than if they had been rebuilt soon after they were pulled from the vessel. 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 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.

Radiation-induced Effects

Radiation-induced degradation 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." The strength and resilience, which normally typifies parts made of this alloy, no longer remains. Although no professional metallurgical examinations have been performed on these components, the cause of this phenomena is speculated to be neutron annealing, because the observed effects are similar to those recorded by researchers who irradiated different reactor materials to low dose ($<10^{20}$ neutron cm^{-2}), thermalized neutrons [2]. With this type of material degradation, spud fingers can become deformed in-service and lose their concentricity, as shown in Figure 2. This type of spud damage can present a myriad of coupling and uncoupling difficulties with the CRA. The spud, like all CRDM components, can be exchanged with a new spare part during rebuilding activities.

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.[3] 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, and variations in the case hardening from the nitriding process. No operational problems were reported for the CRDM whose "striped" index tube is shown in Figure 3, 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

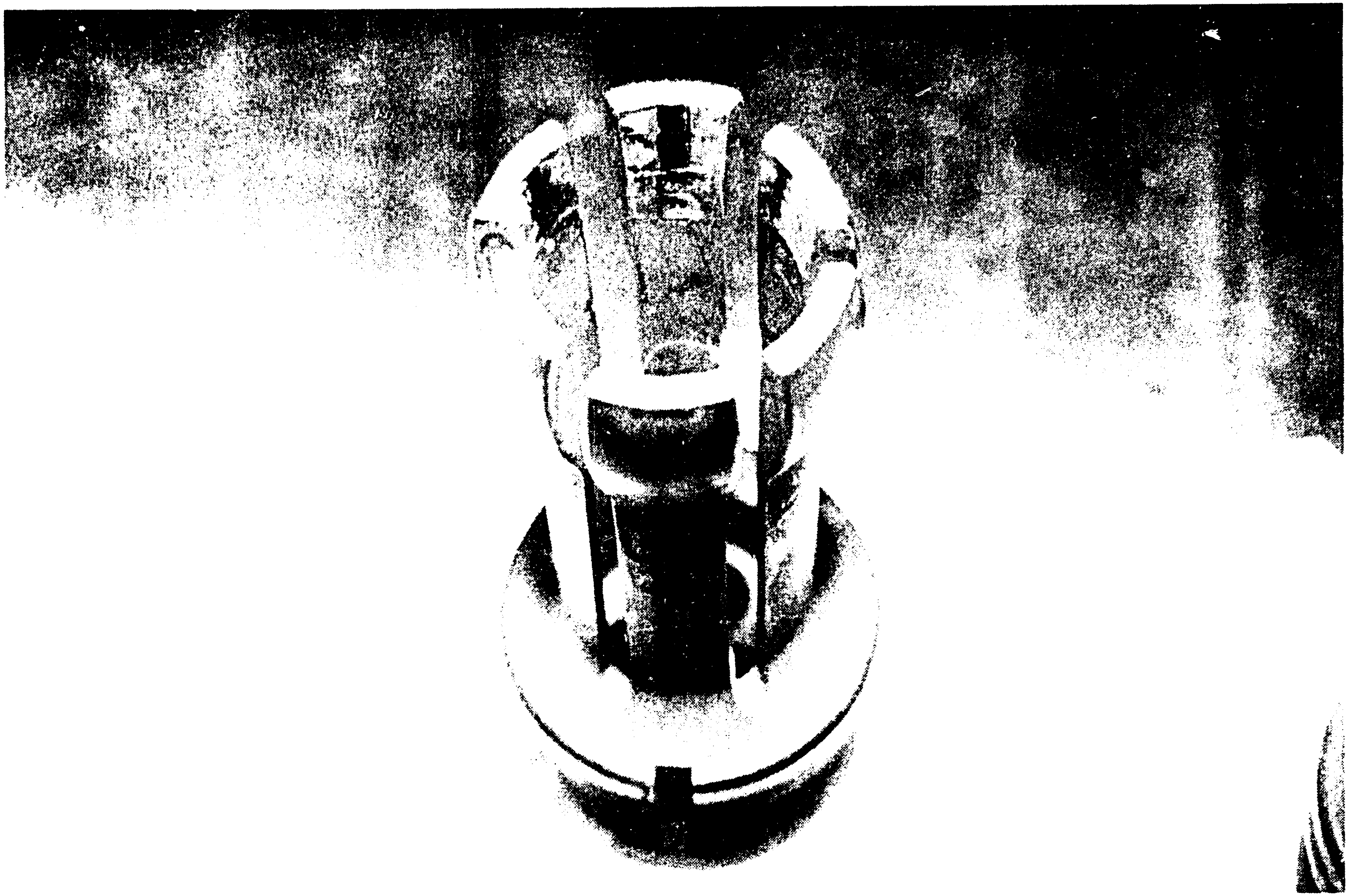

Figure 2. Bent CRDM spud fingers (notice lack of concentricily).

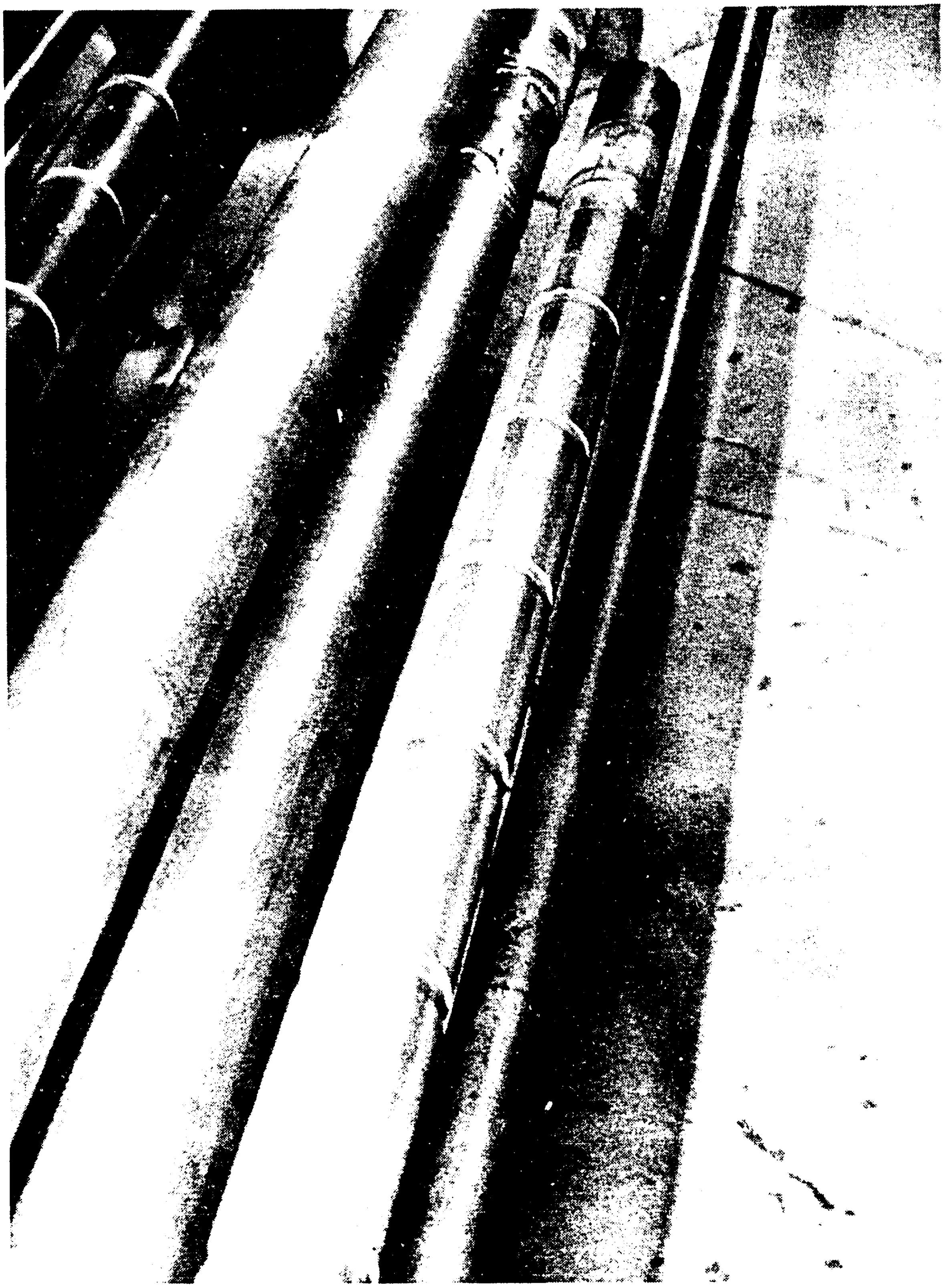

Figure 3. CRDM index tube surface degradation (notice striping left by collet fingers).

normal surface wear, or experience thermal degradation (caused by drive temperatures greater than 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 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 CRDMs are equipped with these improved seals, but an improved replacement seal kit for earlier models is currently not available to utilities.

Inner Filter Disengagement

Each CRDM has an inner and outer filter which serves to collect debris from the cooling water and 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. 4). When 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. 5). 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 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.

After this CRDM has been placed into service, a long, continuous withdrawal signal can cause the disengaged inner filter to become buoyed. Hydraulic pressures push the filter against the uncoupling rod, lifting it upwards and pushing the locking plug above the spud fingers. At this point uncoupling may occur. Even if operations personnel succeed in recoupling the drive with the CRA, repeated uncoupling and recoupling caused by a disengaged inner filter can result in a bent uncoupling rod.

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.

Improper CRDM Storage Methods

The 15-foot-long, 450-pound 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 6. CRDMs should not be stacked on top of each other,

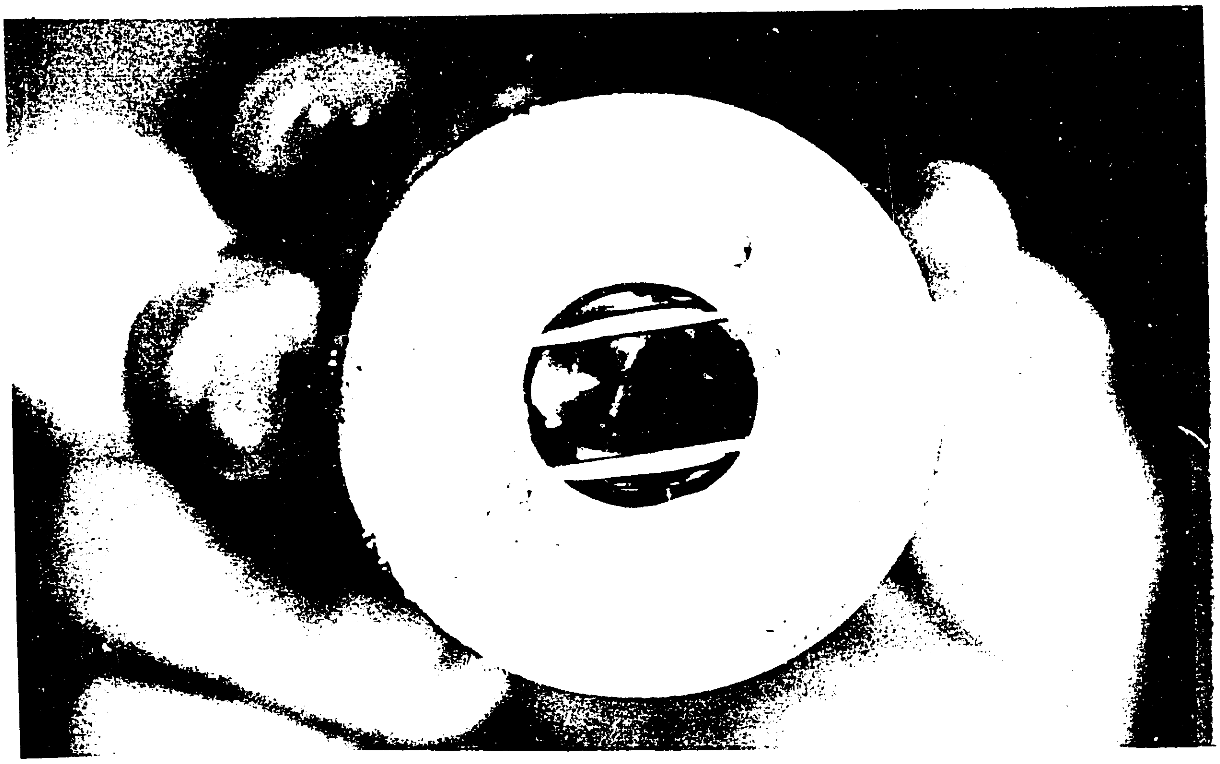

Figure 4. CRDM inner filter spring clip.

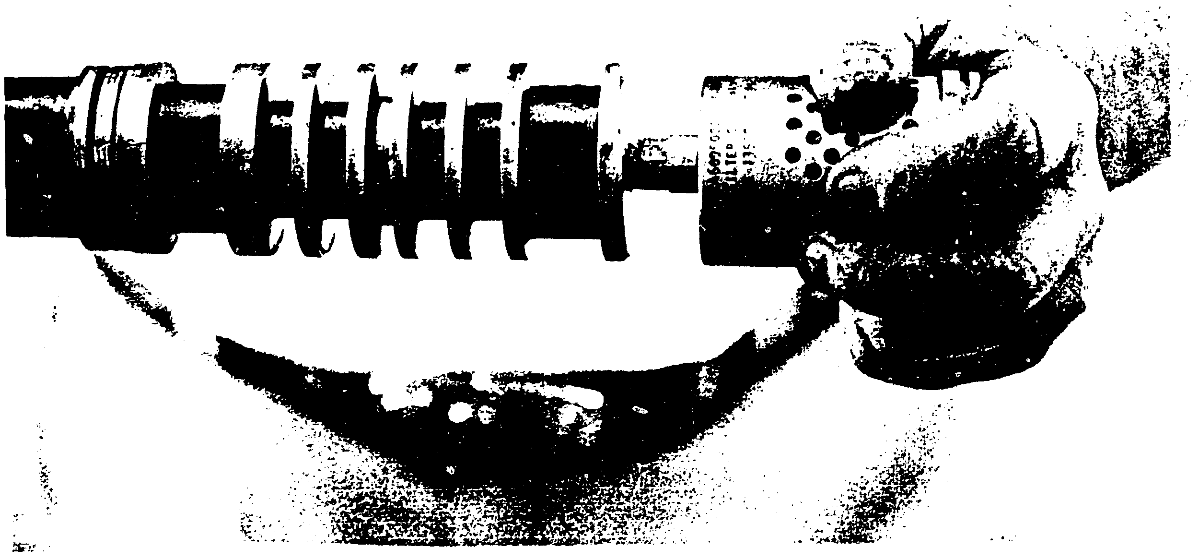

Figure 5. Attachment of inner filter to stop piston.

separated by wooden blocks, which, in 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 7, CRDMs should be stored in racks or vaults with a minimum of 2 points of support located 24 inches from the flange end and 54 inches 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 8. 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 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.

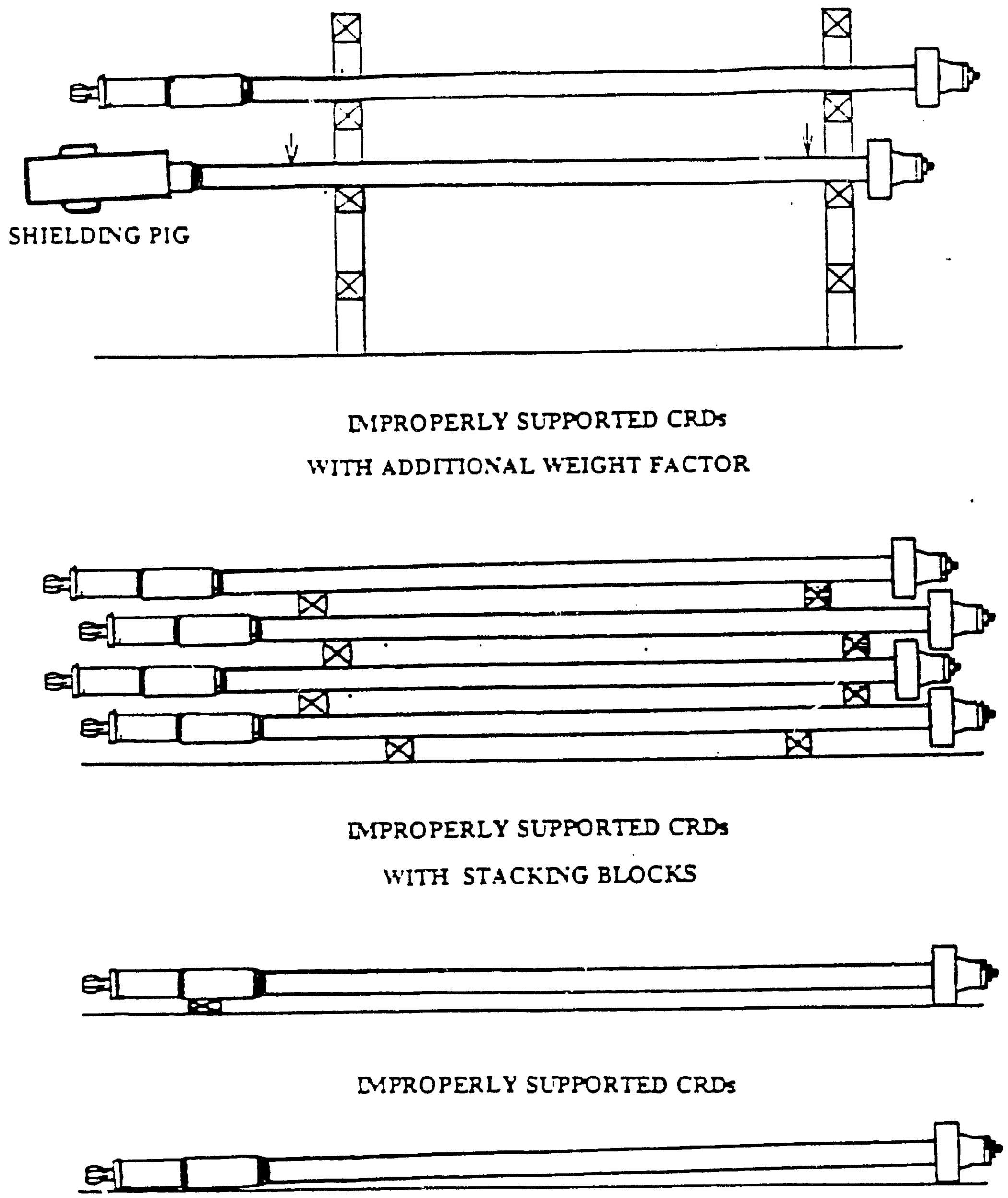

Figure 6. Improper CRDM storage scenarios.[3]

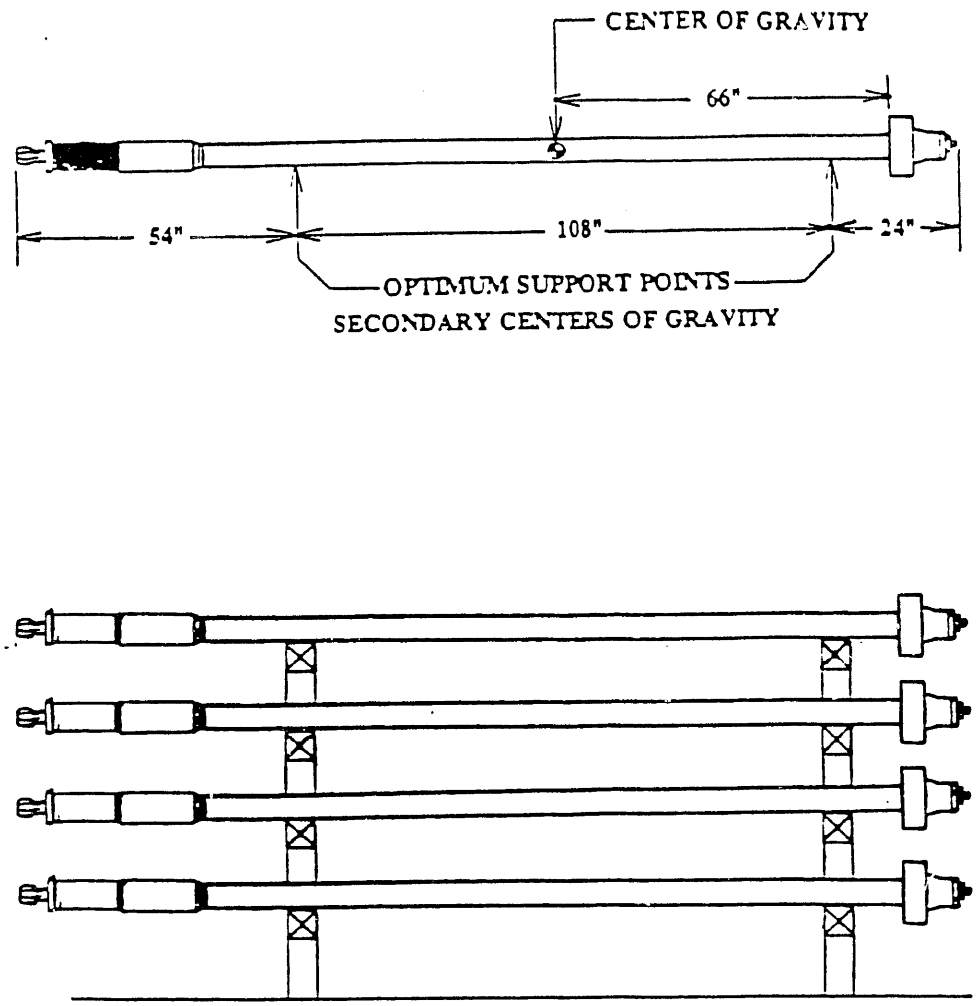

Figure 7. Acceptable CRDM storage arrangement.[3]

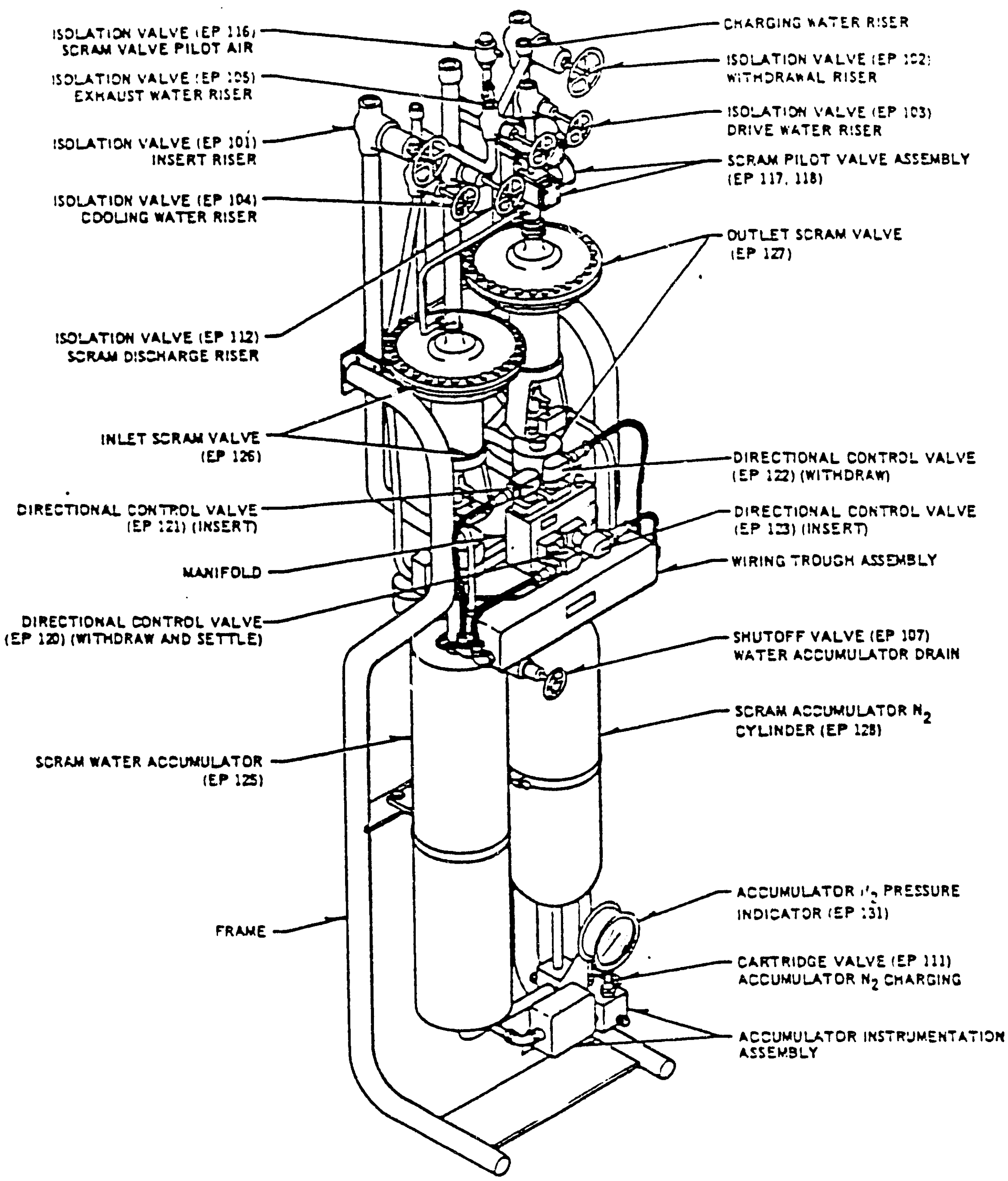

Figure 8. A BWR hydraulic control unit (HCU) and its components.[5]

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 information 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. 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. 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)[4]. 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 rebuilt 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. The majority of these valve failures (80%) 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 these two categories:

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 5.0 gpm.

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

1. Consistently high temperatures throughout length of travel (>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 operational problems, however, do 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 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:

- Inner and outer filters were discarded as waste rather than cleaned.
- Shielded inner and outer filter removal tools were used.
- Flush tanks were used during CRDM rebuilding activities.
- Installed ALARA shielding achieved reductions at several sites that historically have "hot" drives.
- Shielded storage racks and/or customized concrete vaults have been built into CRDM rebuilding rooms.
- 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 embrittlement, 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 sclenoids.

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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2. *Effect of Prior History on the Response of Some Commercial Aluminum Alloys to Low Dose Neutron Irradiation*, Z. H. Ismail and H. G. Mohammed, Nuclear Research Center, Atomic Energy Commission, Cairo, Egypt. *Scripta Metallurgica*, 1989, Vol 23, pp 2067-2072. Available for purchase from Pergamon Press, New York.

3. *Control Rod Maintenance Strategies,* presented by Lee Penney at the ORNL Workshop on Control Rod Drive Aging, January 30, 1991. Available from Nuclear Energy Services, Inc., Danbury, CT.

4. *Aging and Service Wear of Solenoid-Operated Valves Used in Safety Systems of Nuclear Power Plants,* Vol. 2: Monitoring Methods Evaluation," R. C. Kryter, NUREG/CR-4819, Vol.2, September 1991. Available for purchase from the National Technical Information Service, Springfield, Virginia 22161.

5. *Operation and Maintenance Instructions for Hydraulic Control Unit Part Nos. 729E950G1 through G6*, GEK-9582A, General Electric Company, San Jose, CA.

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Aging Assessment of BWR Control Rod Drive Systems

by

Rebecca H. Greene
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Purpose for CRD System Aging Research

- Identify predominant failure modes in CRD system
- Identify CRD system component failure causes due to aging and service wear degradation
- Review current inspection & surveillance methods used to determine system degradation
- Recommend improved maintenance methods and/or surveillance techniques to mitigate CRD system aging

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CRDM Problems Can Affect Plant Operation

- Inoperable and disarmed CRDMs affect optimum fuel cycle efficiency and require changes in control rod sequences.
- Depending on location and quantity, inoperable CRDMs could also result in exceeding the conditions defined by plant technical specifications for safe:

  -- startup
  -- normal operation
  -- shutdown

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Information Sources for Research

- Literature survey - GE SILs, GE Maintenance Manuals (CRD & HCU), NUREG/CR-4731, EPRI NP-3895, EPRI NP-5836M, *NUREG/CR-5699**
- NPRDS Data Research & Review (3432 cases)
- NPAR Questionnaire on BWR CRDMs
- ORNL Workshop on "Managing the Aging of BWR CRDMs"
- Personal contact with utility, commercial, and vendor experts

**to be published 1992*

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CRD System Research Boundaries

- Control Rod Drive Mechanism
- Hydraulic Control Unit (valves, electrical components, tubing)
- Balance of CRD System (remaining system valves, pumps, piping, instrumentation, and electrical components)

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Priority One Failure Modes: CRDMs **must** be exchanged or rebuilt

- Excessive scram time - violation of tech specs
- CRDMs that do not fully insert during a scram
- CRDMs with a history of uncoupling
- CRDMs that will not go into position 48 (fully withdrawn)
- CRDMs that consistently have > 5.0 gpm withdrawal stall flows

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Priority Two Failure Modes: CRDMs **should** be exchanged or rebuilt

- CRDMs with consistently high temperatures throughout length of travel (>350° F)
- CRDMs with unacceptable withdrawal or insertion times (unrelated to HCU)
- CRDMs that exhibit "double-notching" when moving or consistently need increased drive pressure to move (unrelated to HCU)
- CRDMs with high friction traces not attributable to misalignment with fuel assemblies

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Predominant CRDM Failure Causes

- Graphitar Seal Degradation (breakage)
  - thermal embrittlement, service wear, fatigue
- Corrosion
  - water chemistry, entrapped debris
  - collet housing cracking - IGSCC
  - nitrided surface corrosion, service wear
- Improper Storage
  - wet in air > 30 days corrodes nitrided surfaces
  - poor support methods
- Human Error
  - changeout mishandling and rebuilding errors

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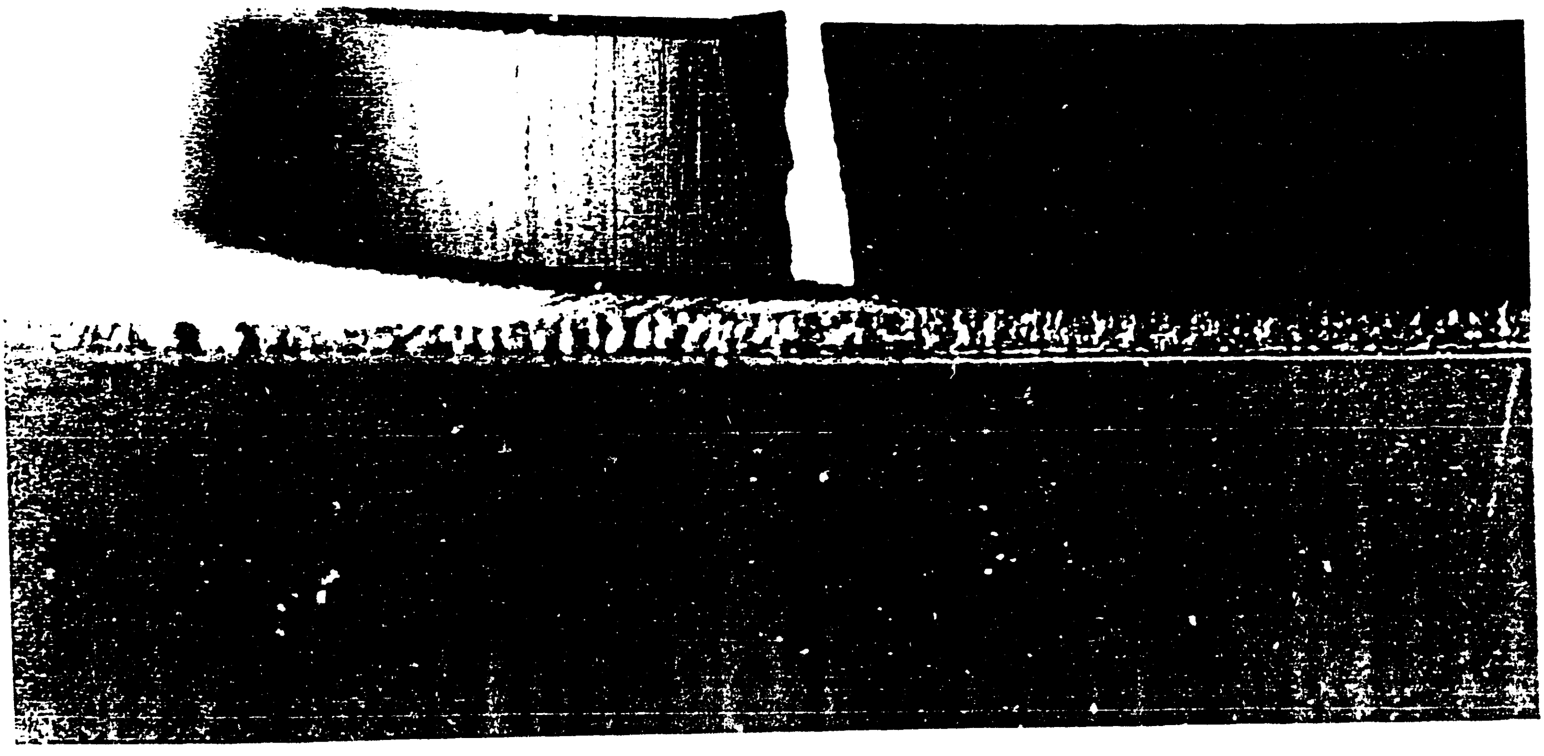
Graphitar-14 is a very brittle material, even when new. This seal broke when it was accidentally dropped on a concrete floor.



Graphitar Seal Degradation

- CRDM operating temperatures > 250° F shorten Graphitar seal life; > 350° - 500° F significantly reduces strength properties of the Graphitar seals
- "Hot scrams" induce extreme thermal transients and expose seals and collet housing to high temperatures (550° F)
- Entrapped debris can create improper seating of Graphitar seals in piston grooves and create forces during scrams that break seals
- Broken seals result from excessive scrams and thermal degradation

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Contributions to CRDM Corrosion

- Poor water chemistry (some plants adding hydrogen)
- Entrapped debris (crud, design changes, vacuuming)
- Improper storage (stored wet > 30 days)

Components affected:

- Nitrided surfaces (index tube, piston tube, collet assembly, guide cap)
- CRDM cap screws (GE SIL #019)
- Collet housing (IGSCC) - accelerated by "hot" scrams

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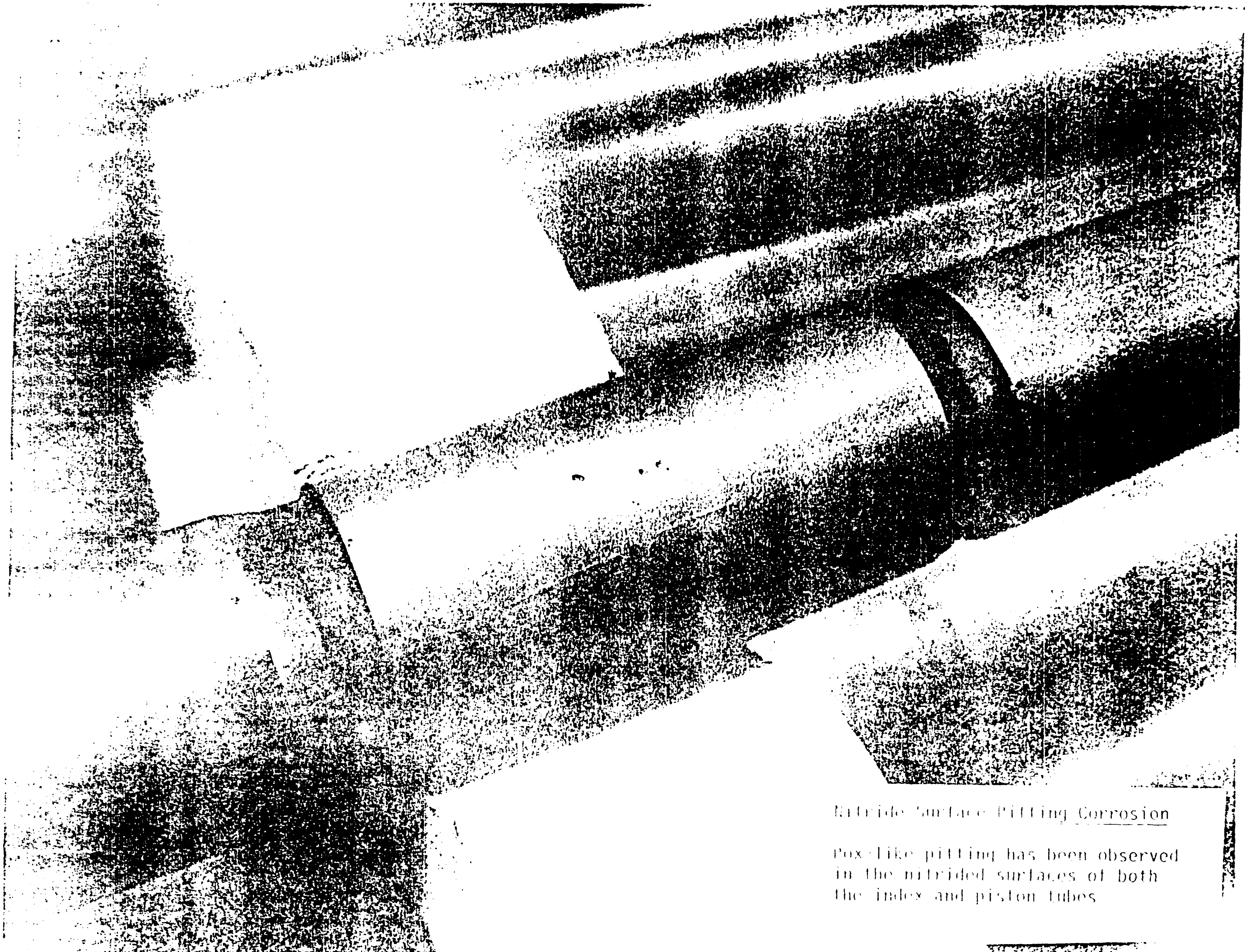

Nitride Surface Pitting Corrosion

Pox-like pitting has been observed in the nitrided surfaces of both the index and piston tubes

[illegible] Surface [illegible]

[illegible]

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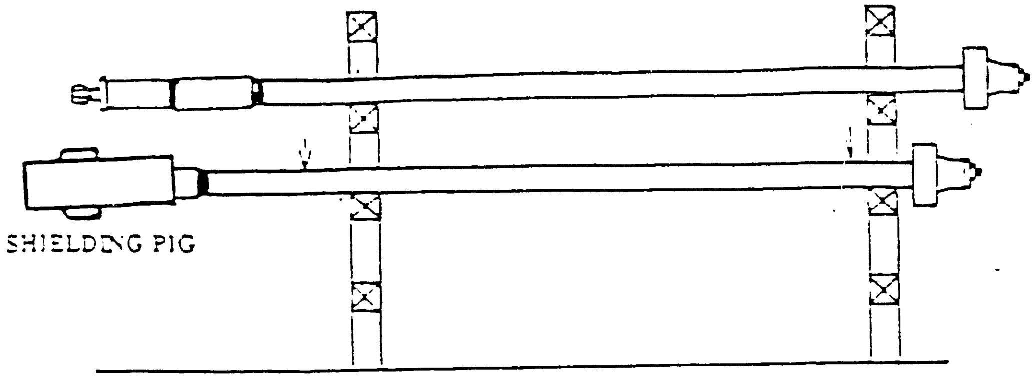
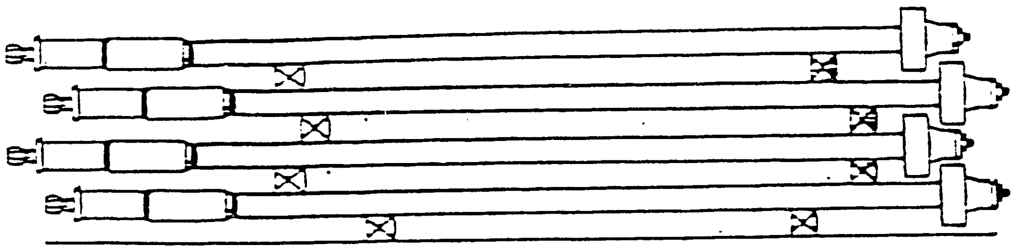
Results of Improper Storage

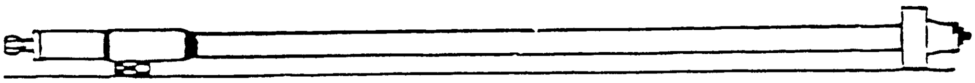
- Plastic deformation of collet housing
- Misalignment of long, internal tubes
- Nitrided surfaces begin to corrode if CRDM is stored wet in air > 30 days (awaiting rebuilding)



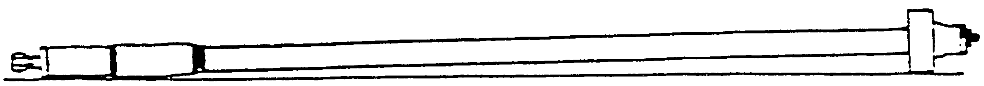
IMPROPERLY SUPPORTED CRDs
WITH ADDITIONAL WEIGHT FACTOR



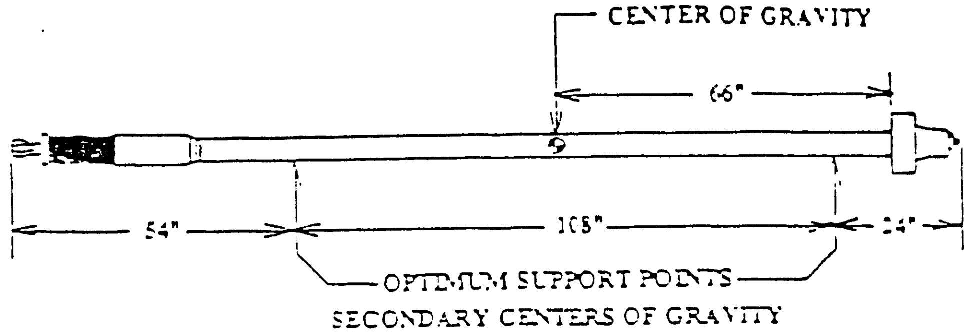
IMPROPERLY SUPPORTED CRDs
WITH STACKING BLOCKS

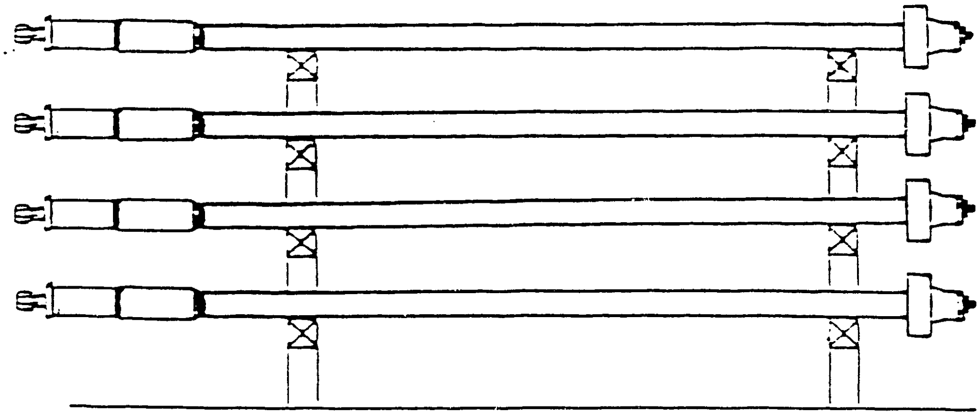


IMPROPERLY SUPPORTED CRDs

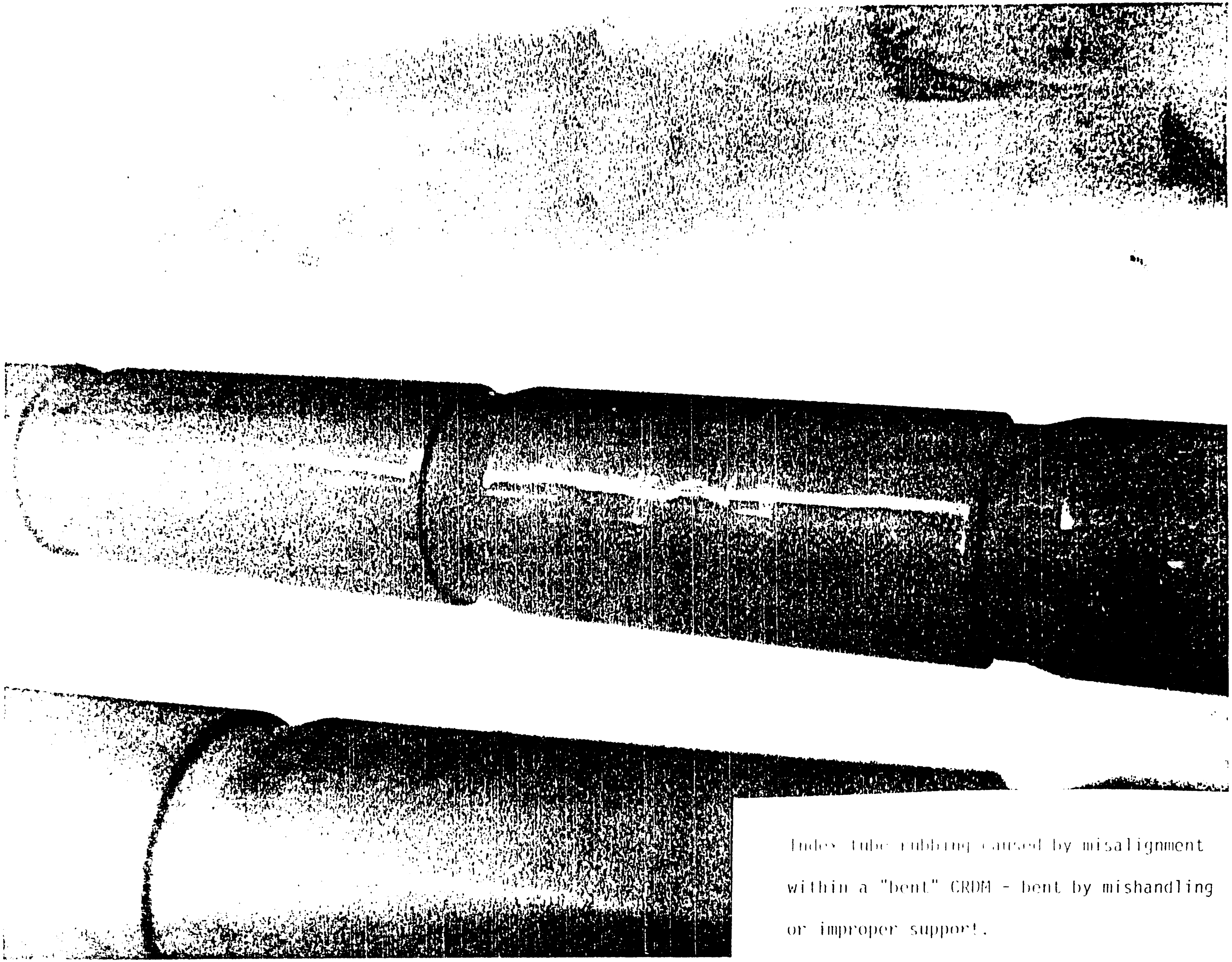


Improper CRDM storage scenarios.





Acceptable CRDM storage arrangement.



Index tube rubbing caused by misalignment within a "bent" CRDM - bent by mishandling or improper support.

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Human Error Contributions

- CRDM changeout mishandling - misalignment, damaging components during installation, and overtorquing capscrews.
- CRDM rebuilding errors -- seals in backwards, spring washers in backwards, disengaged inner filters, misevaluation of serviceability of CRDM components.
- Both tasks are very complex and must be performed under extreme, physically challenging, and somewhat harsh environments.

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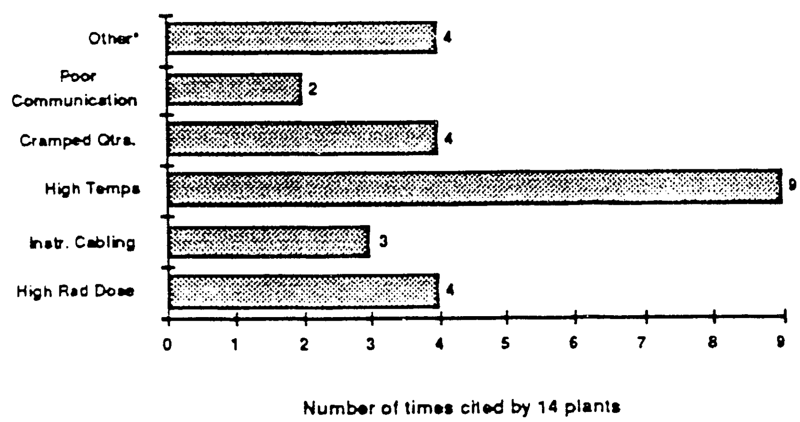
Conditions that Contribute to Improper Maintenance



**Disorientation, remoteness, cumbersome clothing, visual impairment during "rainshower"*

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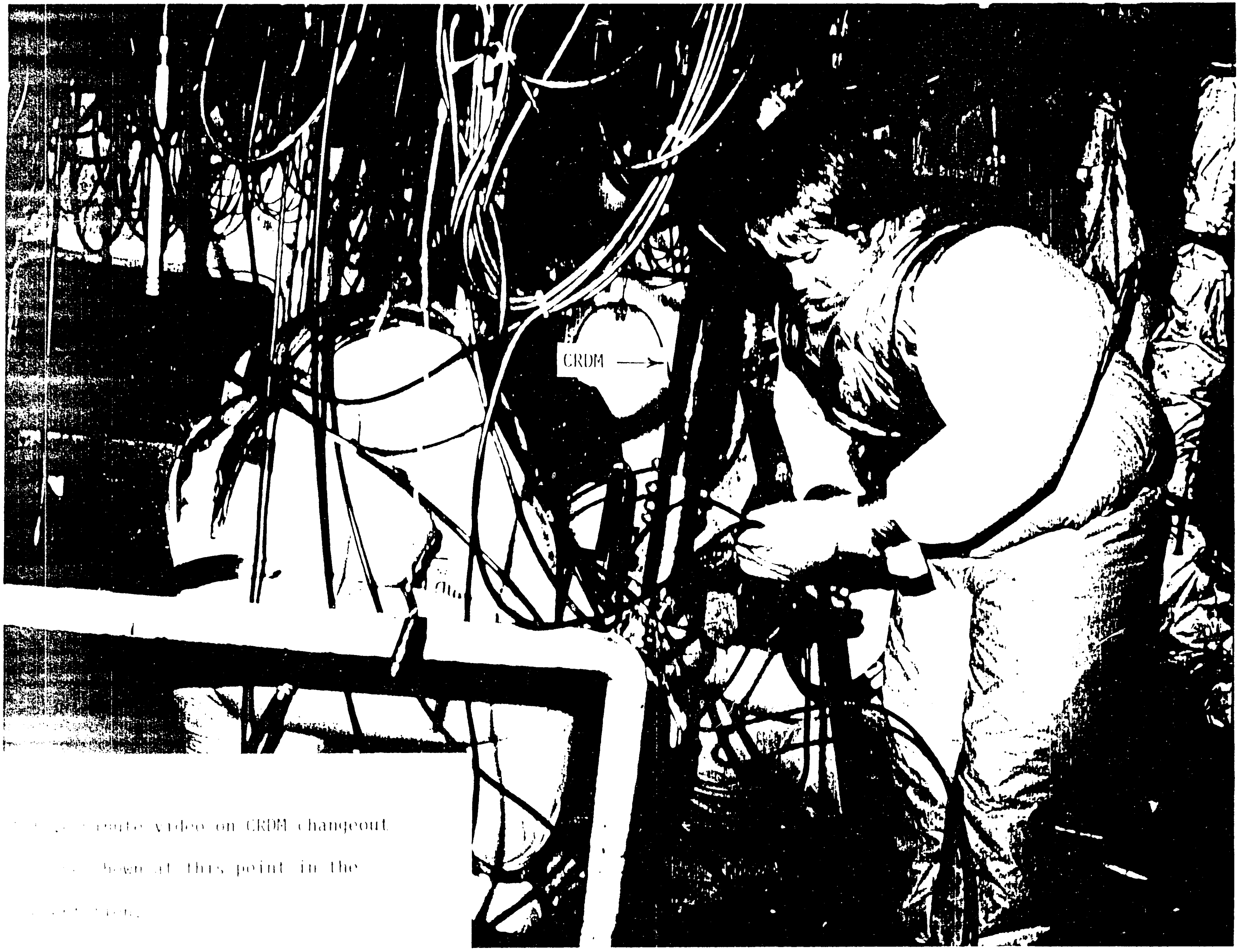

... remote video on CRDM changeout
... shown at this point in the
...

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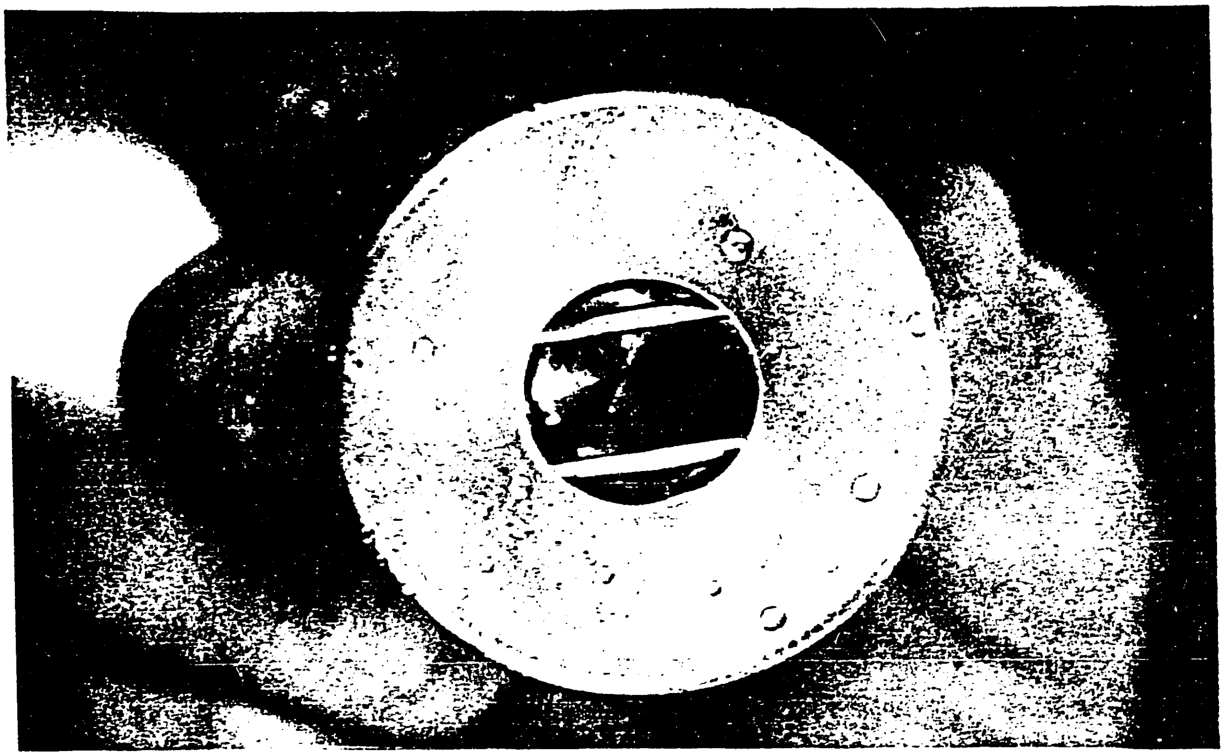
Inner Filter Disengagement

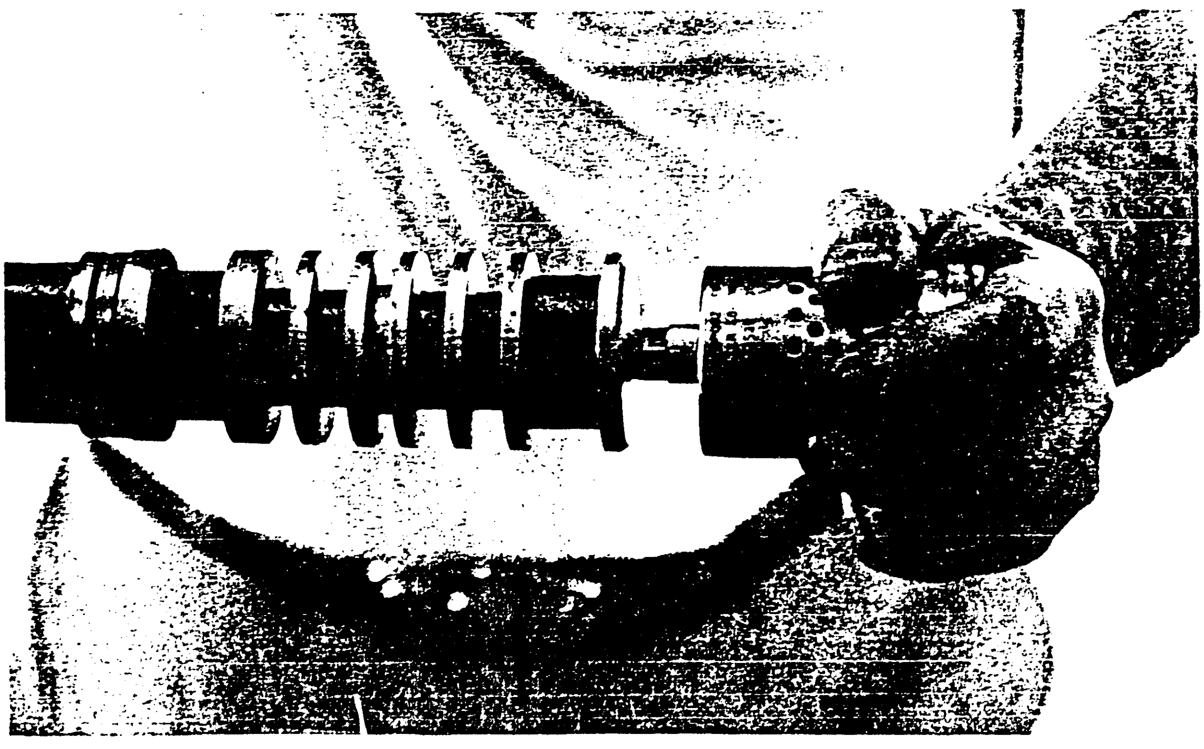
- Common misassembly problem
  -- attributed for 90 failure reports in the NPRDS, 35 specifically cited installation & maintenance error

- Causes uncoupling problems with the CRA
  – repeated uncoupling can also damage uncoupling rod

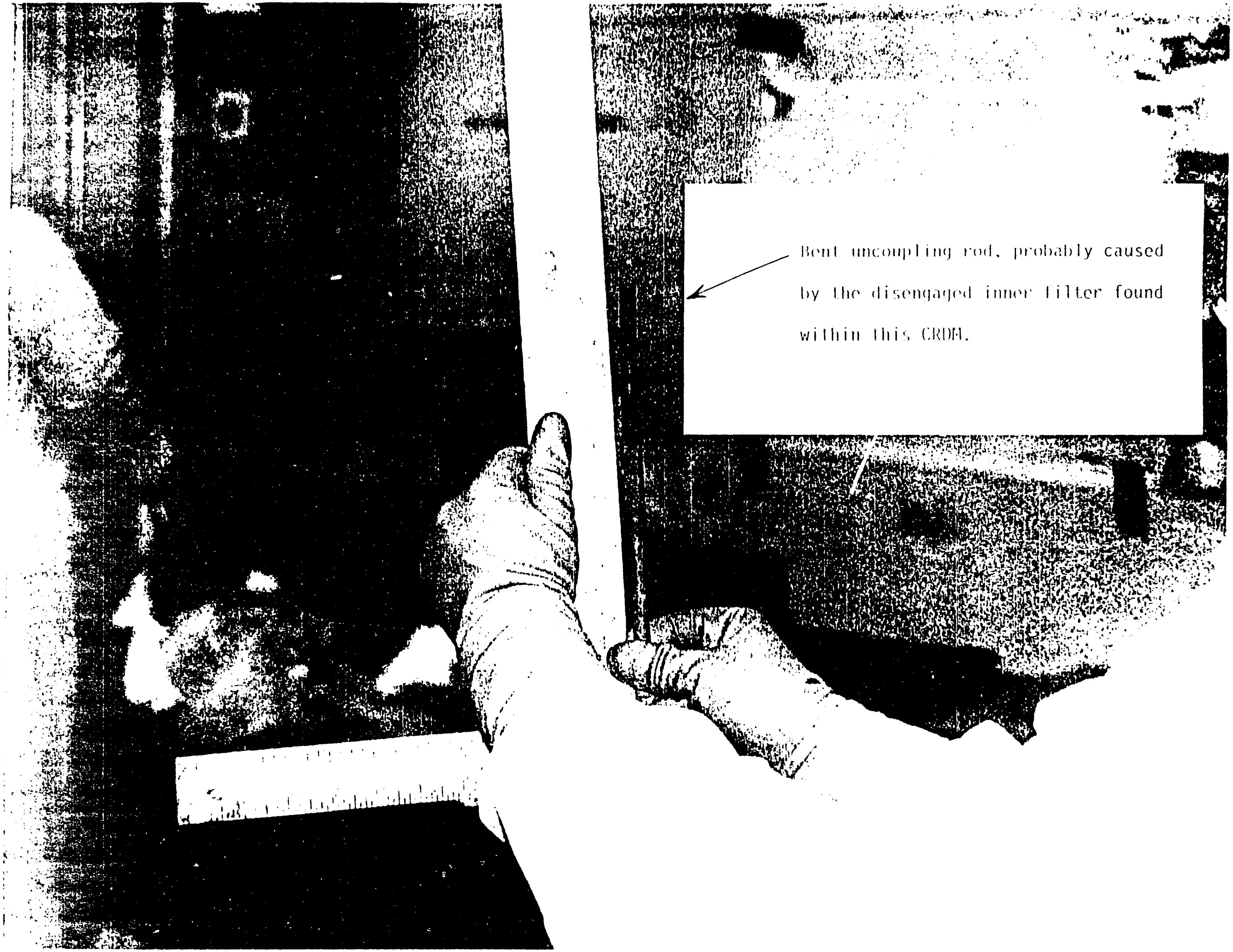
- Toshiba changed attachment configuration to avoid this uncoupling scenario



CRDM inner filter spring clip.



Attachment of inner filter to stop piston.


Bent uncoupling rod, probably caused
by the disengaged inner filter found
within this CRDM.

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Predominant HCU Failures

(HCU part number)

- Accumulator Nitrogen Charging Valve (#111)
  -- U-cup packing & bent stems
- Inlet & Outlet Scram Valves (#126 & #127)
  -- Worn Buna-N diaphragms
- Scram Pilot Valve Assemblies & Solenoids (#117 & #118)
  -- Worn Buna-N discs and coil failures
- Scram Water Accumulator (#125)
  -- Corrosion of the carbon steel tank

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Predominant BOCRDS Failures

- CRD System Pumps and Components (117 reports)
  -- worn out bearings, seals, looseness
- Scram Discharge Volume Valves (44 reports)
  -- entrapped debris causing valves to stick (27%)
- Miscellaneous Electrical Components (207 reports)
  -- normal aging and out-of calibration
- Miscellaneous Instrumentation (79 reports)
  -- normal aging and out-of calibration

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Research Recommendations

- GE and Toshiba have designed a longer-life Graphitar seal that is designed to withstand higher temperatures and have greater strength. When available, its use should extend the CRDM maintenance life and hence, reduce ALARA.
- Where CRDM crud is a problem, utilities should consider vacuuming the vessel around the guide tubes during outages.
- Design change is needed to reduce installation errors in inner filter attachment and avoid possible uncoupling with CRAs.

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Research Recommendations

- Utilities should take steps to increase worker comfort during changeout and rebuilding activities. Special suits, A-C packs, increased lighting, mock-up changeout and rebuilding training, and full-rad dress rehearsals will decrease human errors and reduce ALARA.
- Initiate the routine monitoring and trending of scram valve solenoid operating temperatures (using industrial pyrometers) to detect upward trends that indicate imminent solenoid coil failure.
- Institute the routine monitoring, analysis, and trending of CRD pump vibration signatures to determine and predict bearing failures.

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END

DATE FILMED

12/12/91