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Aging and Service Wear of Control Rod Drive Mechanisms for BWR Nuclear Plants

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Prepared for
U.S. Nuclear Regulatory Commission

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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.

Nearly 23% of the NPRDS CRD system component failure reports were attributed to the CRDM. The CRDM components most often requiring replacement due to normal wear and aging are the Graphitar seals. The predominant causes of aging for these seals are mechanical wear and thermally induced 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.

Since CRDM changeout and rebuilding is one of the highest dose, most physically challenging, and complicated maintenance activities routinely accomplished by BWR utilities, this report also highlights recent innovations in CRDM handling equipment and rebuilding tools that have resulted in significant dose reductions to the maintenance crews using them.

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List of Acronyms

ALARA - As Low As Reasonably Achievable
BOCRDS - Balance of Control Rod Drive System
BWR - Boiling-Water Reactor
CRD - Control Rod Drive
CRDM - Control Rod Drive Mechanism
CTF - Cylinder, Tube and Flange assembly of a BWR CRDM
EPRI - Electric Power Research Institute
FFT - Fast Fourier Transform
FSAR - Final Safety Analysis Report
GE - GE Nuclear Energy
GE SIL - GE Service Information Letter
HCU - Hydraulic Control Unit
HP - Health Physics
IGSCC - Intergranular Stress Corrosion Cracking
INPO - Institute of Nuclear Power Operations
NPAR - Nuclear Plant Aging Research
NPRDS - Nuclear Plant Reliability Data System
NRC - Nuclear Regulatory Commission
ORNL - Oak Ridge National Laboratory
RC&IS - Rod Control and Information System

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The author wishes to express appreciation to the following utilities for sending participants and speakers to the ORNL workshop on Managing the Aging of Boiling-Water Reactor control rod drive mechanisms (BWR CRDMs) and for providing valuable operational information in the CRDM Aging Questionnaire:

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Detroit Edison Co.
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General Public Utilities Corp.
Gulf States Utilities
Illinois Power Co.
Iowa Electric Light & Power Co.
Nebraska Public Power District
New York Power Authority
Niagara Mohawk Power Corp.
Northern States Power Company
Pennsylvania Power & Light Co.
Philadelphia Electric Co.
Public Service Electric & Gas
Tennessee Valley Authority
Vermont Yankee Nuclear Corp.
Washington Public Power Supply

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Summary

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 nearly 3500 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.

Utilities evaluate the operability of their CRD systems by performing individual CRDM scram time testing (as required per plant technical specifications), weekly to monthly step insertion and withdrawal tests, and stall flow testing. When a CRDM fails to meet test timing specifications or begins to show symptoms such as double-notching (erroneously moves two steps instead of one), frequently becomes uncoupled from the control rod blade, exhibits high operational temperatures, or requires excess drive pressure to move, it is usually selected for changeout during a plant refueling or maintenance outage. During an outage, utilities typically replace nearly 16% (on the average) of a unit's CRDMs with new or rebuilt units.

Nearly 23% of the NPRDS CRD system component failure reports were attributed to the CRDM. The CRDM components most often requiring replacement due to normal wear and aging are the Graphitar seals. The predominant causes of aging for these seals are mechanical wear and thermally induced embrittlement. Premature aging of these seals is also caused by excessive amounts of entrapped crud (dirt particles, debris, and foreign materials found in the reactor coolant). Some utilities are vacuuming their reactor vessels inside the guide tubes during refueling outages to remove and reduce the amounts of crud that could travel via the coolant to the CRDM and become entrapped in between its seals sets. This foreign matter creates uneven force distributions at the seal's contact surfaces and causes them to break during scrams.

More than 59% of the NPRDS CRD system failure reports were attributed to components that comprise the hydraulic control unit (HCU). Each CRDM has a companion HCU that contains numerous valves which regulate the flow of coolant that controls the movement of the respective CRDM. The predominant HCU valve components experiencing the effects of service wear and aging are the packing, seals, discs, seats, stems, and diaphragms. The HCU valves reporting the most maintenance activity (due to aging) in the NPRDS are the accumulator nitrogen charging cartridge valve, the scram discharge riser isolation valve, the inlet and outlet scram valves, and the scram pilot valve assemblies and their solenoids.

The original scram water accumulator on all BWR HCUs is a carbon steel tank with chrome plating on the inside. This part has experienced a large amount of corrosion caused by low pH water conditions at various plants. Many utilities have replaced these carbon steel accumulators with a improved component design that features a stainless steel tank.

Throughout the course of this research, it also became evident that as-low-as reasonably achievable (ALARA) dose reduction techniques used during CRD system maintenance have become an issue of interest and study to many utilities. CRDM changeout and rebuilding is one of the highest dose, most physically demanding, and complicated maintenance activities routinely accomplished by BWR utilities. Recent innovations in CRDM handling equipment and rebuilding tools have allowed some utilities to make significant reductions in exposures (as much as 50%) obtained by personnel during the performance of CRDM maintenance activities.

1 Introduction

1.1 Nuclear Plant Aging Research Goals

This document describes work performed in support of the U.S. Nuclear Regulatory Commission's (NRC's) Nuclear Plant Aging Research (NPAR) Program, which was primarily established as a means to resolve technical safety issues related to the aging of electrical and mechanical components, safety systems, support systems, and civil structures used in commercial nuclear power plants.[1]

The goals of the NPAR Program are:

1. identify and characterize aging effects that, if unchecked, could cause degradation of components, systems, and civil structures and thereby impair plant safety;

2. identify methods of inspection, surveillance, and monitoring and of evaluating the residual life of components, systems, and civil structures that will ensure timely detection of significant aging effects before loss of safety function; and

3. evaluate the effectiveness of storage, maintenance, repair, and replacement practices in mitigating the rate and extent of degradation caused by aging.

A comprehensive Phase I aging assessment on Boiling-Water Reactor (BWR) control rod drive mechanisms (CRDMs) was performed by the Oak Ridge National Laboratory (ORNL), and the results are presented in this report.

1.2 Research Objectives

The overall objectives of this Phase I study are to

examine the operational histories of BWR CRDMs,

determine the predominant modes of aging,

evaluate the tests and methodology that utilities employ to determine CRDM degradation, and

recommend measures that utilities can implement to mitigate CRD system aging.

1.3 System Boundary

The system boundary used for this Phase I study closely corresponds to that defined by the Nuclear Plant Reliability Data System (NPRDS) for the BWR CRD system.[2] Figure 1.1 is a schematic representation of the CRD system components considered for this research. The functions of the major components evaluated for this study are described in Sect. 2. NPRDS failure information on the control rod blades was not considered in this research effort.

1.4 Analysis Methodology

After the system boundary was defined, a detailed study was conducted on the CRD system components. A comprehensive information search was performed to obtain data on operational and failure characteristics of this system. The sources of this information are as follows:

A discussion on the design and function of the BWR CRD system and its major components is presented in Sect. 2. The majority of this portion of the report is taken from a BWR Final Safety Analysis Report, (FSAR), technical reports, and system manuals. This section is provided to support the terminology that is used throughout the report on the components comprising the CRD system.

The NPRDS data base (1974 to 1990) contains 3432 component failure reports on the CRD system from 36 BWR units. The NPRDS reports contain a vast array of maintenance data that also include those cases that would require reporting as Licensee Event Reports (LERs). A separate investigation of the LER data base was considered redundant for this study since it would contain information already submitted to the NPRDS. General results of the NPRDS analysis are presented in Sect. 3.

A comprehensive literature survey was conducted on BWR CRDMs and related system components. Sources of information include BWR FSARs, plant technical specifications, various Electric Power Research Institute (EPRI) and NRC reports, industrial periodicals, and vendor operation and maintenance manuals on CRDMs and hydraulic control units (HCUs). The best source of written information on CRD system operational abnormalities is the GE Service Information Letters (GE SILs) that are issued to all BWR utilities.

Training on the disassembly and reassembly of a BWR CRDM was obtained at Apex Technologies Corporate Headquarters in Clearwater, Florida. This enabled a personal examination of the CRDM components that are normally replaced during CRDM rebuilding, and provided a first-hand understanding of how components could easily be damaged or misassembled during routine maintenance activities. In addition, an inspection of the components of two HCU models and a longitudinal cross section of a CRDM (on display at the USNRC's Technical Training Center in Chattanooga, Tennessee) was made while completing a course on General Electric (GE) BWR technology.

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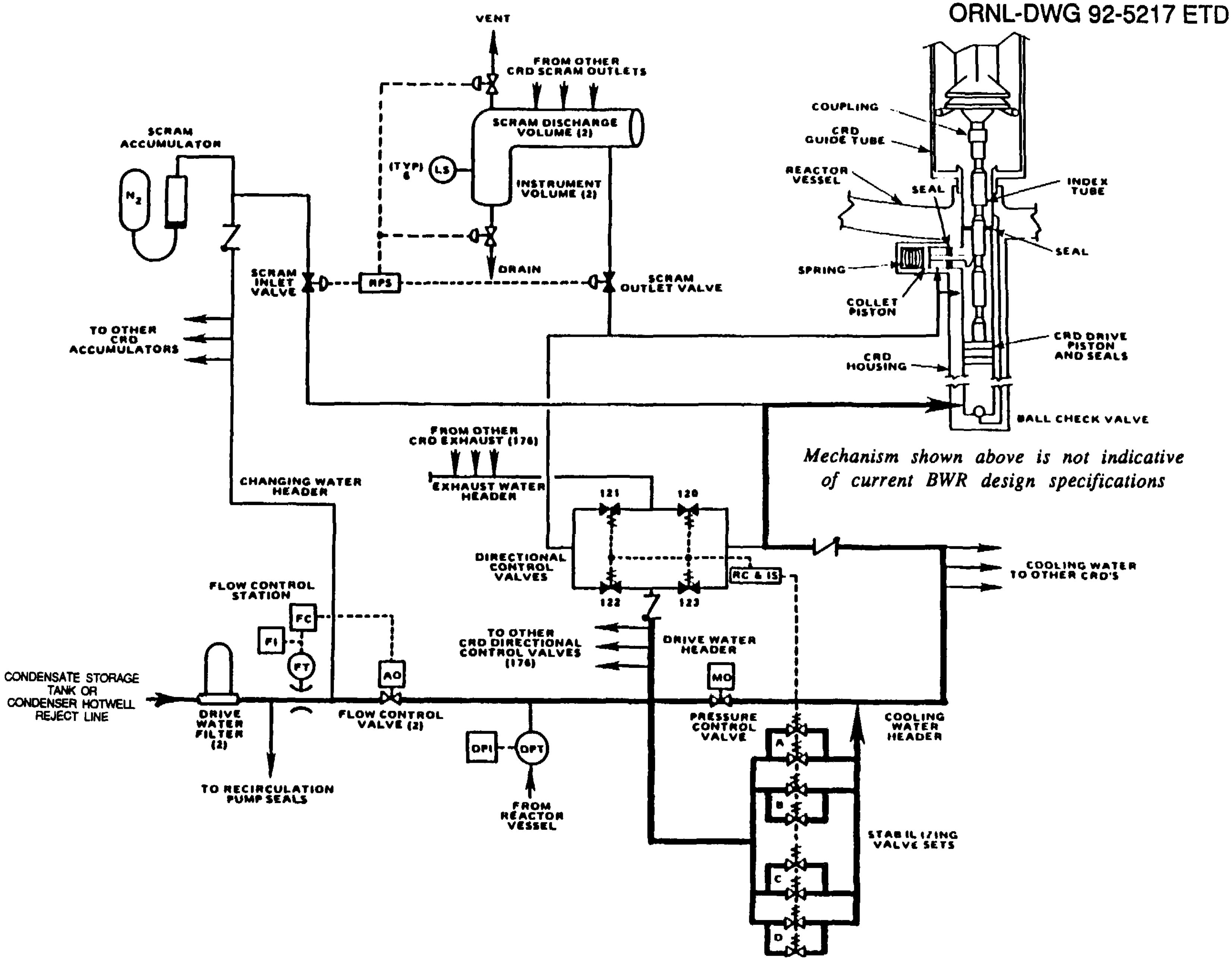

Figure 1.1 Schematic of NPAR Research Boundary for BWR CRD Systems.[3]

To obtain first-hand degradation and maintenance information on the CRD system, ORNL developed an eight-page CRDM aging questionnaire and distributed it (with the assistance of EPRI) to all domestic BWR plants. The response and interest in the survey and its related aging research was so strong that ORNL sponsored a three-day workshop to discuss the results with BWR utilities. To broaden the perspective of the information exchange that would occur, utility, vendor, and commercial representatives were invited to give presentations on CRDM aging and maintenance topics. The workshop, which had 26 utility and 14 vendor and commercial attendees, established a foundation for identifying and understanding CRDM aging concerns that might not have been obtained with conventional research tools. In addition, the event yielded personal contacts that have been invaluable to this study. The results of the questionnaire and workshop are presented in Sect. 4.

As the "flagship" utility for the workshop endeavor, Commonwealth Edison invited ORNL researchers to personally observe the CRDM changeout activities during the March 1991 maintenance outage at the LaSalle County Nuclear Station. To reduce as-low-as reasonably achievable (ALARA) levels obtained during this normally high-dose activity, the management at this utility has promoted an aggressive training program for CRDM maintenance personnel, funded the development of new CRDM rebuilding tools, instituted innovative changeout procedures designed to streamline efforts, and, hence, reduced doses. Training videotapes of LaSalle Station's enhanced CRDM changeout and rebuilding procedures were also provided to ORNL for this NPAR study. Information on these endeavors, presented by LaSalle personnel at the workshop, brought tremendous interest from all participants. Witnessing the CRDM changeout at LaSalle provided the opportunity to examine maintenance and ALARA reduction techniques on a first-hand basis. This information is discussed in Sect. 5.

The conclusions and recommendations of the BWR CRDM aging study are presented in Sect. 6.

2 CRD System Design Description

The purposes of the CRD system are to position control rod assemblies (CRAs) within the reactor core to change reactor power and to rapidly shut down the reactor. The functional classification of the CRD system is that of a safety-related system because of the rapid shutdown (scram) capability.

The CRD system consists of the CRDMs, and the CRD hydraulic system, which, for the purpose of this report, is separated into HCUs and the remaining valves, pumps, and headers (balance of the CRD system - BOCRDS) that supply, move, and retain the operating fluid of the CRD system.

The CRD hydraulic system provides the hydraulic fluid (demineralized water) for normal insertion and withdrawal of CRAs. Additionally, the CRD hydraulic system provides cooling water for the CRDMs and recirculation pump seals and maintains a source of stored energy for the scram function. Figure 2.1 shows the basic hydraulic water flow path, which consists of centrifugal pumps, filters, control valves, HCUs, and headers that supply hydraulic fluid to each of the CRDMs.

Each CRDM is a double-acting, mechanically latched, hydraulic cylinder using reactor-quality water as its operating medium. Control rod movement is accomplished by admitting water under pressure into the appropriate part of the CRDM. The CRDM movement is transmitted to the CRA, which is engaged to the CRDM at the spud. The drive mechanism is capable of inserting or withdrawing a CRA at a slow, controlled rate as well as providing scram insertion for rapid shutdown of the reactor.

2.1 CRDM

The CRDM is a mechanically latched, hydraulic cylinder assembly that uses demineralized water as its operating fluid for normal and scram control rod operation. As shown in Fig. 2.2, the basic components of the CRDM consist of a CRD housing, an index tube, a piston tube, a drive piston and a stop piston (both with Graphitar seal sets), a collet locking mechanism, a position-indicating probe tube, and the CRDM flange. Table 2.1 contains a listing of the CRDM materials used in some of the primary CRDM components. The collet locking mechanism in the CRDM (the collet fingers engaging the index tube notches) enables the control rod to be positioned at 6-in. increments of stroke and to be held in a stationary position for indefinite periods of time. Control rod position is obtained from reed switches mounted inside the position-indication probe. These reed switches open or close during rod movement when a permanent magnet gets in their vicinity. The reed switches are provided at 3-in. increments of drive piston travel. Since the notches are 6-in. apart, indication is available for each half notch of rod travel. Even numbered readouts, '00' to '48', indicating the normal fully inserted to fully withdrawn positions (excluding overtravel in either direction), are provided at each latched drive position. Odd numbered readouts, '01' to '47' (or '--' in some plants), indicate the midpoints between the latched positions. The BWR/6 model CRDMs have dual reed switches (one is redundant) and the pre-BWR/6 models have single reed switches.

The inner cylinder, outer tube, and flange assembly (CTF) is a single-piece unit. The flange provides the means of mounting the CRDM to the CRD housing flange. The outer tube and inner cylinder form an annulus through which water is applied to the collet locking mechanism to unlock the index tube.

The drive piston and index tube comprise the driving link with the CRA. The index tube contains 25, 6-in. increments at which a CRA may be positioned. The collet locking mechanism is designed to ensure that the index tube is locked to hold the control rod at a selected position in the reactor core. The CRDM cannot be withdrawn before an insert signal is first applied to disengage the collet locking mechanism.

One of the major differences between CRDM models used in the various BWR designs is manifested in the buffer region. Figure 2.3 shows a comparison of the buffer designs between BWR/6 and pre-BWR/6 applications. The BWR/6 design utilizes orifices and a buffer piston to slow the drive piston at the top of its stroke during a scram, whereas the earlier designs utilized orifices and spring (Belleville) washers. The modifications in buffer designs not only contributed to faster scram times but helped to minimize Graphitar seal breakage that occasionally occurred during scram operations.

2.1.1 Normal CRDM Operation

During normal power operation, the CRD system provides cooling-water flow to all of the CRDMs and seal water flow to both recirculation pumps. When the CRDM is stationary, cooling water (which originates from the condenser hotwell reject line) enters through the insert port of each CRDM and is allowed to flow between the outer tube and thermal sleeve via a cooling water orifice. Cooling water flow is normally maintained to each CRDM at all times except when a signal is applied to move the CRA. The condensate storage tank contains another source of CRDM cooling water that is normally used during plant shutdown conditions.

2.1.2 CRDM Insert Operation

CRDM insert operation is accomplished by opening both insert directional control valves 121 and 123, as shown in Fig. 2.4. The opening of these valves supplies water from the drive water header, applies drive water pressure to

Table 2.1. Materials used in BWR CRDM components

Component	Material
Flange and plugs	Grade F304 stainless steel
Cylinder, tube, and flange assembly	Wrought 304 stainless steel in earlier designs
	Cast 304L collet retainer tube; stainless steel in replacements and newer designs
Piston tube	Type 304 stainless steel in earlier designs; ASME SA-249 or SA-479 Grade XM-19 stainless steel in later designs
Index tube	Type 304 stainless steel in earlier designs; ASME SA-249 or SA-479 Grade XM-19 stainless steel in newer designs
Collet piston	Type 304 stainless steel
Collet fingers, coupling spud, collet spring	Inconel alloy X-750
Drive and stop piston seals and bushings	Graphitar
Piston seal C-springs	Inconel alloy X-750
Piston rings	Haynes 25
Ball check valve	Haynes setllite or tungsten carbide base alloy
Elastomeric O-ring seals	Ethylene propylene
Drive piston head	17-4 PH (precipitation hardened) stainless steel
O-rings	Teflon-coated, type 304 stainless steel

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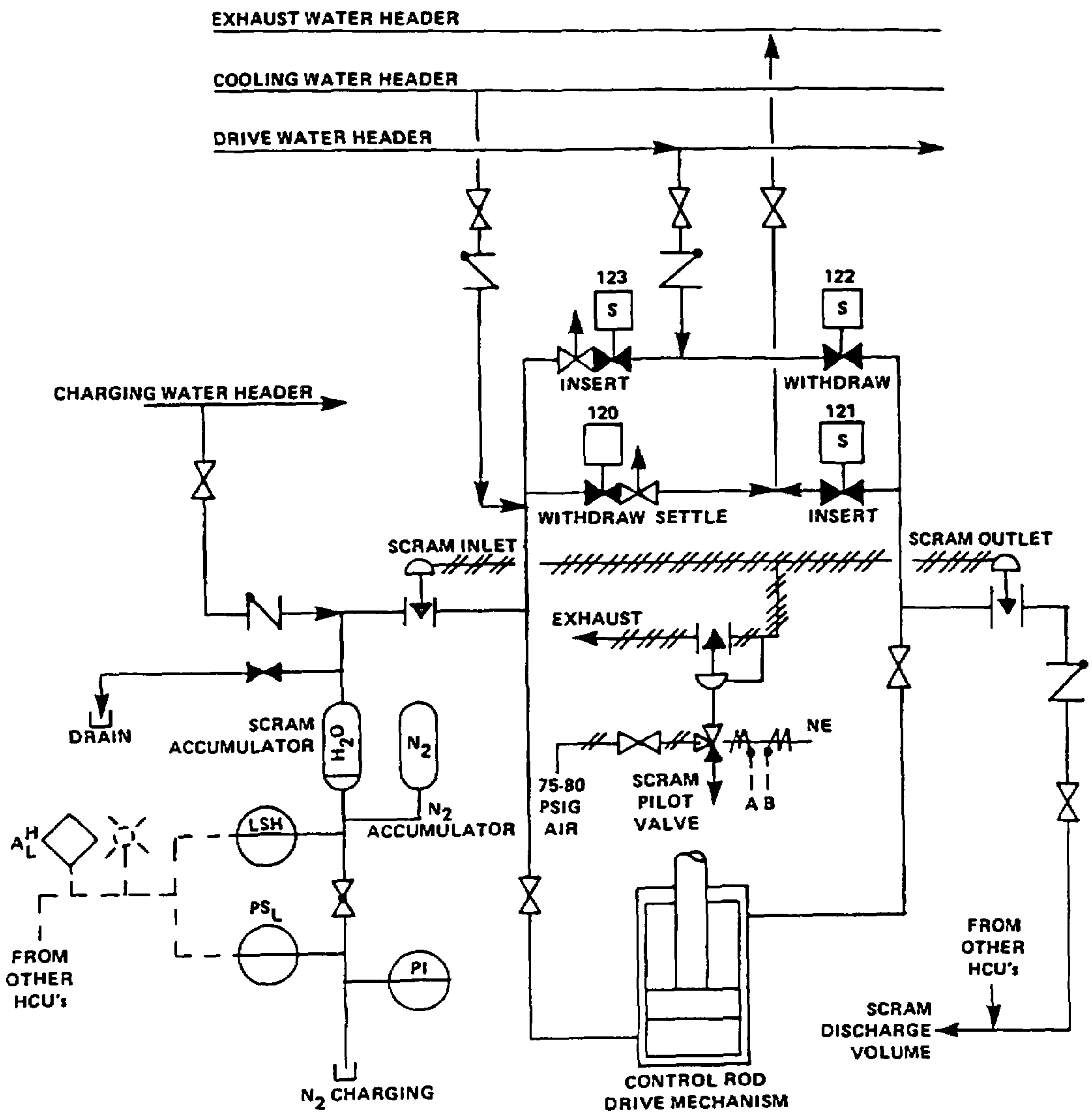

Figure 2.1 CRD hydraulic system schematic.[3]

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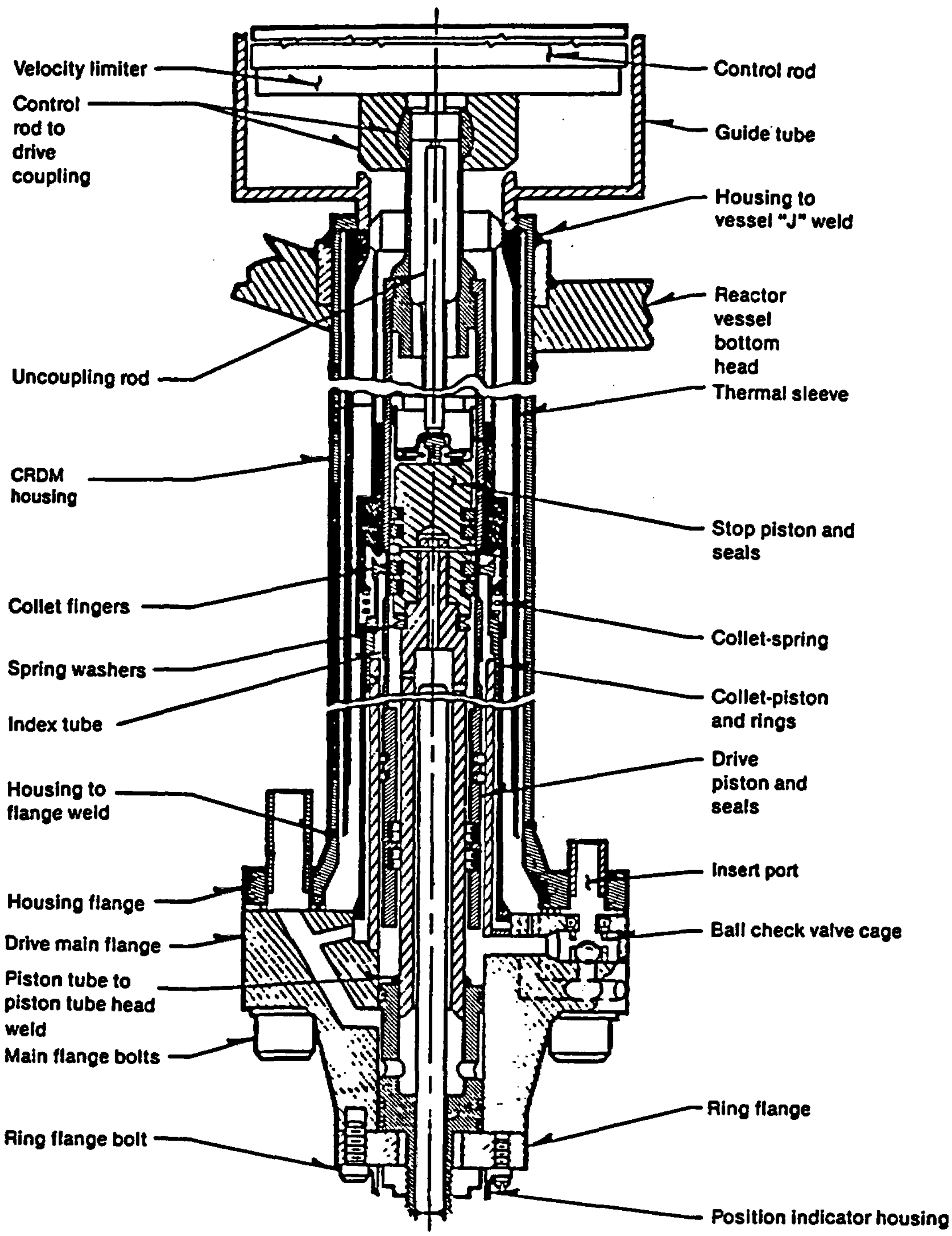

Figure 2.2 Primary CRDM components.[1]

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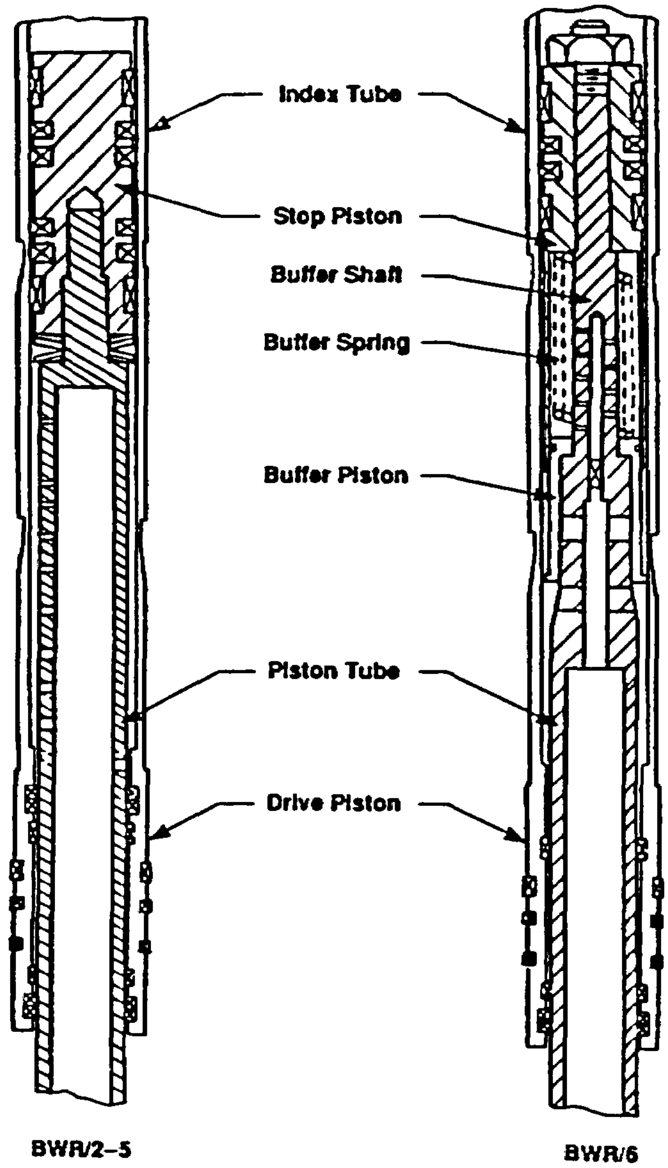

Figure 2.3 CRDM buffer designs.[4]

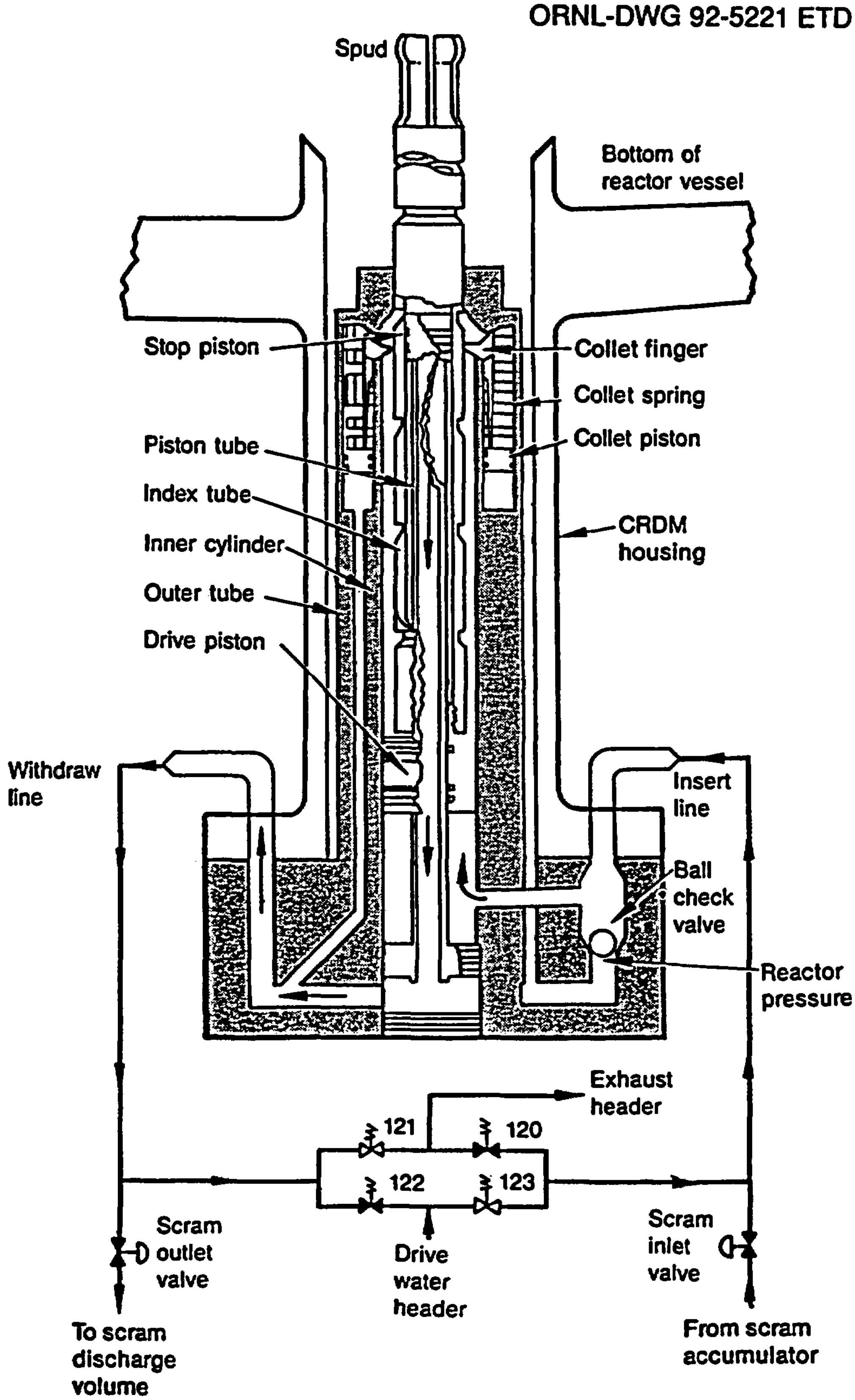

Figure 2.4 CRDM insert operation.[3]

the underside of the drive piston, and allows water to flow from the volume above the drive piston to the exhaust header. Since the drive water is at 1.2- to 1.8-MPa (180- to 260-psi) higher pressure than the reactor pressure, the ball check valve remains closed.

The differential pressure that is created across the drive piston forces the drive mechanism to insert the control rod into the core. With the drive moving upward, the collet fingers move outward and provide no mechanical restriction to movement of the index tube.

2.1.3 CRDM Withdrawal Operation

"The weight of the control rod blade and the index tube/drive piston assembly is approximately 125N (280 lb) and the tops of the notches on the index tube are square. Therefore, the friction between the index tube notch and the collet fingers is too great to allow a pressure force from the collet piston to remove the fingers from the square notches. So, initially, an insertion signal is applied for a short time (0.5 s), which causes the rod to insert 51 to 76 mm (2 to 3 in.). As the rod inserts, the collet fingers slide out over the tapered bottom of the notch in the index tube."[4]

Immediately following the brief insert signal a withdraw signal is applied to the drive mechanism by opening the 120 and 122 directional control valves as shown in Fig. 2.5. Drive water pressure is simultaneously applied to the collet piston and the area above the drive piston, while the volume below the drive piston is discharged to the exhaust header. As this is accomplished, the area above the piston is pressurized with drive water and a differential pressure is created that withdraws the drive.

2.1.4 CRDM Settle Operation

At the termination of normal control rod insert or withdraw signals, the rod control and information system automatically energizes and opens the withdraw directional control valve 120 for several seconds. This opens the volume under the drive piston to the exhaust header, permitting the drive to settle downward into the new, latched position.

2.1.5 CRDM Scram Operation

When a reactor scram is initiated by the reactor protection system, several operations occur: the scram inlet valves open to admit pressurized water from the scram accumulator to the area below the drive piston, the scram outlet valves open to vent the fluid above the drive piston to the scram discharge volume, and all of the directional control valves close. The flow path within the CRDM internals (as shown in Fig. 2.6) is the same to that of the insertion mode. However, because of the higher differential pressure across the drive piston, scram insertion occurs much faster than normal insertion.

Upon a reactor scram, the scram water accumulator provides the initial pressure to insert the control rod, but when this pressure drops below reactor pressure, the ball check valve opens, and reactor pressure can complete the scram stroke. The CRDMs normally operate at steady-state cooling-water temperatures below 120°C (250°F). However, when the ball check valves opens and reactor coolant is used to scram the CRDM, this high-temperature water [285°C (545°F)] imposes a thermal transient and shock to the CRDM internals. This latter operation is commonly referred to as a "hot" scram.

2.2 HCU

The HCU, shown in Fig. 2.7, includes all the hydraulic, electrical, and pneumatic equipment necessary to move one CRDM during normal or scram operation. There is a companion HCU associated with each CRDM in a reactor. Each HCU performs three specific functions:

1. stores energy (in the accumulators) and contains the valving configuration (via the scram inlet and outlet valves) that enables the CRAs to scram;
2. contains the valving configuration for normal CRDM movement using solenoid-operated, directional control valves; and
3. provides a cooling-water flow path to the CRDM.

BWR/6 HCU charging water accumulator pressure is ~1800 psig, as opposed to 1500 psig on previous accumulator designs. This design enhancement along with the increased nitrogen tank volume and pressure contributes to the faster scram times achieved with the BWR/6 model.

2.2.1 Directional Control Valves

The purpose of the directional control valves (120, 121, 122, and 123 as shown on Fig. 2.1) is to direct drive and exhaust water for CRA movement. The rod control and information system provides proper sequencing and duration of the signals used to operate the directional control valves.

2.2.2 Scram Inlet and Outlet Valves

The scram inlet and outlet valves (126 and 127 as shown on Fig. 2.1) control the flow of water necessary for rapid rod insertion. These scram valves are normally held closed by air pressure applied to their actuators. The scram valves are opened by removing the air pressure and allowing spring force to push the valve open. Control of the air supplied to the scram valves is accomplished with the use of scram solenoid valves. The scram solenoid valves are normally energized and become deenergized during scram operations.

2.2.3 Scram Accumulators

The scram accumulator is a piston water accumulator pressurized by a volume of nitrogen gas in a nitrogen

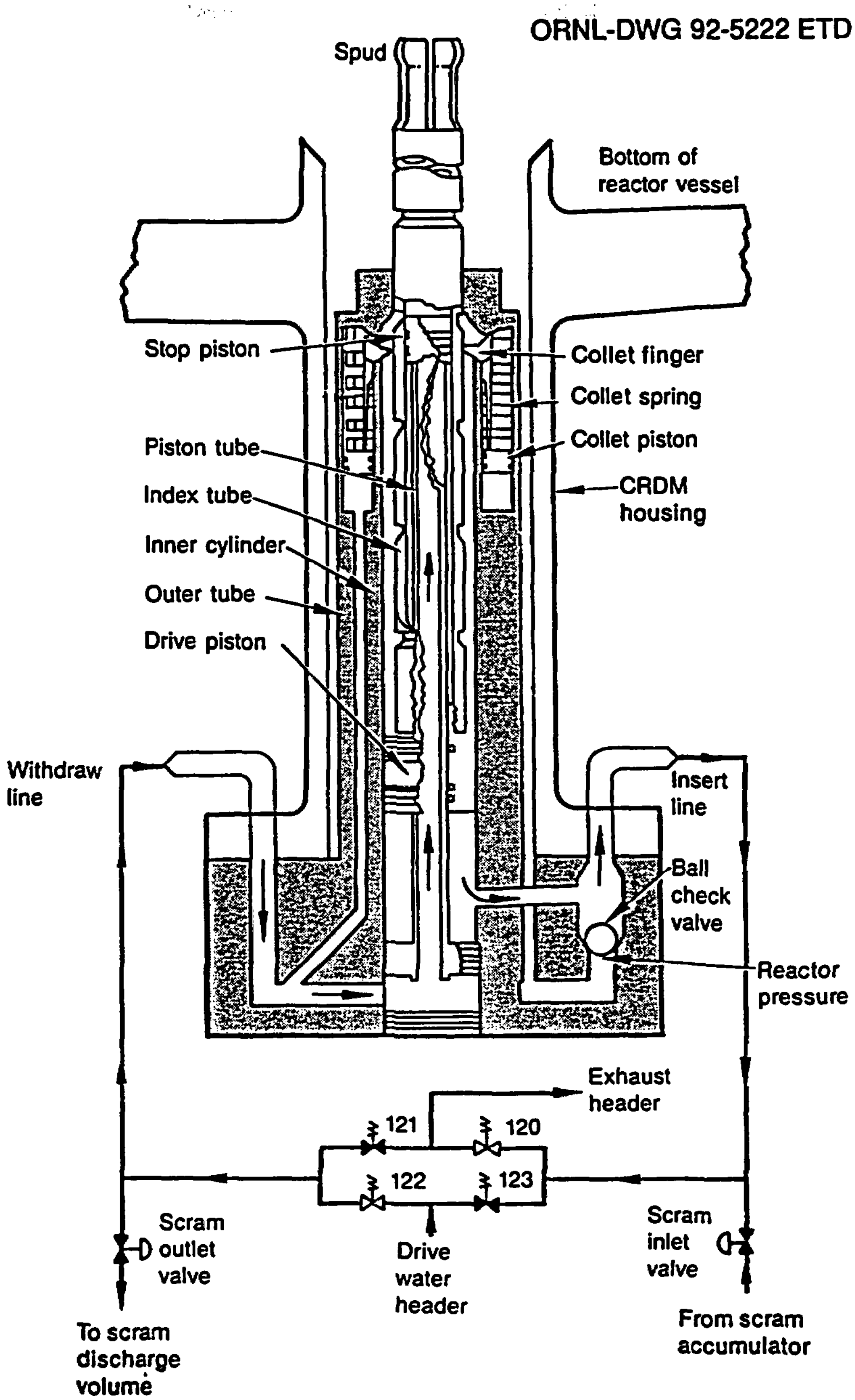

Figure 2.5 CRDM withdrawal operation.[3]

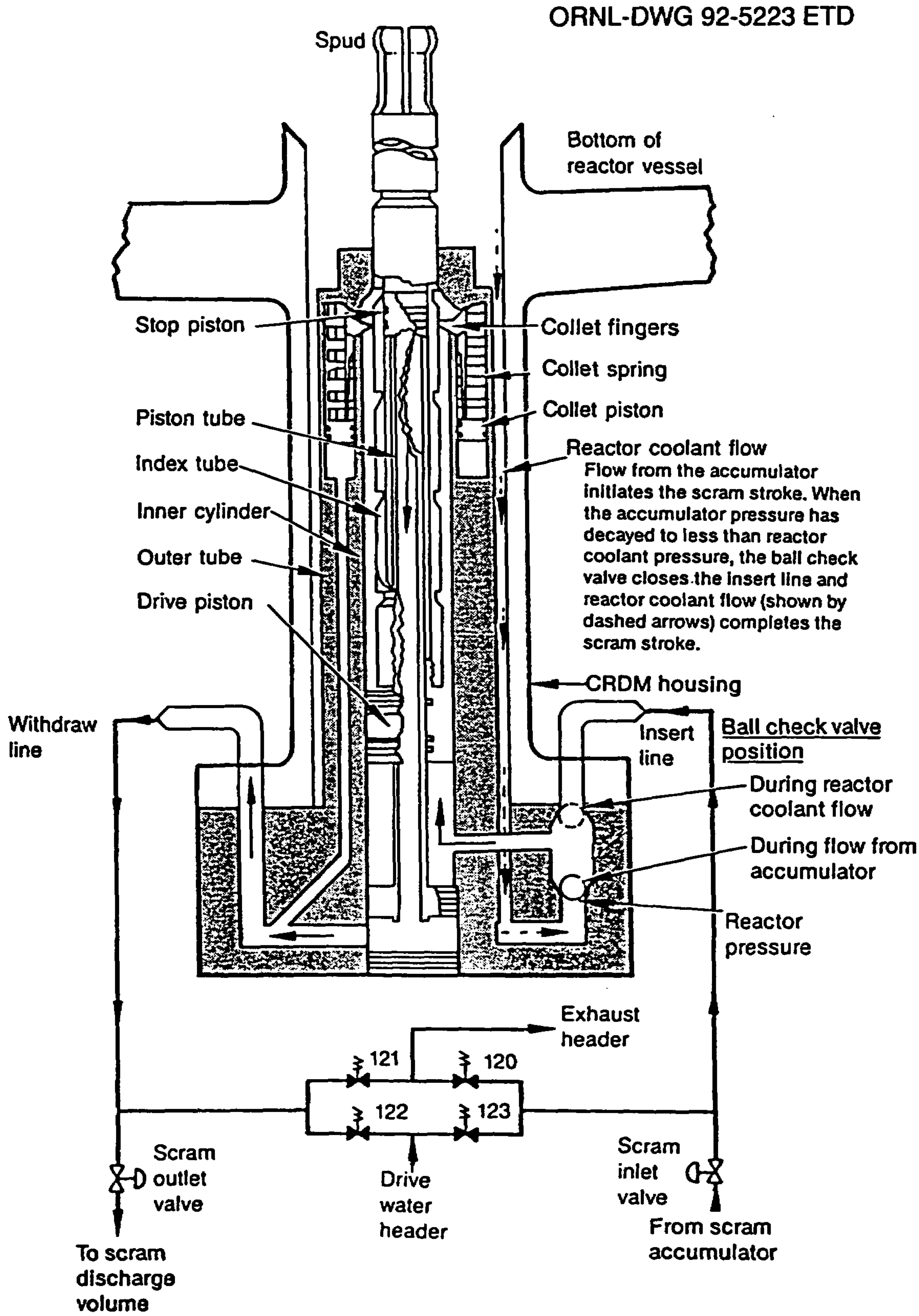

Figure 2.6 CRDM scram operation.[3]

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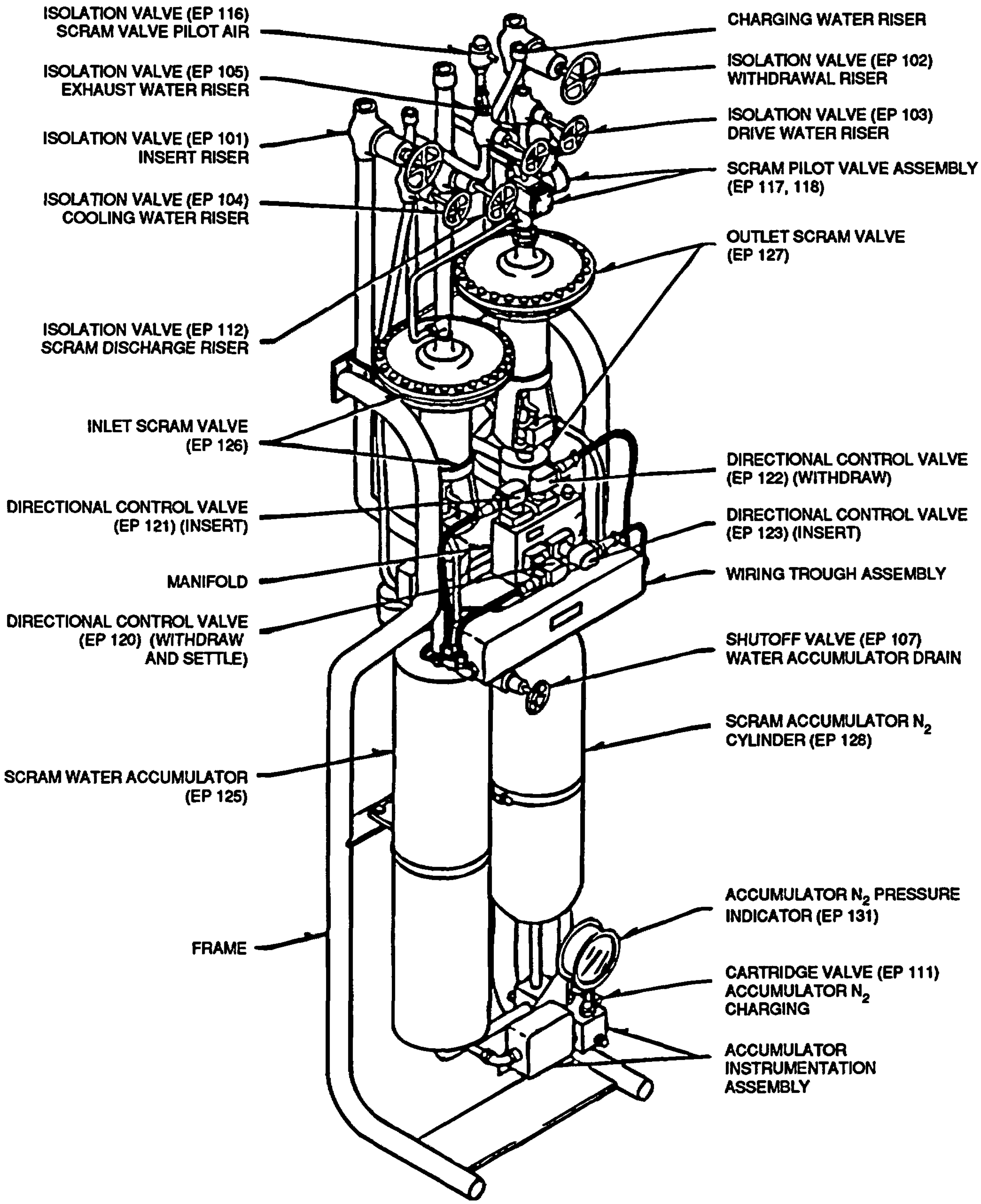

Figure 2.7 Hydraulic control unit (HCU).[3]

cylinder. The accumulators and their instrumentation occupy the lower part of the HCUs. The piston in the scram accumulator forms a barrier between the high-pressure nitrogen gas used as the source of stored energy and the water used to initiate the scram. Under normal plant operating conditions the piston is in full down position. The CRD hydraulic pump continuously pressurizes the scram accumulators through the charging water header.

2.3 BOCRDS

The remaining components of the CRD system have been grouped into the BOCRDS for the purpose of this Phase I aging study. The primary components contained in this grouping are highlighted in the following paragraphs.

2.3.1 Charging Water Header

The charging water header and its associated valves supply the high-pressure water required for charging the water side of the scram accumulators on the hydraulic control units.

2.3.2 Flow Control Station

The flow control station consists of a flow element, a transmitter, a flow controller, and two 100% capacity air-operated flow control valves. The flow controller establishes a flow setpoint, set by the operator, to maintain the proper flow to the drive water header and the cooling-water header. The flow control valve automatically reacts to deviations in the flow, sensed by the flow element, and makes any necessary adjust-ments in flow. Only one flow control valve is in service at any given time.

2.3.3 Drive Water Pressure Control Station

The drive water pressure control station consists of a motor-operated valve and four sets of stabilizing valves. The motor-operated pressure control valve is throttled to maintain ~260 psig above reactor pressure in the drive water header, which supplies the operating hydraulic fluid used for normal movement of the CRDM and its associated CRA into or out of the core. For this reason, there is flow in the drive water header only during CRD movement.

BWR/6s have four identical sets of stabilizing valves that are installed in parallel; pre-BWR/6s have two sets. Each set consists of two solenoid-operated valves. The stabilizing valves bypass the motor-operated pressure control valve with a flow equivalent to that needed for either insertion or withdrawal of one to four control rods.

2.3.4 Cooling Water Header

The CRD system cooling water header and its associated valves supplies cooling water to each CRDM The temperature of the cooling water should not exceed 120°C (250°F) to prolong the service life of Graphitar seals within the CRDM. The cooling-water pressure is maintained slightly above reactor pressure by the action of the automatic flow control valve and the pressure drop across the drive water pressure control station.

2.3.5 Scram Discharge Volume

The scram discharge volume and its valving consists of two piping headers, that connect to all hydraulic control units and drain into two independent, redundant instrument volumes. The scram discharge volume is sized to receive and contain the volume of water discharged by all of the CRDM following a reactor scram (independent of the instrument volumes). During normal operation, the scram discharge volume is empty and vented to atmosphere by normally open, air-operated globe valves that automatically close on a scram signal from the reactor protection system.

2.3.6 CRD Pump and Related Components

The CRD system has two fully redundant, 100% capacity, centrifugal pumps that supply water to the HCU accumulators following a reactor scram. There are redundant filters located at the pump suction and exhaust lines that protect the pump from foreign debris and prevent such materials from being discharged to the HCU.

Each pump has a relief valve to exhaust any excessive pressure in the pump suction piping. A pump motor heater and lube oil pump are also provided with each CRD pump. Manually operated suction isolation gate valves (both normally open) permit the operator to switch to the standby pump. Discharge stop check valves, also manually operated, are normally locked open and prevent reverse flow through the idle pump. The seals of the two CRD pumps are connected by a positive pressure seal line through a normally open, manually operated gate valve so that the operating pump supplies a positive pressure on the seals of the idle pump. This prevents air from entering the system via the seals of the standby pump.

A small, minimum flow line is also provided downstream of each CRD pump and upstream of each CRD pump discharge stop check valve. These flow lines have stop check valves to prevent backflow through the idle pump and are normally locked open.

3 NPRDS Data Analysis

3.1 Description of the Analysis

The goal of the NPRDS analysis was to identify and examine any repeating cause-effect-correction trends that might exist for failing CRD system components. There are 36 BWR units that have contributed 3432 CRD system component failure reports (from 1974 to 1990) to the NPRDS. These data are skewed, not by plant age, but by the date the plant started contributing information to the NPRDS. For example, the first NPRDS CRD system component failure report for one BWR plant which began commercial operation in 1969 occurred in 1981. There are widely varying numbers of failure reports from plants with similar ages, but it does not mean that there are fewer problems occurring at one plant when compared to another. In the evaluation of NPRDS failure data, it is important to realize that errors can occur when (1) utility maintenance personnel assess the problem, (2) the failure description is documented, and (3) the failure description is interpreted by the researcher. For these reasons, this aging study only uses the NPRDS data to determine the existence of trends in the reported failures. Although it is a very resourceful and beneficial research tool, the NPRDS data does not present a comprehensive view of CRD system degradation.

It is also important to define the term "failure" as it is used throughout this report. A failure refers to the inability or interruption of the ability of a system, structure, or component to perform its design function within acceptance criteria. For example, a valve that has a failure report in the NPRDS may have only needed adjustment to accomplish its design function. In other scenarios, this valve may need rebuilding or replacement before it can be returned to service. The term "degradation" is frequently used in the reporting and interpretation of component failures. Degradation refers to the immediate or gradual deterioration of the characteristics of a system, structure, or component which could impair performance of any of its design functions.

After scanning the NPRDS information from a few of the BWR plants, it was evident that the failure reports on the CRD system components could easily be categorized since the GE part identification was a common factor for all the BWR plants. This aging study identified 91 CRD system components itemized in Table 3.1. During the evaluation of the NPRDS failure reports, each failure entry was compiled according to component, observed symptom, method of discovery, reported cause of failure, and mode of action taken by the utility to restore component service.

3.1.1 Discovery Method Categories

The modes of discovery cited by NPRDS failure reports were analyzed to determine the extent to which CRD system component failures were being detected prior to a service demand. That is, do the existing maintenance and monitoring procedures yield the necessary "early warning signals" that enable utilities to successfully practice "reliability centered maintenance" on the CRD system? Figure 3.1 displays the results of this analysis. A total of 2470 CRD system component failures (72%) were discovered by scheduled testing or routine observation. Another 833 failures (24.3%) were observed by control room personnel. There were 69 failures (2.0%) reported due to a failed service demand and 60 cases (1.7%) that recorded no discovery method. Although the statistics for this NPRDS data analysis do not yield indisputable results, the trend of the data does confirm that the great majority of CRD system component failures do not catch the utilities by surprise.

Six categories were selected to describe the method of discovery identified for each failure report:

1. *Periodic Monitoring*: This group includes any required or planned surveillance testing performed during "at power" operating conditions to assess operational parameters such as insert, withdrawal, and scram timing; CRDM stall flow testing; or any special inspection. To be placed in this category, the NPRDS description narrative had to identify any degree of "at power testing."

2. *Control Room Observation*: Reactor operators are often the first personnel to detect abnormal CRD system operation via unusual instrument indications, such as high water level or low nitrogen pressure alarms from HCUs, or questionable control rod readings from the rod control and information system (RC&IS). The failure entry was attributed to this method of discovery if the NPRDS narrative cited an alarm, abnormal RC&IS reading, or report from the reactor control room.

3. *Maintenance or Routine Observation*: This method of discovery includes maintenance on the CRDM or related system components that occurred during outages, amidst routine preventive maintenance, corrective maintenance that was scheduled for another reported problem, or scheduled as the result of a routine "walk-down" during power operations.

Table 3.1 List of CRD system components analyzed with NPRDS data.

Analysis Component Number	General Electric Identification*	HCU Component Descriptions
C1	101	Insert riser isolation valve
C2	102	Withdrawal riser isolation valve
C3	103	Drive water riser isolation valve
C4	104	Cooling water riser isolation valve
C5	105	Exhaust water riser isolation valve
C6	107	Water accumulator drain shutoff valve
C7	111	Accumulator nitrogen charging cartridge valve
C8	112	Scram discharge riser isolation valve
C9	113	Charging water riser isolation valve
C10	114	Scram discharge check valve
C11	115	Charging water check valve
C12	116	Scram valve pilot air isolation valve
C13	117	Scram pilot valve assembly
C14	118	Scram pilot valve assembly
C15	120	Withdrawal and settle directional control valve
C16	121	Insert directional control valve
C17	122	Withdrawal directional control valve
C18	123	Insert directional control valve
C19	125	Scram water accumulator
C20	126	Inlet scram valve
C21	127	Outlet scram valve
C22	128	Scram accumulator nitrogen cylinder
C23	129	Water accumulator leakage level
C24	130	Nitrogen pressure switch
C25	131	Accumulator nitrogen pressure indicator
C26	132	Instrumentation block over-pressure rupture unit

*General Electric identification numbers may not be the same for all components at all BWR plants. If an identification number is not provided in the table, it was not available when the report was written.

Table 3.1 (continued).

Analysis Component Number	General Electric Identification*	HCU Component Descriptions
C27	134	Filter element (drive water)
C28	135	Filter element (water to/from CRD under-piston port)
C29	136	Filter element (water from CRD over-piston port)
C30	137	Drive water check valve
C31	138	Cooling water check valve
C32	P1	Test plug (driving pressure, integral with FE-134)
C33	P2	Test plug (exhaust pressure)
C34	P3	Test plug (CRD under-piston pressure, integral with FE-135)
C35	P4	Test plug (CRD over-piston pressure)
C36	P5	Test plug (scram discharge pressure, integral with check valve 114)
C37	P6	Nitrogen charging connector
C38		Miscellaneous HCU tubing and fittings
C40		Unspecified HCU valve
C41		Unspecified HCU component
C39		Miscellaneous HCU instrumentation
C42		HCU electrical component
C43		Undetermined HCU component
C44	106	Accumulator charging water isolation valve
C45		HCU electrical relay, fuse, or switch
C46		Miscellaneous HCU solenoid valve
C47		Miscellaneous speed adjuster needle valve
C48		Undesignated scram pilot valve solenoid
C49		HCU cabling
C50		CRDM ball check valve
C51		CRDM housing flange
C52		CRDM inner filter
C53		CRDM outer filter
C54		CRDM drive piston seals (sometimes, stop piston seals are also mentioned)
C55		CRDM stop piston seals

*General Electric identification numbers may not be the same for all components at all BWR plants. If an identification number is not provided in the table, it was not available when the report was written.

Table 3.1 (continued.

Analysis Component Number	General Electric Identification*	HCU Component Descriptions
C56		CRDM collet housing and/or the cylinder, tube, and flange assembly
C57		CRDM collet finger
C58		CRDM graphitar seals (unspecified)
C59		CRDM O-rings (unspecified)
C60		CRDM hold-down capscrews
C61		CRDM bushings (unspecified)
C62		Undetermind CRDM component
C63		CRDM uncoupling rod
C64		CRDM spud
C65		Position indicating probe(PIP)
C66		Rod position and indication system
C67		Rod select matrix
C68		CRDM strainer
C69		Cooling water orifice
C70		CRD guide tube
C71		CRD piston tube
C72		CRD system pump
C73		CRD system pump component
C74		CRD system pump motor
C75		CRD system pump suction line valves
C76		CRD flow control valve
C77		Miscellaneous CRD system valve
C78		CRD system instrumentation and/or gauges
C79		CRD pump instrumentation, electronic components, circuit breakers, switches
C80		Miscellaneous CRD system solenoid valve
C81		Miscellaneous CRD system circuit breaker or fuse
C82		Miscellaneous CRD electrical relay, switch, controller, transmitter, or power supply

*General Electric identification numbers may not be the same for all components at all BWR plants. If an identification number is not provided in the table, it was not available when the report was written.

Table 3.1 (continued).

Analysis Component Number	General Electric Identification*	HCU Component Descriptions
C81		CRD pump associated valve (miscellaneous)
C82		CRD system miscellaneous filter, strainer
C83		CRD system miscellaneous stabilizing valve
C84		CRD system piping
C85		CRD pump associated piping, tubing, fittings
C86		Scram discharge volume miscellaneous valves
C88		Charging water header valves (miscellaneous)
C89		Control room miscellaneous CRD system indicator
C90		Snubber

*General Electric identification numbers may not be the same for all components at all BWR plants. If an identification number is not provided in the table, it was not available when the report was written.

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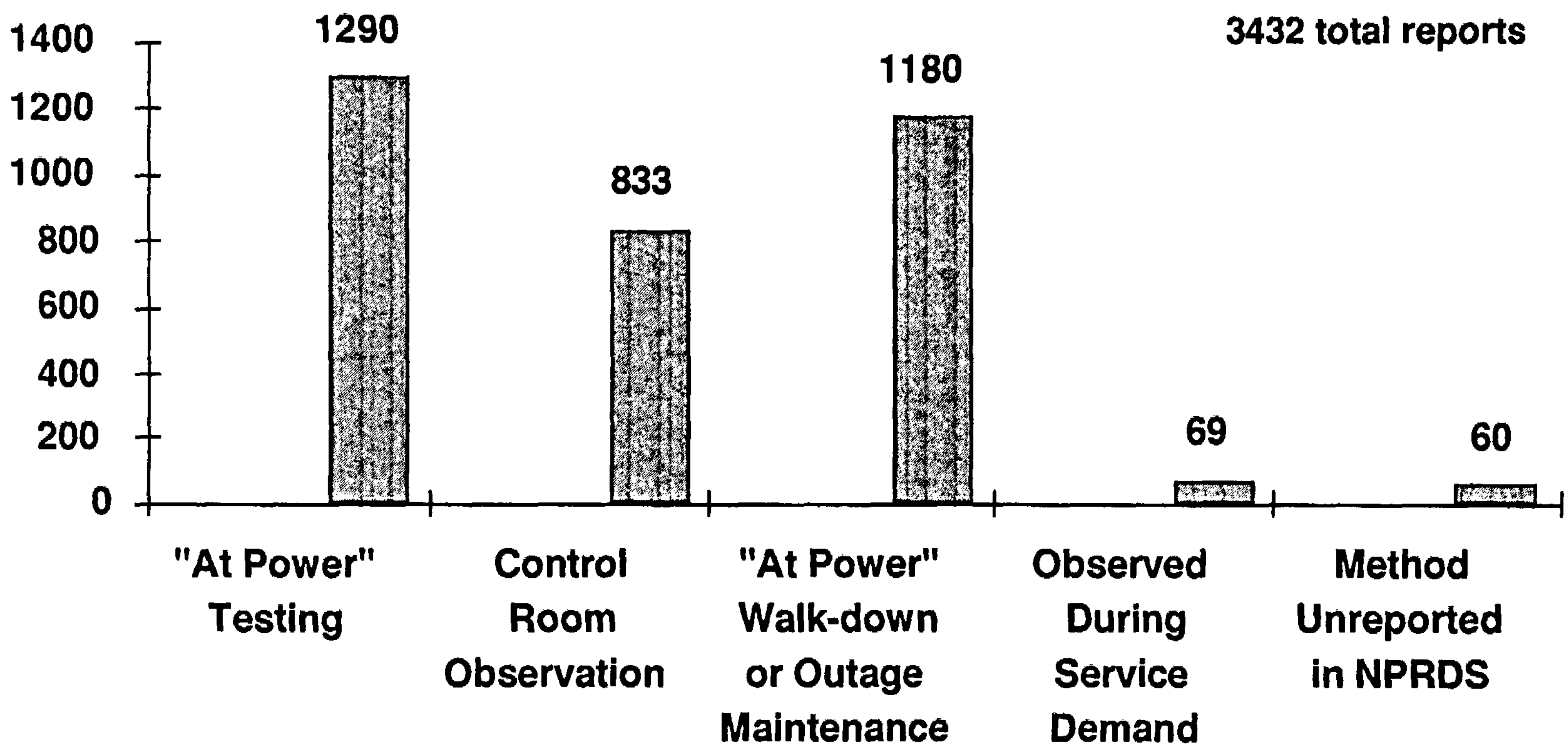

Figure 3.1 CRD system failure discovery methodology percentages.

4. *Service Demand*: This type of discovery method was attributed to NPRDS reports that were issued because the component failed to provide its designed service as required during normal operations, scrams, or any operational abnormality. This is the least desirable method of failure discovery, since it provides no indication of a degraded condition before a component's service demand.

5. *Other*: This category was defined to contain any NPRDS report that did not qualify for any of the other discovery methods. Fortunately, it was not used during the NPRDS CRD system analysis efforts.

6. *Unknown Method of Discovery*: In a few of the NPRDS reports, no method of discovery was described. This category was assigned to these cases.

3.1.2 Reported CRD System Component Failures

As earlier stated, there were 91 CRD system components identified from the NPRDS analysis. These components were grouped according to their location: on the HCU, in the CRDM, or the BOCRDS. According to the NPRDS reports, the majority of the failures (59%) occurred on HCU components. About 23% of the failures were directly attributed to CRDM components, and 18% originated from the balance of CRD system (BOCRDS). The distribution of these failures is shown in Fig. 3.2. Section 3.2 discusses the predominant CRD system component failures as reported in the NPRDS.

3.1.3 Reported Failure Symptoms

In reviewing the NPRDS failure data on the entire CRD system, 29 different failure symptoms were identified and associated with the various component failures. Table 3.2 contains a list of these symptoms. More than one symptom was cited in some of the failure narratives. To be consistent throughout the evaluation, the first reported symptom was the one associated with the failures. The data analysis assumes that if a certain symptom was placed first among two or more listed in the failure narrative, then it occurred more predominantly during the component failures. This assumption may not have always been correct but had to be made because of the scope of the analysis.

3.1.4 CRD System Component Failure Modes

There were 33 failure modes described in the NPRDS failure narratives on the CRD system components. Table 3.3 contains a list of these failure modes. Many of the narratives did not cite the formal "root cause" failure modes such as corrosion, fatigue, mechanical wear, etc., that are normally defined and used for aging research. The effects of these degradation mechanisms, such as worn valve packing, worn O-rings, and worn bearings, are typical of many of the causes of failure identified in the NPRDS data. The term "normal aging" or "normal wear" was frequently listed as the cause of failure. Degradation caused by natural or normal aging is the expected gradual deterioration of the operational characteristics of a system, structure, or component, that is due to aging mechanisms that occur with time or use under error-free pre-service and normal operating conditions that could impair the performance of any of its design functions. To be consistent during the data evaluation, the failure modes that were reported were also used to name failure mode categories in this analysis. The failure reports on the scram water accumulator provide a good illustration of this analysis, as shown in Table 3.4. This sample evaluation uses the failure causes and symptoms codes previously defined in Tables 3.2 and 3.3. The majority (115) of the NPRDS reports attributed the failure of this component to normal wear and aging, 41 reports identified corrosion as the cause, another 19 reports cited failures caused by the O-rings being worn from aging, 10 cases credited the failure to aged seals, and the remaining 4 reports did not identify a cause of failure. The failure scenario identified at one BWR plant for this component is the following: ". . . the chromium cladding in the carbon steel tank is porous enough to allow seepage of water through the cladding without any break-down of the cladding. The seepage eventually results in base metal (carbon steel) rusting and blistering of the cladding."[6] Normal wear is the primary mode of failure identified by the utility for this component, but corrosion is the predominant root cause of failure.

3.1.5 Corrective Actions to CRD System Component Failures

The actions taken by utilities to restore component service were grouped into six categories and are described in the following paragraphs. This information was processed to complete the cause-effect-correction scenario for each NPRDS failure report. Figure 3.3 provides a comparison of these utility actions. As reported in the NPRDS, to restore CRD system service, more than 70% of the maintenance involved the replacement of the system component or CRDM with a new or rebuilt unit.

1. *Component serviced*: This action indicates that the component was cleaned, flushed, repaired, and restored to its normal function. This category also includes any replacements of small components that are a part of minor CRD pump maintenance.

2. *Component replaced*: This category indicates that the component was replaced with a new or rebuilt unit or completely overhauled (as in the case of a CRD pump) to restore normal service.

3. *CRDM removed from service*: Very few of the CRDM failure reports (16 of 3432) simply stated that the control rod was inserted to position '00' and the CRDM electrically disarmed. The normal course of action would also require the replacement of this

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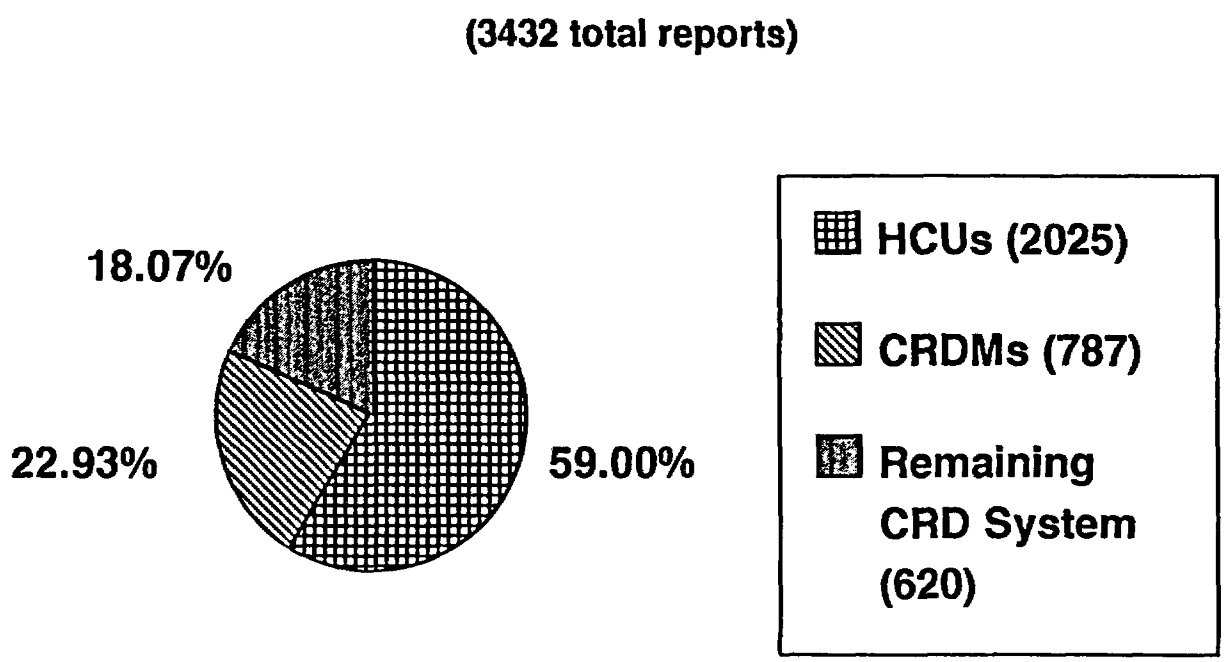

Figure 3.2 CRD system failure distribution.

drive, but the NPRDS narrative was incomplete, and this was the only action reported.

4. *CRDM replaced with new or rebuilt unit*: This is the predominant course of action utilities report for a CRDM that is determined to be in a degraded condition.

5. *No corrective action reported*: Only one failure report in the NPRDS data indicated that there was no corrective action taken for this component problem.

6. *Modification of plant procedures*: In two NPRDS reports, this was the only corrective action that was reported to have been taken.

Table 3.2. NPRDS reported CRD system failure symptoms

Analysis Component Number	Reported symptoms in NPRDS failure narrative
S1	Visibly leaking fluid (water, air, oil, or nitrogen gas), or fluid leaking past a normally closed valve
S2	CRDM high stall flow rate
S3	Abnormal CRDM withdrawal time rate
S4	Abnormal CRDM insert time rate
S5	Abnormal CRDM scram time rate
S6	Excess drive pressure required to move CRDM or "hard to move"
S7	Abnormal rod position indication reading — includes rod drift, scrams on half-scram logic, and double notching
S8	CRDM cannot be withdrawn normally
S9	CRDM cannot be inserted normally
S10	Abnormal CRDM temperature reading
S11	Rod uncoupled
S12	No symptoms recorded
S13	Component failed normal function
S14	Abnormal instrument reading
S15	High water level (may include alarms)
S16	Abnormal pressure indication (usually low, may include alarms, especially if leaking nitrogen gas)
S17	CRDM system pump alarms (may include pump trips)
S18	High noise level
S19	High vibration level
S20	Reactor water level abnormal
S21	Abnormal inspection or testing result
S22	Abnormal lubricant color, level, temperature, smoking
S23	Abnormal or high differential pressure
S24	Abnormal flow rate
S25	Abnormal amperage, voltage, or power requirements
S26	Abnormally low CRD stall flow rate
S27	High buffer time
S28	Rod scrams to position "02" and is not fully inserted
S29	Damaged by maintenance error

Table 3.3. NPRDS reported CRD system failure modes

Analysis Component Number	CRDM and HCU failure modes
M1	Manufacturer error
M2	Installation error
M3	Maintenance error (if CRDM component, rebuild error such as detached inner filter or misinstalled uncoupling rod)
M4	Weld failure (includes weld fatigue failure)
M5	Entrapped debris causing component failure
M6	Incorrect operation of component or system
M7	Failure due to normal wear or aging
M8	Corrosion
M9	Looseness
M10	Unknown failure mode
M11	Valve disc or wedge worn — aging
M12	Valve seat worn — aging
M13	Valve stem worn — aging
M14	Valve seals worn — aging
M15	Valve packing worn — aging
M16	Electrical component failure — aging
M17	Abnormal lubricant level or lack thereof
M18	Multiple valve aging (worn seat and/or stem, seals, packing, O-rings, etc.)
M19	Bent, cracked, or broken component due to aging or service wear
M20	O-rings worn from aging
M21	Aged solenoid component (e.g., coil and fuse)
M22	Aged seal or gasket material
M23	Worn out bearings
M24	CRDM collet housing cracking (IGSCC)
M25	Bent or damaged valve stems
M26	Worn valve diaphragms
M27	Instrumentation out of calibration, setpoint wrong, or setpoint drift
M28	Misalignment
M29	Gearbox aging
M30	Entrapped moisture or water-affected proper operation
M31	Valve actuator or operator out of adjustment
M32	Erosion
M33	Piping deterioration

Table 3.4. Scram water accumulator NPRDS failure analysis.

COMPONENT DESCRIPTION: *C19 - SCRAM WATER ACCUMULATOR (EP-125)*

NUMBER OF REPORTED FAILURES: 189 **PERCENT OF NPRDS:** 5.51 %

REPORTED FAILURE DISCOVERY METHOD: (1) 34.92 % (2) 30.16 % (3) 32.80 % (4) 2.12 % (5) ____ % (6) ____ %

REPORTED CAUSES AND OBSERVED SYMPTOMS OF COMPONENT FAILURE:

(1st) CAUSE	M7	SYMPTOMS:	(1st)	S15	(2nd)	S1	(3rd)	S9
Total Number	115		(4th)	S13	(5th)		(6th)	
(2nd) CAUSE	M8	SYMPTOMS:	(1st)	S15	(2nd)	S1	(3rd)	S16
Total Number	41		(4th)		(5th)		(6th)	
(3rd) CAUSE	M20	SYMPTOMS:	(1st)	S1	(2nd)	S15	(3rd)	S16
Total Number	19		(4th)		(5th)		(6th)	
(4th) CAUSE	M22	SYMPTOMS:	(1st)	S1	(2nd)	S15	(3rd)	S16
Total Number	10		(4th)		(5th)		(6th)	
(5th) CAUSE	M10	SYMPTOMS:	(1st)	S1	(2nd)	S15	(3rd)	
Total Number	4		(4th)		(5th)		(6th)	
(6th) CAUSE		SYMPTOMS:	(1st)		(2nd)		(3rd)	
Total Number			(4th)		(5th)		(6th)	

ACTIONS TAKEN BY UTILITIES TO CORRECT FAILURE: (1) 36.51 % (2) 62.96 % (3) ____ % (4) ____ % (5) 0.53 % (6) ____ %

COMMENTS: *This component has the second largest failure reporting in the NPRDS. Almost 83% of the failures are attributed to aging and corrosion of the component. The majority of the remaining cases cite worn O-rings or gaskets. The predominant symptom is a high water level and/or alarm for the component. Earlier model HCUs used carbon steel water accumulators that have experienced corrosion in almost all BWR plants. Flakes of the inner chromium liner broke off and became entrapped at the seal and deteriorated O-rings and gaskets. GE offers a stainless steel upgrade replacement that has no reported corrosion history. Many affected units have been upgraded to this model.*

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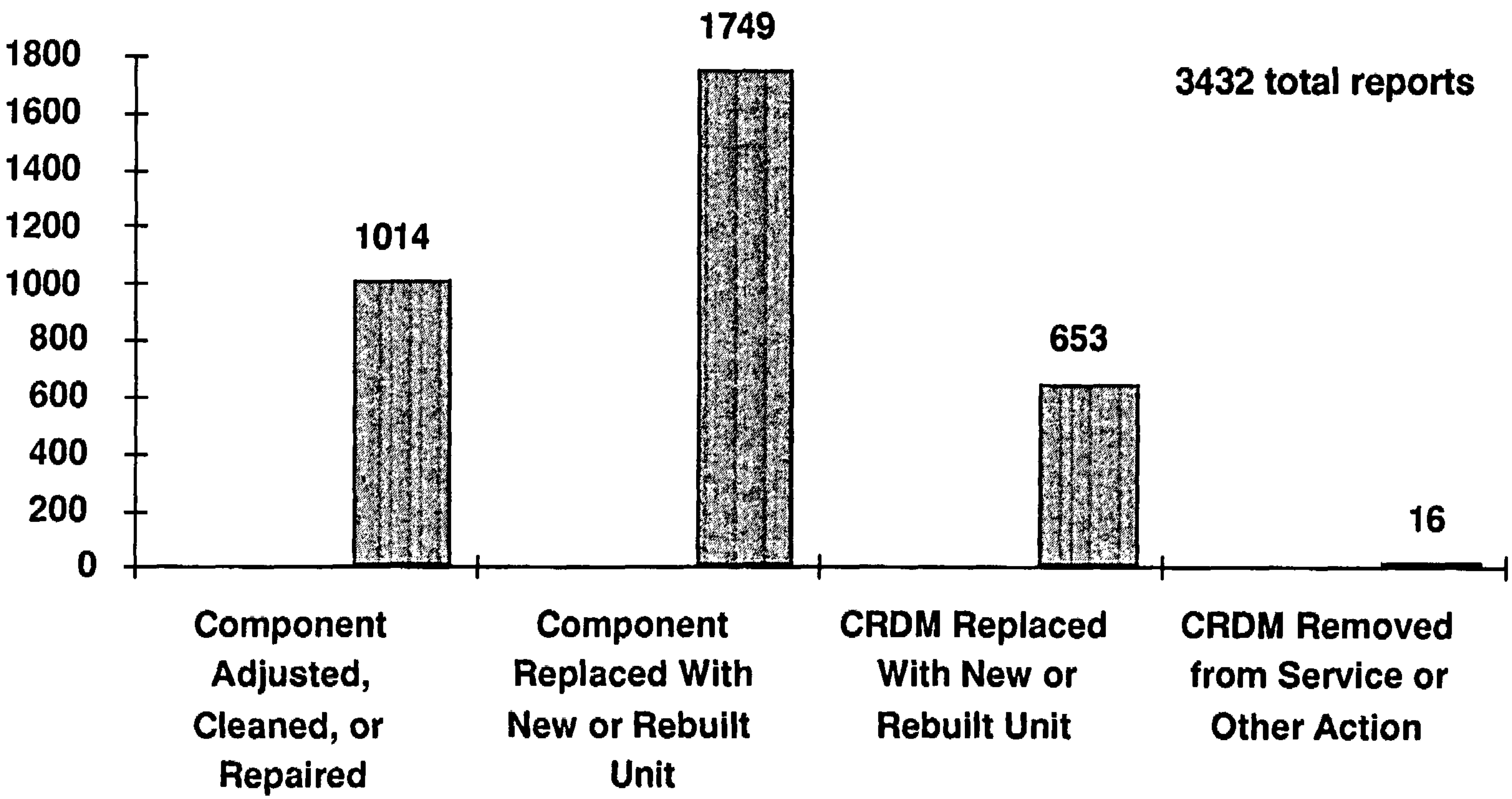

Figure 3.3 Comparison of utilities' corrective actions to reported CRD system failures.

3.2 Predominant Component Failures

As earlier stated in Sect. 3.1, there were 91 different CRD system components identified in this NPRDS analysis. After a categorization of all the failures, it was easy to determine which components had experienced the most failures. The following sections discuss these components, some of the root causes of their failures, and any actions that can be taken to mitigate their degradation. There is no statistical significance to the selection of these components other than the fact that they had more failure occurrences reported to the NPRDS.

3.2.1 HCU Component Failures

More than 59% of the 3432 CRD system failures reported to the NPRDS were attributed to components located on the HCU. The following paragraphs discuss the predominant HCU component failures.

3.2.1.1 Accumulator nitrogen charging cartridge valve (No. 111)

There were 526 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 the second leading cause (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 actually be the result of incorrect installation. GE 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 and also result in damaging the packing.

3.2.1.2 Scram discharge riser isolation valve (No. 112)

There were 187 failure reports on this particular valve. One BWR unit reported 184 of these failures. During a refueling inspection of this valve, cracks were found in the valve stem and disk in enough valves to warrant replacement of nearly all of this unit's No. 112 valves. This inspection was probably the result of GE SIL No. 419, which recommended a liquid penetrant examination of the wedges of the No. 112 valve.[7] A BWR/3 had reported to GE that a CRDM failed to scram because the wedge had separated from the stem of a No. 112 valve and prevented exhaust flow from the CRDM. GE identified the cause of the fracture as IGSCC. There were two manufacturers of these valves, Dresser, Inc. (Hancock), and the Vogt Valve Company. GE stated in the information letter that both kinds of valves could be subject to the same type of failure. If the worn valves were part of the originally installed equipment, they had performed 11 years of service before being replaced.

3.2.1.3 Scram water accumulator (No. 125)

The NPRDS has recorded 189 failure reports of this component with 119 of them requiring replacement. As earlier reported in Sect. 3.1.4, the chromium plating of the carbon steel tank was porous enough to allow water to seep in and cause corrosion of the carbon steel. GE issued SIL No. 66 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 will result in control rod insertion.[8] In addition, flakes of Teflon from the seat can also become entrapped in the cooling water orifice of the companion CRDM. GE and the Toshiba Corporation have developed a stainless steel replacement unit for this component. The predominant symptom of accumulator degradation reported in the NPRDS is a repeating high water level alarm.

3.2.1.4 Inlet and outlet scram valves (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 discussed in Sect. 3.2.1.3, 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 its SIL No. 457, GE 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.[9] A supplemental letter from GE 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.[10] 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.

3.2.1.5 Scram pilot valve assemblies and solenoids (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). GE issued SIL No. 128, 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.[11] Since there is a continuous heat source from these normally energized solenoids, surface temperatures could be periodically monitored and trended to detect coil degradation, which was the cited as the secondary cause of failure for these valves (increasing temperatures can indicate imminent coil failure).[12] Industrial pyrometers could be used to obtain these data. GE also recommended in SIL No. 128 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 because the Buna-N parts in these valves have at least a 7-year shelf and in-service life from the packaging date on the rebuilt kit.[13] One utility reported substituting Viton-A O-rings in this solenoid instead of Buna-N type. The symptoms of scram pilot valve and solenoid degradation include slow scram times, leaking air, and abnormal solenoid noise (chattering, rattling, or ac hum).

3.2.2 CRDM Component Failures

Nearly 23% of the NPRDS CRD system component failures were attributed to the CRDM. A large number of these reports (189) did not specify a CRDM component, but, nevertheless, the CRDM was identified as needing maintenance and was exchanged for a new or rebuilt unit. If the HCU valves and valve configurations have been adjusted and/or verified as correct, and the CRDM insert or withdrawal stall flows are still not within acceptable limits, or if scram times for a particular drive exceed technical specifications, the utility changes out the CRDM with a new or rebuilt unit.

3.2.2.1 CRDM drive and stop piston seals

There were 275 NPRDS failure reports attributed to Graphitar-14 seals. The predominant degradation mechanisms for the Graphitar seals are mechanical wear and thermally induced embrittlement. The purpose of the seals and bushings is to form a hydraulic pressure boundary within the CRDM that enables the index tube of the device to be inserted and withdrawn, thus positioning the control rod assembly in the reactor core. Figure 3.4 shows a close-up photographs of two (of several) types of CRDM seals. Figure 3.5 shows the seal locations on a Model B CRDM drive piston. Even when new, Graphitar-14 is a very brittle material that can fracture rather easily (the right seal in Fig. 3.4 accidently fell on a concrete floor and broke). Graphitar seal degradation may be exhibited by withdrawal stall flows >5.0 gpm (not attributable to HCU valve configuration), non '00' scrams (the drive not fully inserted after a scram), increased pressures required to move the drive, and elevated temperatures throughout the length of drive travel.

The primary cause of Graphitar seal degradation is mechanical wear, which is exhibited by seal breakage, surface scratches and scoring. Seals slide against the inside of the cylinder, tube, and flange housing as differential hydraulic pressures move the index tube up and down. Ideally, seals and bushings are perfectly seated in the drive and stop piston grooves; the HCU receives demineralized water from the condensate reject line or from the condensate storage tank and delivers this operating medium to the CRDM. Although there are filters on the HCU and also within the CRDM to entrap crud, in many cases, this debris becomes entrapped in between the Graphitar seal sets and their seating surfaces, creating uneven force distributions during scram impacts that can cause seals to improperly function and break. Crud found in the hydraulic medium for the CRDM not only contributes to Graphitar seal degradation but accelerates corrosion activities by scratching and pitting CRDM component surfaces.

The CRDM can also perform "hot scrams" using coolant directly from the reactor vessel. This type of scram can also cause seal degradation since it suddenly exposes the CRDM to reactor water temperatures of around 285°C (545°F). GE stated in SIL No. 173 that CRD temperatures above 120°C (250°F) can shorten CRD Graphitar seal life and increase CRD drive maintenance, and that CRD temperatures of 177°C to 288°C (350°F to 550°F) would result in a significant reduction in strength of the Graphitar seals. The letter further advised that temperatures over 177°C (350°F) may also result in a measurable delay in scram response time.[14] Normal CRD operating temperatures may range from 49°C to 121°C (120°F to 250°F), depending on core location, CRDM coolant flow rates, seal integrity, and the amount of entrapped crud in the drive. All utilities "exercise" their CRDMs at least one notch on a regular basis (weekly to monthly); this verifies CRDM operability and helps loosen entrapped crud between the seals, but GE recommends a special CRDM flushing procedure in SIL 173 to remove crud that can also clog the cooling-water orifice. To further mitigate the crud problem, GE and Toshiba also introduced design changes in the cooling-water orifice that enlarged the flow path and reduced the opportunity for debris entrapment.

The Nuclear Energy Division of the Toshiba Corporation, which supplies BWR components to the GE-designed

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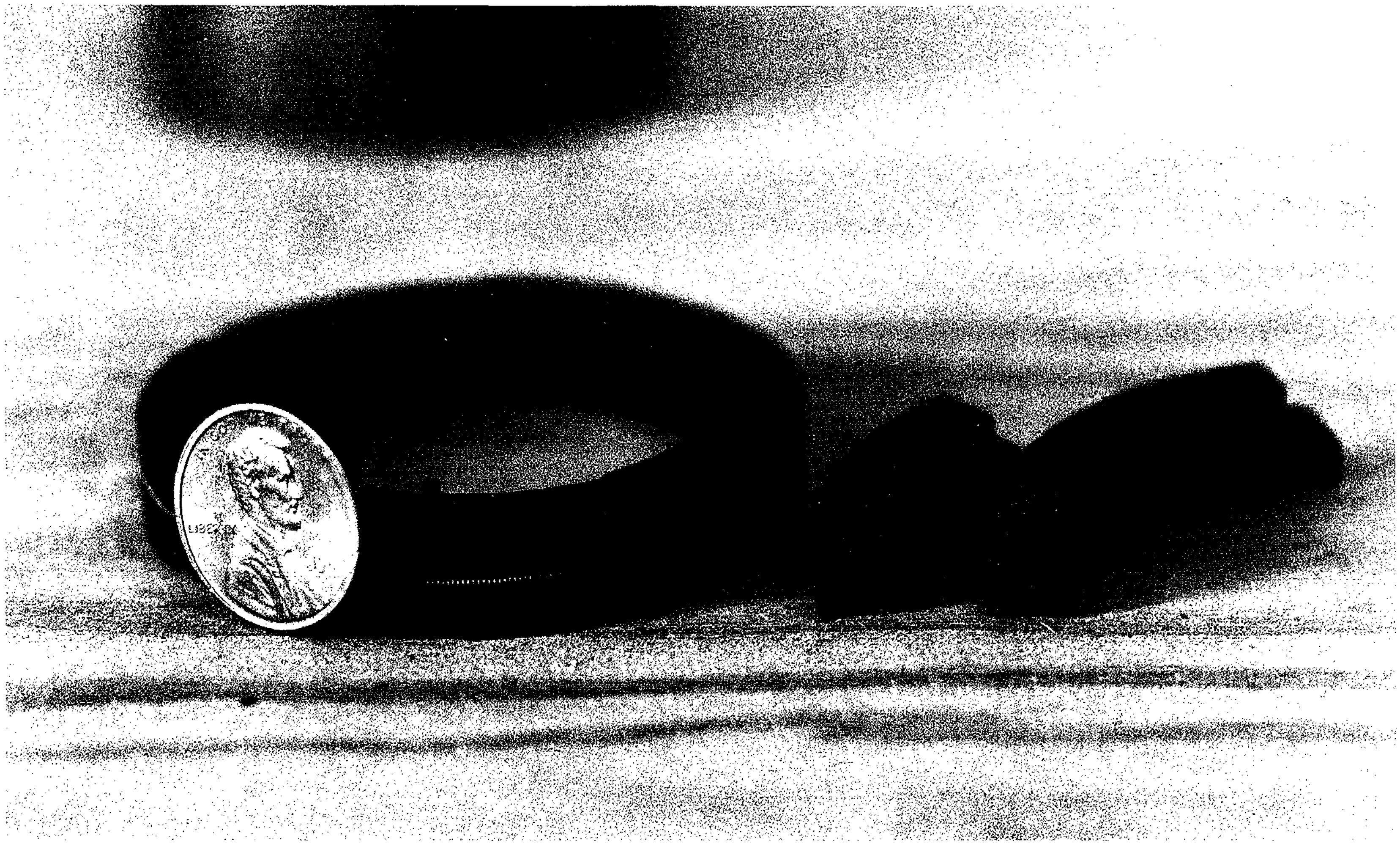

Figure 3.4 Close-up photograph of a CRDM radial seal and fractured external drive seal.

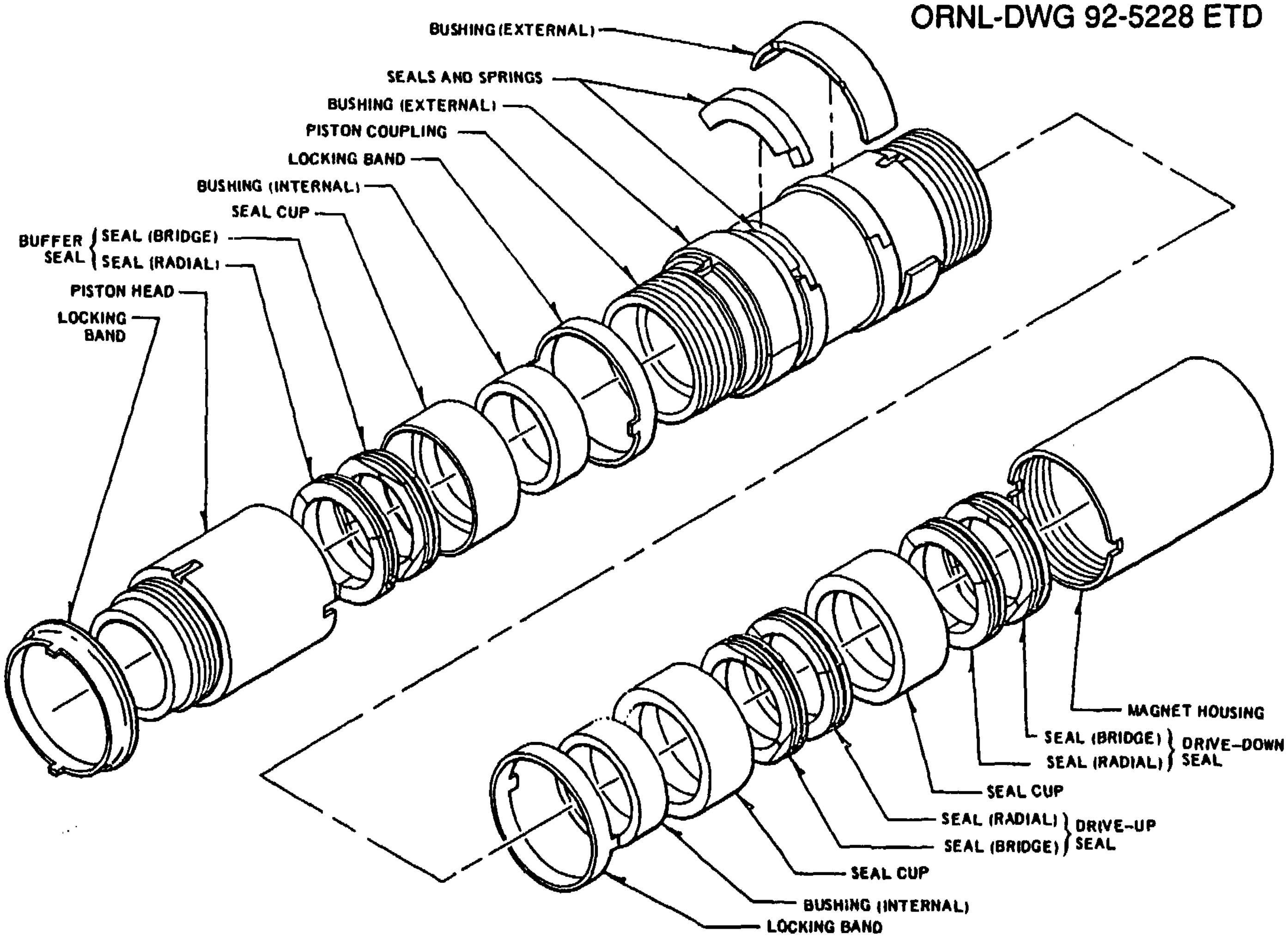

Figure 3.5 Model B CRDM drive piston seal locations.[16]

BWR plants operating in Japan, released in 1974* a newly developed CRD carbon seal ring (called the Toshiba seal ring -TSR) to replace the conventional, GE-designed Graphitar seals used in their CRDMs. The TSR claims higher mechanical properties (strength, hardness, and toughness) to prevent cracking during CRDM operation and offers two comparison charts in their marketing literature[15] that are reproduced, courtesy of Toshiba, in Fig. 3.6(a) and (b). GE has also developed an improved Graphitar seal that became available in January 1992 in the rebuild kit for both BWR-6 and pre-BWR-6 control rod drives. The improved Graphitar seals are anticipated to increase the service life of a CRDM and, furthermore, reduce the long-term acquired doses resulting from less required maintenance for CRDMs during a BWR's operational life.

3.2.2.2 CRDM inner filter

Each CRDM has inner and outer filters, which serve to collect debris from the reactor water that might otherwise damage the CRDM. The inner filter has been attributed with 90 reports of failure 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.3.7). 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. 3.8). 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. Figure 3.9 is a photograph taken of a bent uncoupling rod of a drive believed to have been damaged by exhibiting a history of this type of uncoupling problem.

3.2.3 BOCRDS Component Failures

If a 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 BOCRDS component failure. There are 20 BOCRDS components identified in this analysis (listed in Table 3.3), and most of them are rather general in their description. Only 18% of the failures reported in the NPRDS were attributed to components comprising this category. This section discusses three of the component categories having the higher numbers of failure reports.

3.2.3.1 CRD system pumps and pump components

The CRD system pumps and pump components had 54 and 63 reports of failure, respectively. About 37% of the pump failures were caused by worn bearings. Nearly 15% of the reports identified pump inlet and outlet piping erosion and deterioration, another 13% cited worn seals and/or gaskets, and 19% of the reports attributed the failures to normal wear or aging. Over 98% of the pump failures were discovered by testing or routine maintenance. In the pump component category, seals and bearing failures were predominant with 26% and 27% of the failure reports, respectfully, with looseness being a problem 10% of the time. It was difficult to be more specific in classifying the pump report failures because of generalized descriptions in the narratives, but it is correct to cite bearings, seals, piping and parts erosion, and looseness as the most prevalent problems reported in CRD pumps. 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.[17] Bearing anomalies, misalignment, unbalance, looseness, and soft foundations are readily observed, analyzed, and diagnosed using fast Fourier transform (FFT) analysis. Other programs utilize oil analysis to identify degradation of metallic parts. 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, the pumps are entirely rebuilt.

*Personal correspondence to R. H. Greene, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., from Yoshitsugu Koyama, Engineering Manager, Reactor Component Design, Toshiba Corporation, Yokohama, Japan, December 18, 1990.

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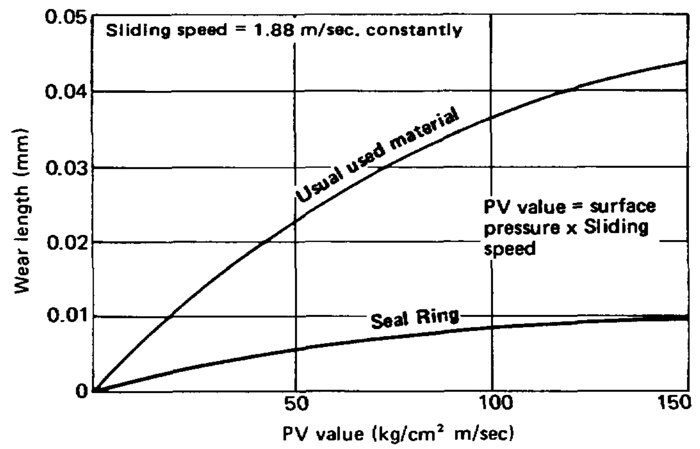

Figure 3.6(a) Comparison of CRDM seal wear characteristics: wear length vs PV.*

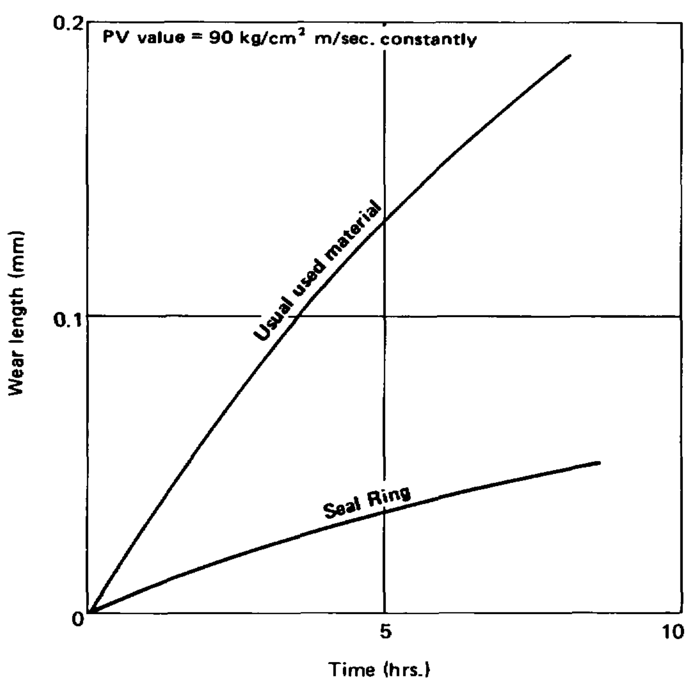

Figure 3.6(b) Comparison of CRDM seal wear characteristics: wear length vs time.*

* *Figures 3.6(a) and (b) are provided courtesy of the Toshiba Corporation.*

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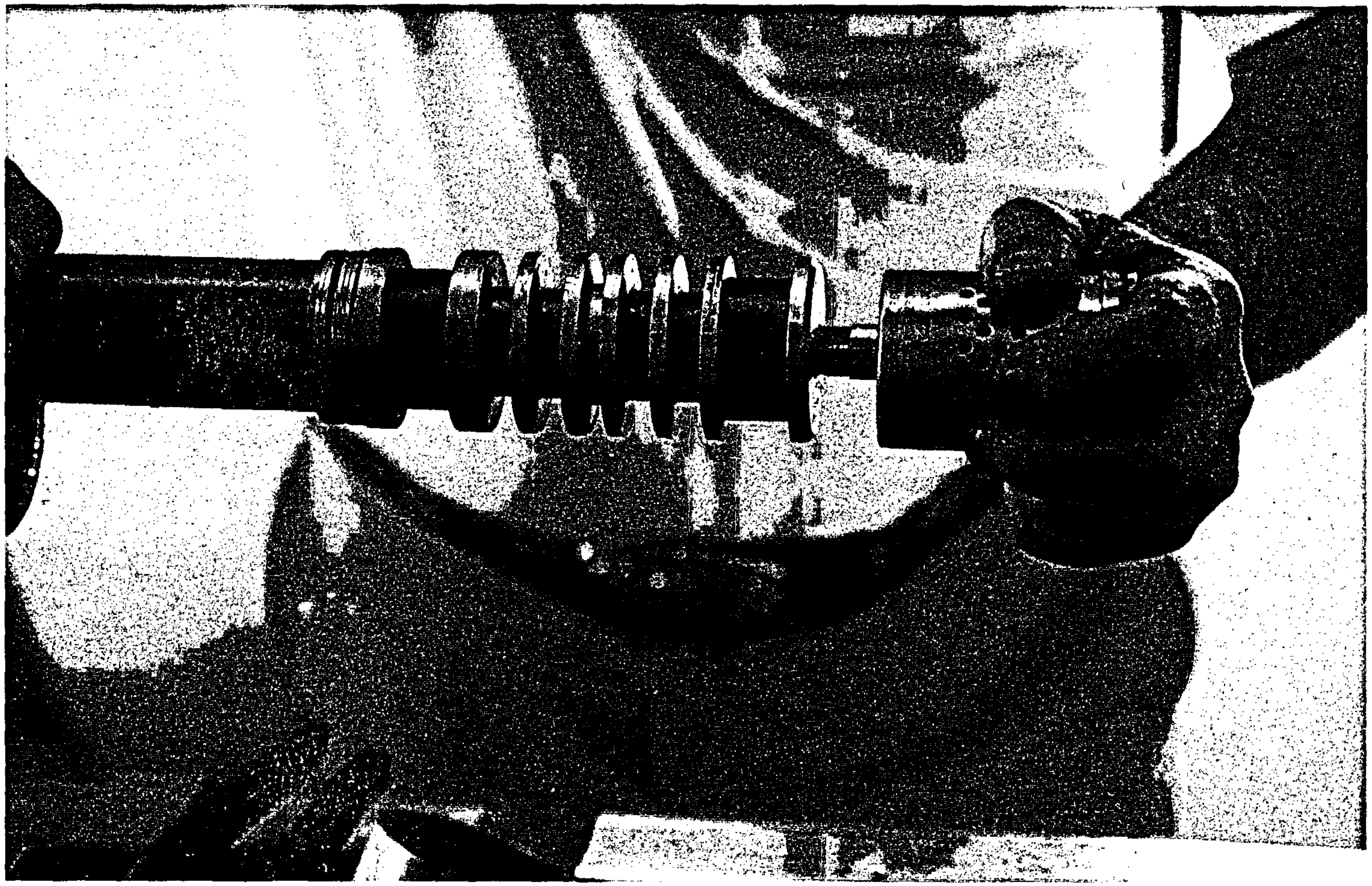

Figure 3.7 Inner filter attachment on end of CRDM stop piston.

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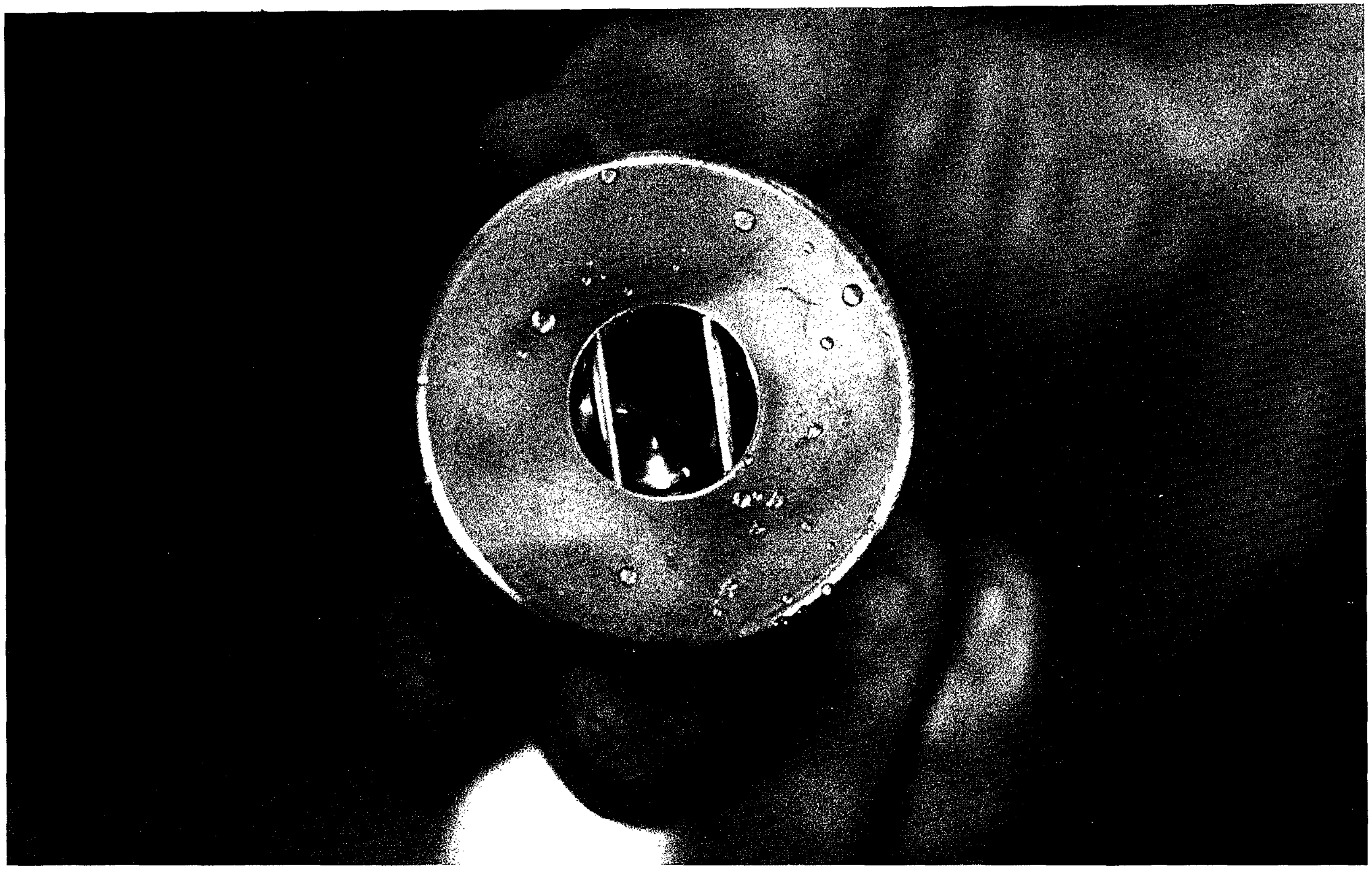

Figure 3.8 Spring clip mechanism on CRDM inner filter.

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Figure 3.9 Bent CRDM uncoupling rod.

3.2.3.2 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 as 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.

3.2.3.3 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. 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 via either adjustment or complete replacement. There were no electrical component reports on the CRDM.

3.2.3.4 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.

3.3 Evaluation of the NPRDS Analysis

The NPRDS analysis of CRD system failure data provided degradation trends on several specific components on the HCU and a few inherent to the CRDM and BOCRDS. The majority of the CRD system maintenance activity occurs on HCU, probably because of the many valves located on this device known to have components that degrade with normal service. The components on the HCU are readily identified by the GE part number, which makes failure reporting easier to accurately document. Maintenance on the CRDM normally requires that it be completely rebuilt. There were many narratives (189) that simply referenced the CRDM and cited no distinct component that had degraded. The BOCRDS failure narratives often contained references to components that were difficult to group either by a number or description because of varying plant nomenclature. Consequently, it was difficult to precisely categorize many component failures in the BOCRDS because of these inadequacies.

One major CRDM component problem that was seemingly overlooked by the results of NPRDS analysis is the collet housing cracking (IGSCC) phenomenon that occurred on the cylinder, tube, and flange (CTF) assemblies of many of the earlier model CRDMs (prior to BWR-6). There were only 45 failure reports in the entire data base attributed to this component, but one BWR plant reported at the CRDM Aging Workshop that 46% of its drives (85) required replacement of the CTF assembly due to this type of degradation.[18] The data base reporting guidelines have varied since the NPRDS was organized, and this has resulted in inconsistencies in the types and amounts of information reported by utilities in the past.

These discrepancies prompted the development and distribution of a BWR CRDM aging questionnaire to gather information directly from the CRD personnel at each plant site. The results of this endeavor are presented in the following section.

4 CRDM Aging Questionnaire and Workshop

4.1 Description of the Questionnaire and Workshop

After reviewing the NPRDS CRD system failure data from several BWR plants and comparing them with GE SILs which had been issued on the system, it became apparent that a better understanding of the reported aging information might be obtained directly from CRD engineers and technicians. Inquiries concerning CRDM failure mechanisms were made to several utility and commercial experts who had acquired many years of experience in BWR CRDM changeout and rebuilding. The testimonies from these individuals provided a first-hand viewpoint of CRDM degradation that was missing from many NPRDS reports. Since their perspective was considered essential to performing an accurate and comprehensive aging assessment, it was decided to develop and distribute to each BWR plant site a CRDM aging questionnaire that would survey the overall performance of the CRD system.

A preliminary questionnaire was developed and circulated for comments to five different experts representing the utility, commercial services, and vendor organizations. The revised questionnaire was distributed to specific BWR CRD personnel via the EPRI. The majority of the plant personnel were personally contacted before and after they received the questionnaire. The utility community voiced such an interest in the results of the survey that ORNL decided to sponsor a workshop to present its findings. Commonwealth Edison also agreed to be the "flagship" utility for the effort and announced the meeting on the Nuclear Network.

The workshop, entitled "Managing the Aging of BWR CRDMs", was the first meeting of its kind to be held solely for CRDM specialists. Altogether, 43 people attended the 2 1/2-day workshop: 26 utility personnel (from 21 BWR plants), 14 commercial representatives (from 9 different companies), and 3 staff persons from ORNL. In addition to the ORNL researchers, there were speakers from four utilities and six commercial companies. Demonstrations were conducted showing the use of new CRDM rebuilding tools and a quick identification procedure on a CRDM mock-up, and a tour was given of a mobile CRD training simulator. An invaluable result of the workshop was an aging and maintenance information exchange between utilities and related services companies that is likely to continue for many years. Utility attendees were also furnished with a directory of US BWR CRD engineers and CRD commercial services personnel so that the dialogue could easily be maintained.

Appendix A contains a copy of the eight-page CRDM Aging Questionnaire that was returned by 73% of the US BWR plant sites (representing 26 units). Not all of the questions were completed by the CRD personnel, primarily because several of the plant sites were too new to respond to some of the more "historical" questions concerning aging and degradation. Regrettably, there were six plant sites containing units with 15 or more years of service that did not respond to the questionnaire. Nevertheless, of the units submitting information to the survey, the average operating age was 10 years and ranged from 1 to 21 years of commercial service. The following sections contain an evaluation of the information these plants submitted to this research effort.

4.2 General Information

For the plants that provided data to the aging questionnaire, the CRD engineer had an average of 3.9 years of experience (Fig. 4.1). Because the personnel turnover in this position has created a limited experience base, the continuity of long-term maintenance goals for the CRD system may be disrupted. For most utilities, this individual has this job for two outages, where most of the "hands on" experience is obtained, and then is transferred to another position. Because CRDM maintenance is labor intensive, lengthy experience and training of CRDM maintenance staff can positively contribute to the anticipated maintenance life of a CRDM.

Nearly 43% of the CRDMs (1295) in the survey are the model C drive, closely followed by 29% model B drives (885), with the remainder comprising models A, D, E, and F (Fig. 4.2). The model A, B, and C drives were original equipment in BWR/2, 3, 4, and 5 plants, and the model D drives were installed in the BWR/6 plants. Model D, E, and F drives all have the improved design (including later model HCUs) that contributed to faster scram times, as shown in Fig. 4.3. Many of the earlier model drives had been upgraded with components that underwent major design enhancements, such as the BWR/6-style cooling-water orifice, uncoupling rod, and cast 304L stainless steel cylinder, tube, and flange assemblies (to mitigate IGSCC). For the questionnaire, the majority of the age of the currently installed CRDMs was 5 years or less (~51%), followed next by drives between 6 and 10 years old (~41%). These numbers illustrate the dominance of the younger, larger plants who responded to the survey (Fig. 4.4).

Among the 18 units who answered the question, there are 420 spare CRDMs for an average of 23 spares per unit. When a utility must refurbish a number of CRDMs greater than the number of spares available on site, then some of the CRDMs that were pulled must be rebuilt, tested, and reinstalled during the outage. This direct-path outage work can result in spare parts problems, particularly if a major component, such as the cylinder, tube, and flange assembly, exhibits collet housing cracking and cannot be returned to service. The majority of these spares are model C, but several of the BWRs had a combination of models in service because they are slowly replacing earlier designs with the newer ones as the

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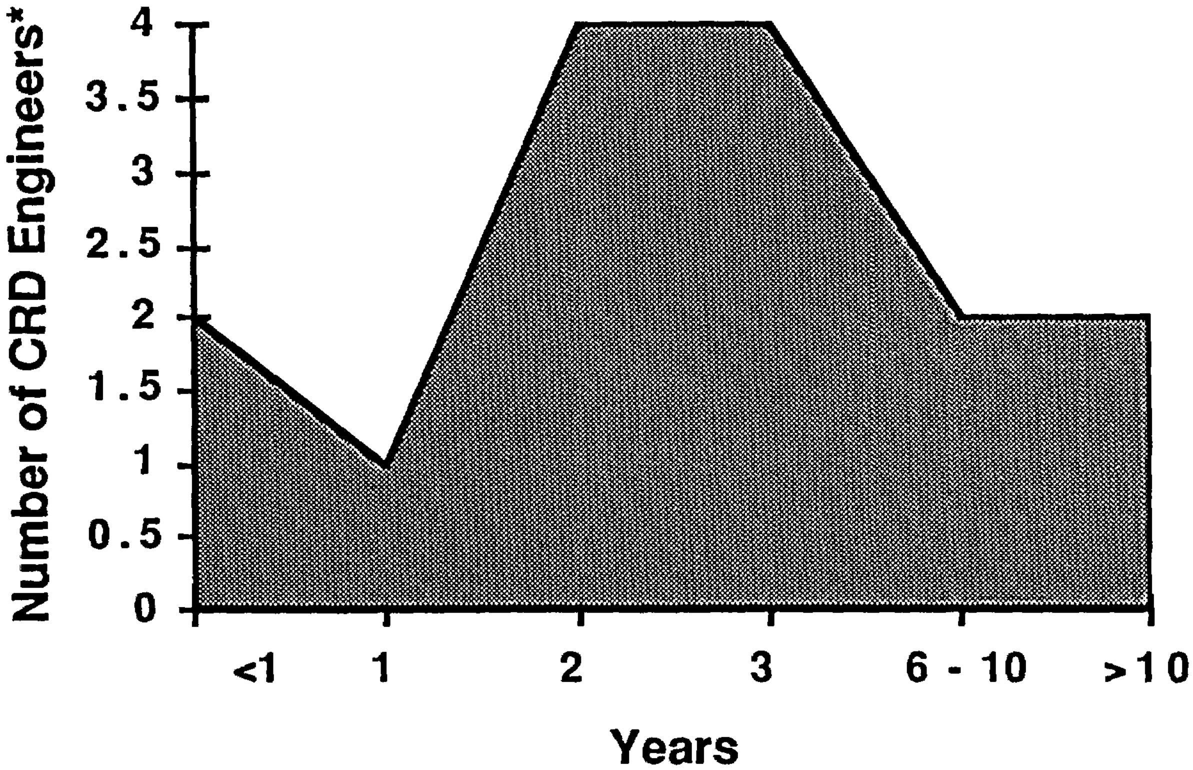

*Term applies to the primary contact person for this study. Average time in the position = 3.9 years. Average age of BWR unit reporting = 9 years.

Figure 4.1 CRD engineers: duration of experience in position.

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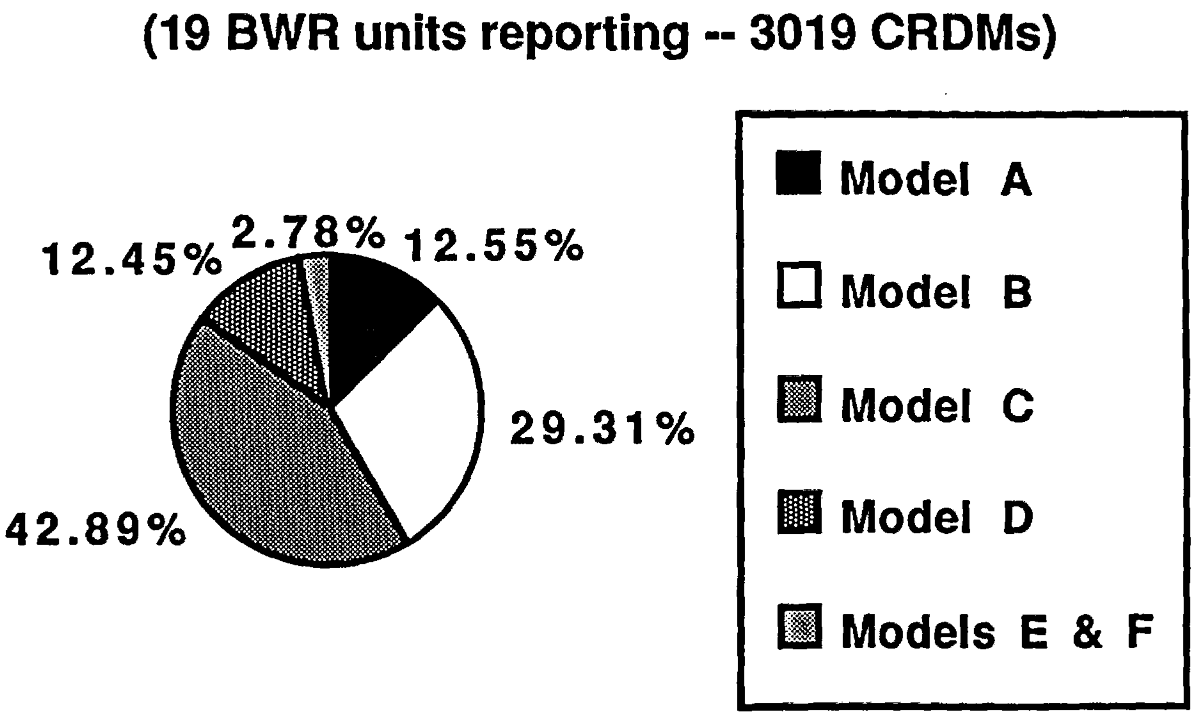

Figure 4.2 CRDM models reported in operation.

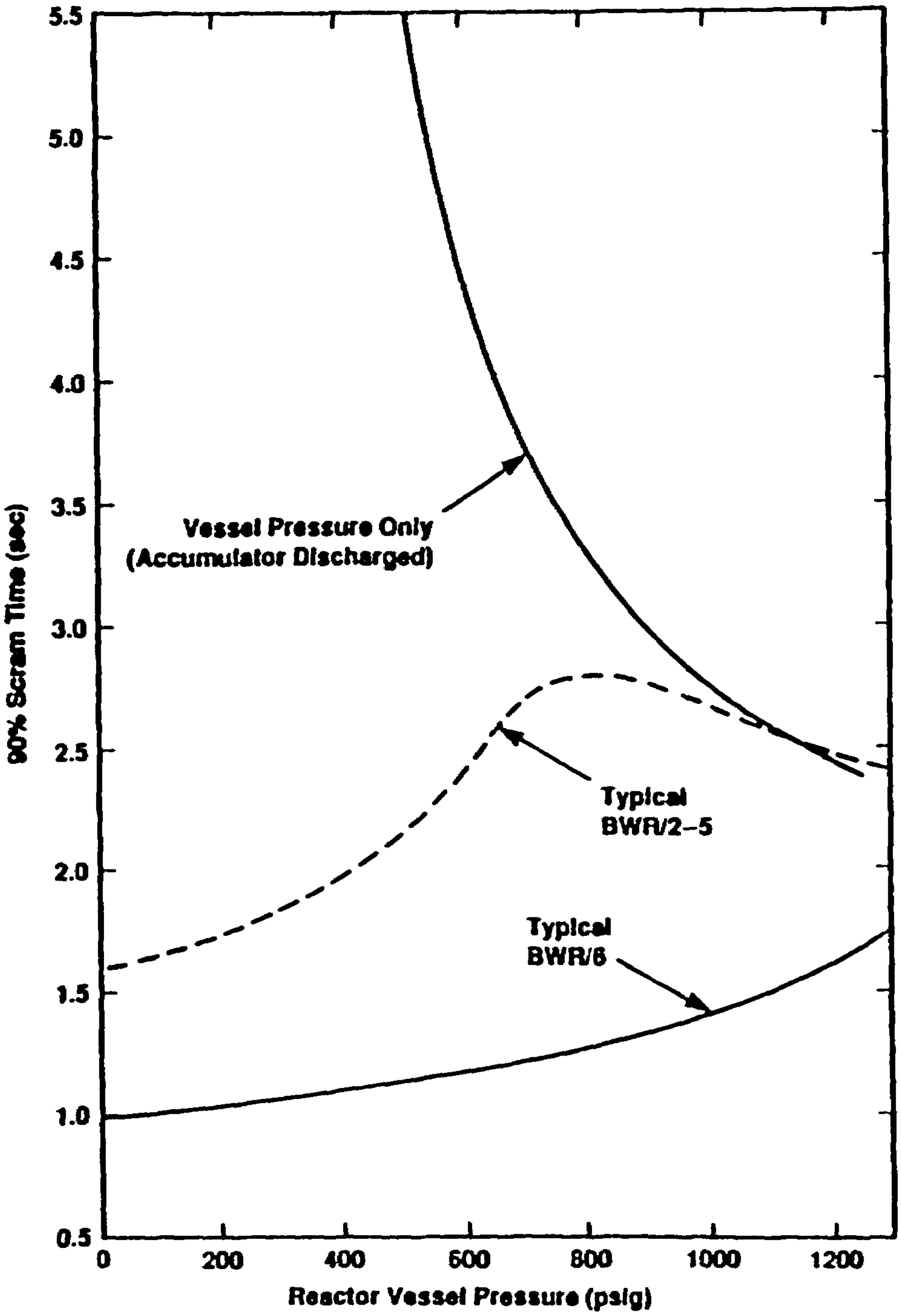

Figure 4.3 BWR CRDM scram times.

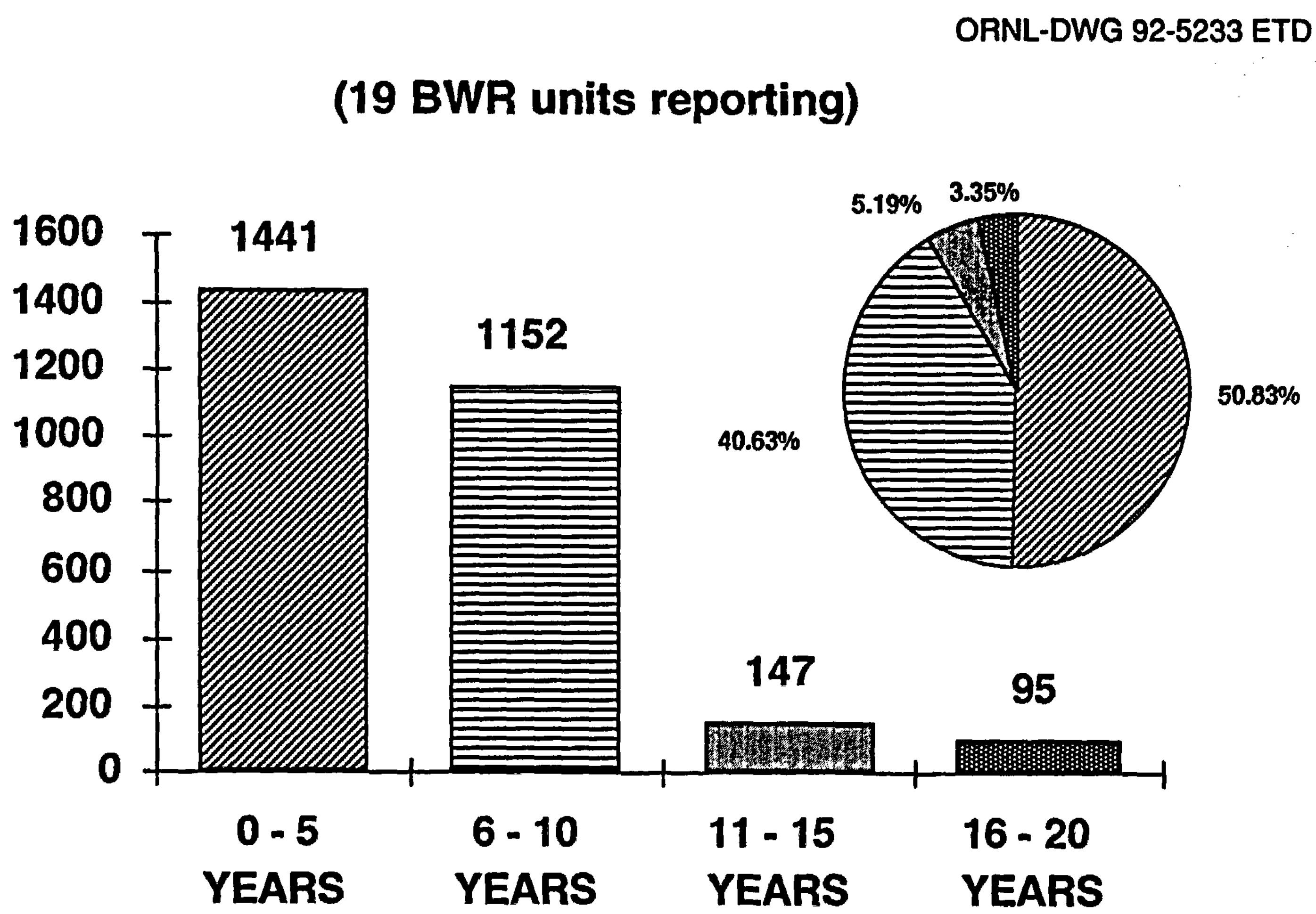

Figure 4.4 Age of installed CRDMs from reporting BWRs.

drives are changed out (Fig. 4.5). This practice was further demonstrated by the numbers and models of CRDMs that had been retired (Fig. 4.6).

The models of HCUs in service were more evenly distributed, as shown in Fig. 4.7, although more than 85% of these are associated with the slower scram times. Model 767E800 is the BWR-6 design, and the other three models are associated with BWR/2, 3, 4, and 5 plants. Even though some of these older BWR units have been replacing their CRDMs with the later design models, they cannot achieve faster scram times with them. The BWR/6 CRD system design also has improved water and nitrogen scram accumulators on the HCU, as well as larger-diameter CRD system piping. Of the 17 plants responding to the question, only five of them had entire spare HCUs in their inventories. The components on the HCU are easily exchanged; from all the plants surveyed, only one HCU has been reported being entirely changed out.

4.3 CRDM Storage Methods

The 15-ft-long, 450-lb CRDM can be a challenge to store. Inadequate storage support has been blamed for a few observed cases of CRDM "sagging" that were confirmed by performing runout measurements along the length of the drive.[19] This sag is not a relaxation of the metal over a period of time but an induced plastic deformation caused by improper storage methods and/or mishandling. Utilities store CRDMs horizontally in customized shielded vaults, specially designed racks, and sometimes in their original shipping crates. Most plants reported that the storage scenarios were in humidity-controlled, open environments. The flange ends of the CRDMs are sleeved in vapor-tight, plastic covers, and usually packaged with dessicant.

CRDM components can be damaged by laying drives on the floor with only the collet housing and the flange end supporting the weight. CRDMs should not be stacked on top of each other, separated by wooden blocks; this 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 and places a moment on the collet housing, as shown in Fig. 4.8. Improper storage techniques can deform the drive and cause a misalignment of the internal tubes, which can result in abnormal rubbing and surface wear. Figure 4.9 shows a surface rub on an index tube that was attributed to misalignment. CRDMs should be stored in racks or vaults with a minimum of two points of support located 24 in. from the flange end and 54 in. from the spud end (Fig. 4.10). There are also storage rack designs that provide three points of support.

Occasionally, CRDMs are stored wet in air for more than 28 days before they can be rebuilt, probably due to strained outage schedules. The CRDM's nitrided surfaces (includes the index and piston tubes) are particularly susceptable to corrosion when stored wet or in high humidity environments. Figure 4.11 and 4.12 illustrate corrosion activity on the notch of an index tube and pitting corrosion occurring along the length of a piston tube. This corrosion also makes it more difficult to disassemble the CRDM for rebuilding. CRDM components can be inadvertently damaged during a difficult disassembly process from mishandling. Two utilities are currently employing a long-term storage technique, which places its "hot" CRDMs in a 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 12 to 18 months in storage, it is anticipated 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 deterioration.

Because of nitride surface corrosion, rebuilt CRDMs should always be stored as dry as possible. Hair dryers have been used to try to remove moisture from the many channels in the flange end of the CRDM (see Fig. 4.13). Most utilities store CRDMs with dessicants but did not indicate if they were regularly changed out. Dessicants have time-dependent absorption rates. Many commercial varieties change color as they entrap moisture, and some brands can be reused. Military armament storage sites are known to change out dessicants on a monthly schedule. Utilities should evaluate the effectiveness of the humidity control of their CRDMs in storage, implement activities that will promote a drier localized environment, and institute a dessicant changeout schedule if one does not exist.

4.4 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 can vary the rate and effects of CRDM aging, the historical recommended maintenance interval of a CRDM has been 10 years. When asked if their facility had a regular practice of changing out a minimum percentage of CRDMs during each outage, nine plants reported that they indeed had minimum percentages, which varied from 10 to 25% per cycle, the average being 16%. These nine plants also indicated they were trying to adhere to a long-term maintenance goal of 100% of all CRDMs rebuilt for every 10 years of operation. One plant commented that they only rebuilt a number of CRDMs equal to the number of spares they had. Another facility stated that it could not rebuild more than 24 CRDMs per outage because of the space limitations in the rebuilding and staging areas. Those utilities having shorter fuel cycles had lower rebuild percentages than those with longer fuel cycles. When asked in the questionnaire if time was the only consideration in selecting CRDMs for changeout, one station reported that drives should be changed every 10 to 15 years for

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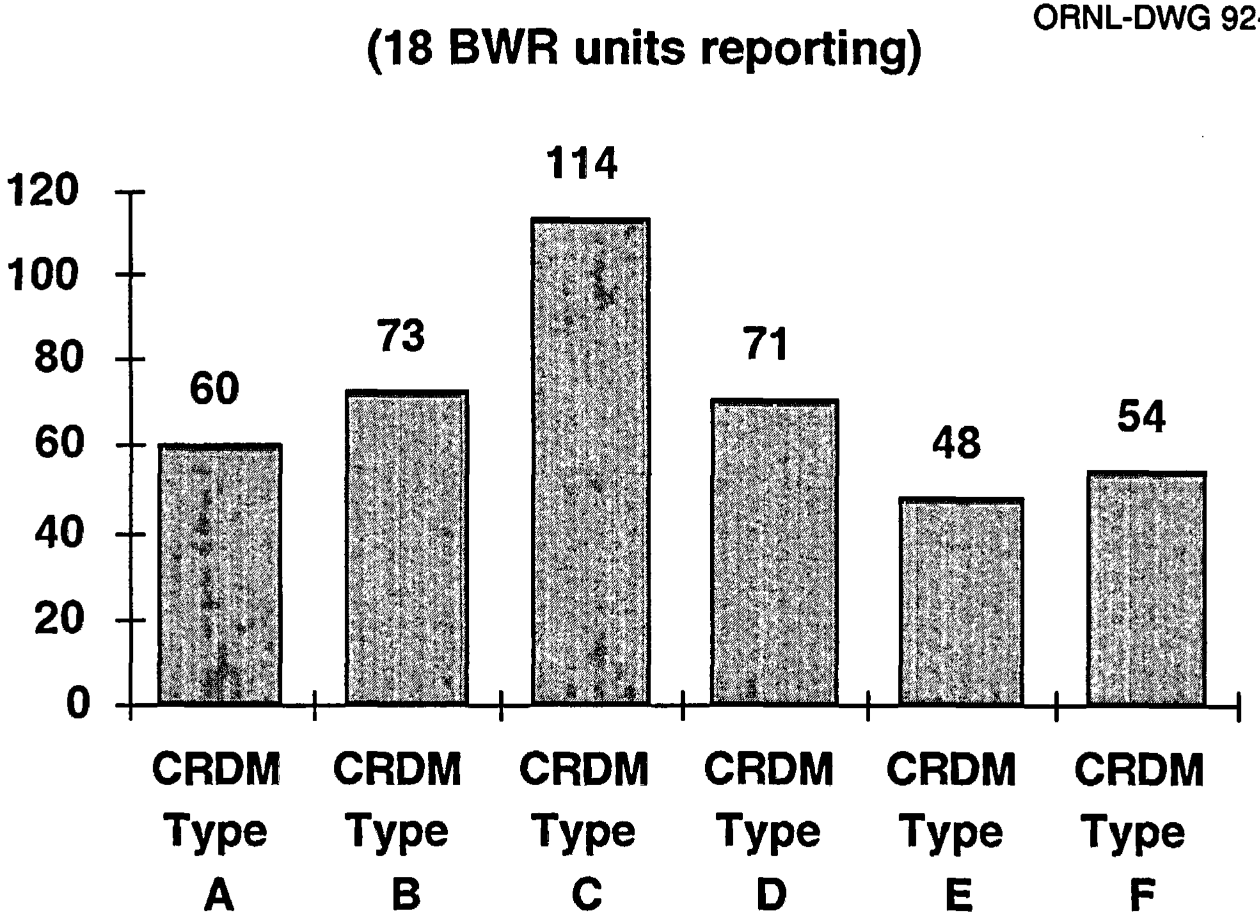

Figure 4.5 CRDM spare inventory reported by model.

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(18 BWR units reporting)

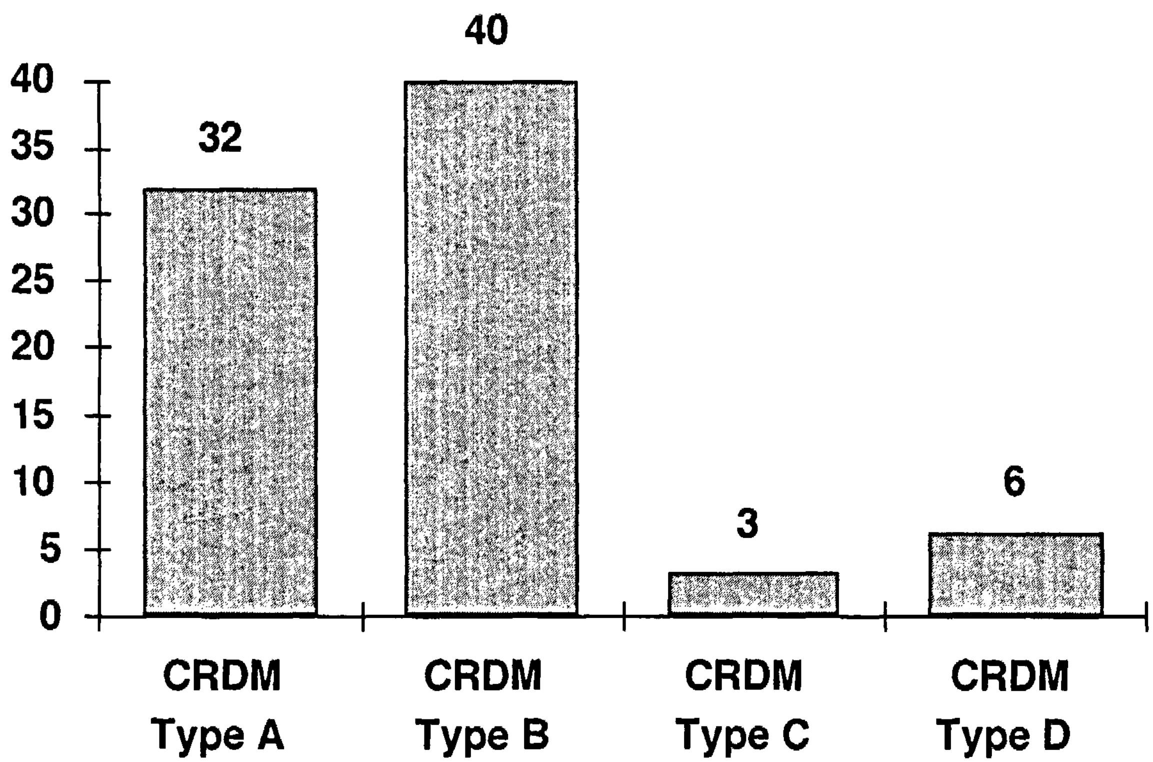

Figure 4.6 Retired CRDMs reported by model.

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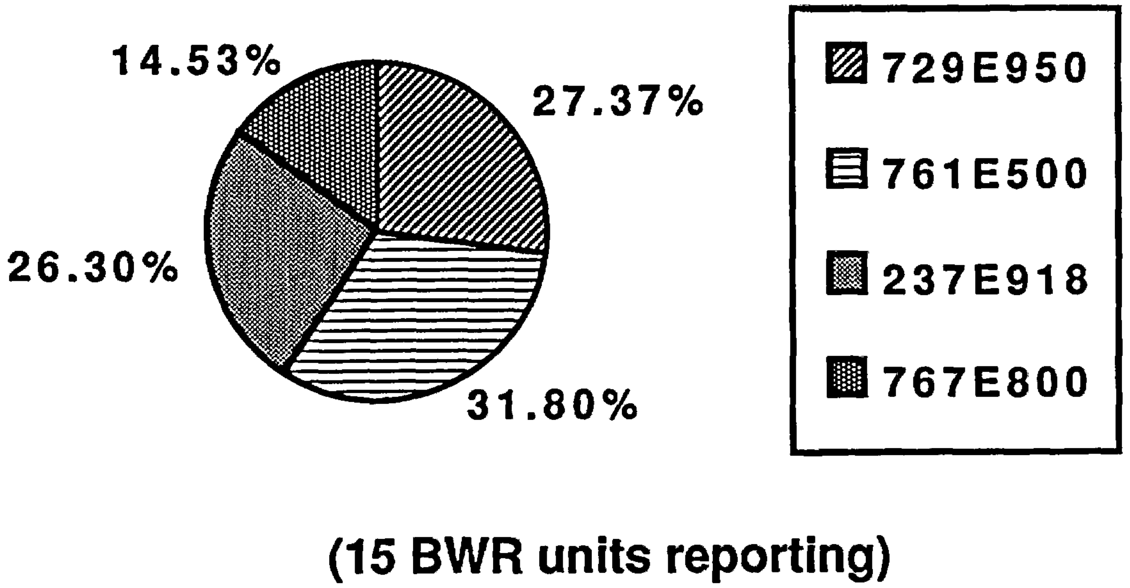

Figure 4.7 HCU models reported in operation.

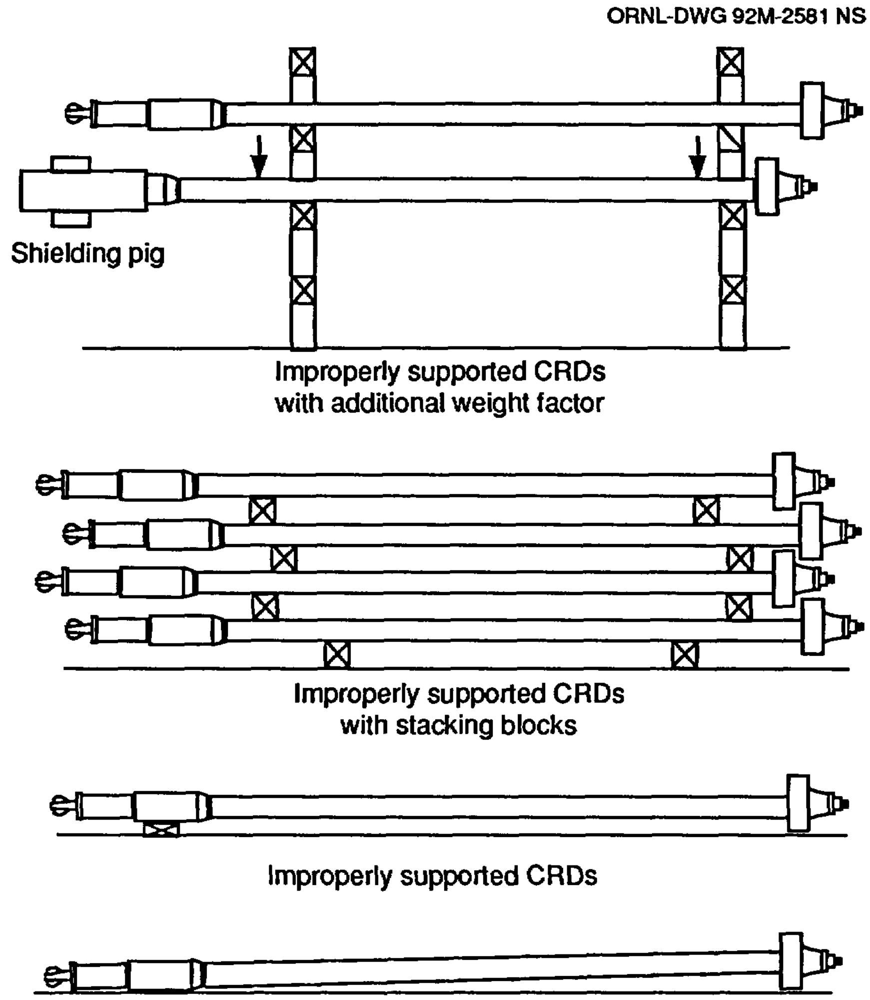

Figure 4.8 Improper CRDM storage scenarios.[19]

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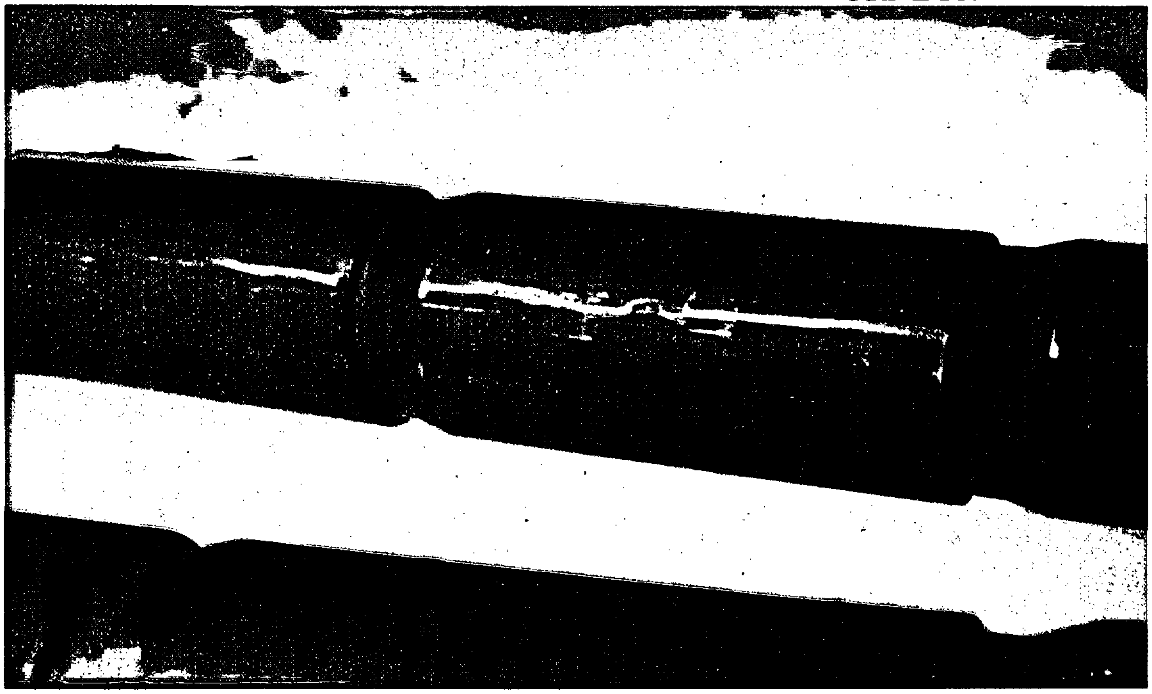

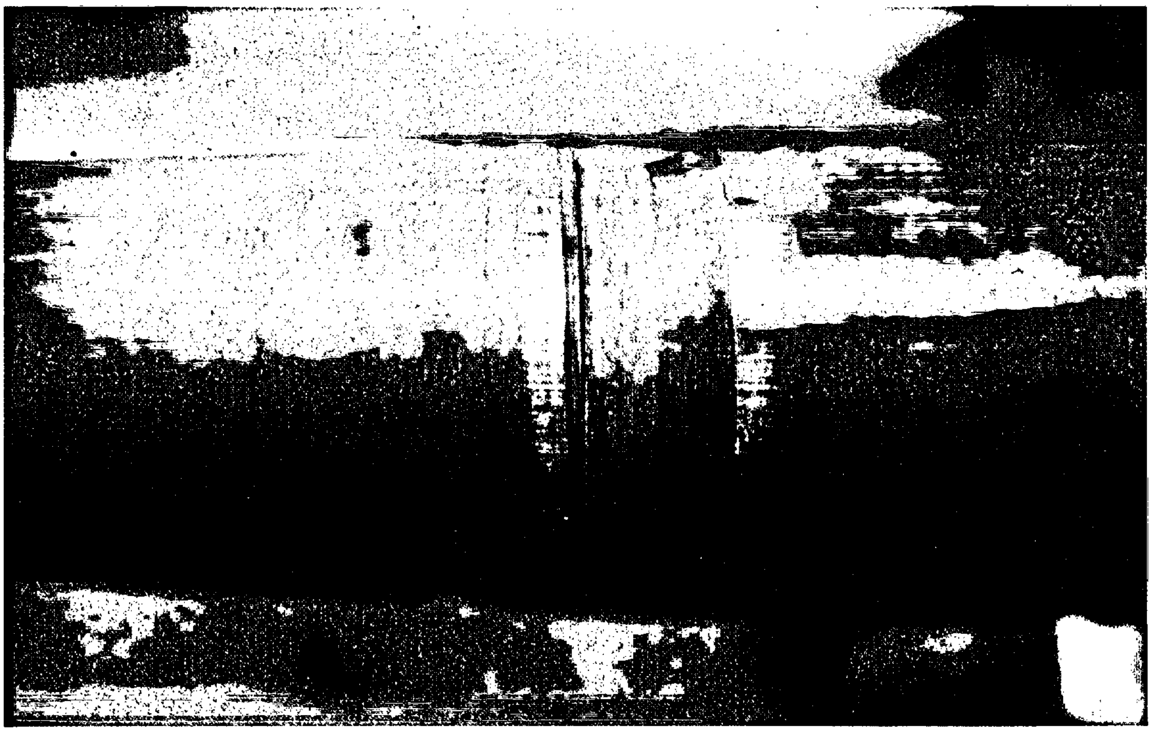

Figure 4.9 CRDM index tube surface rub attributed to misalignment.

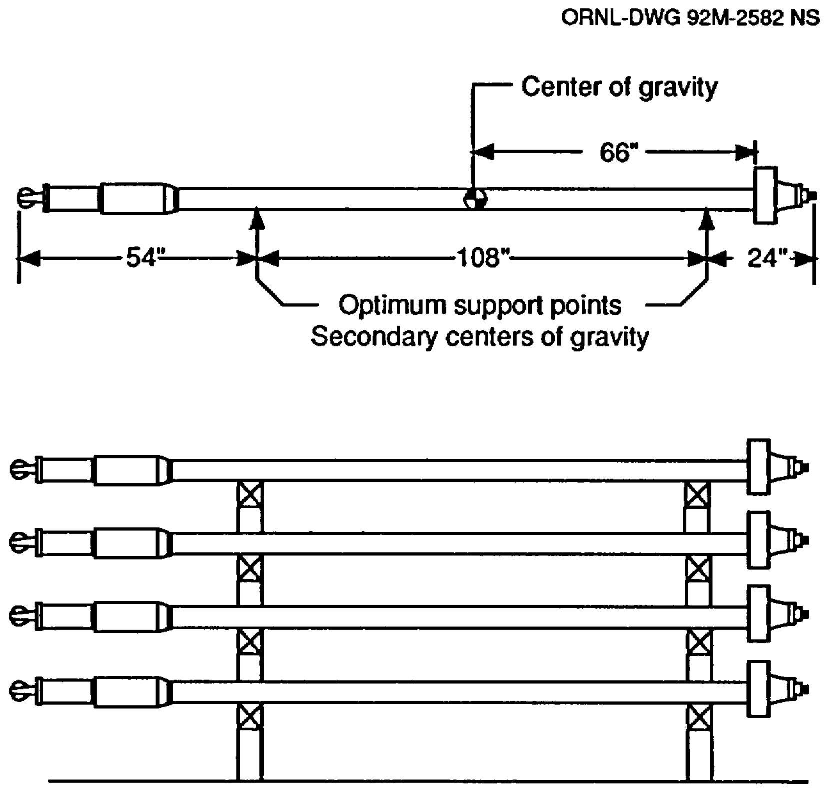

Figure 4.10 Optimum storage arrangement for CRDMs.[19]

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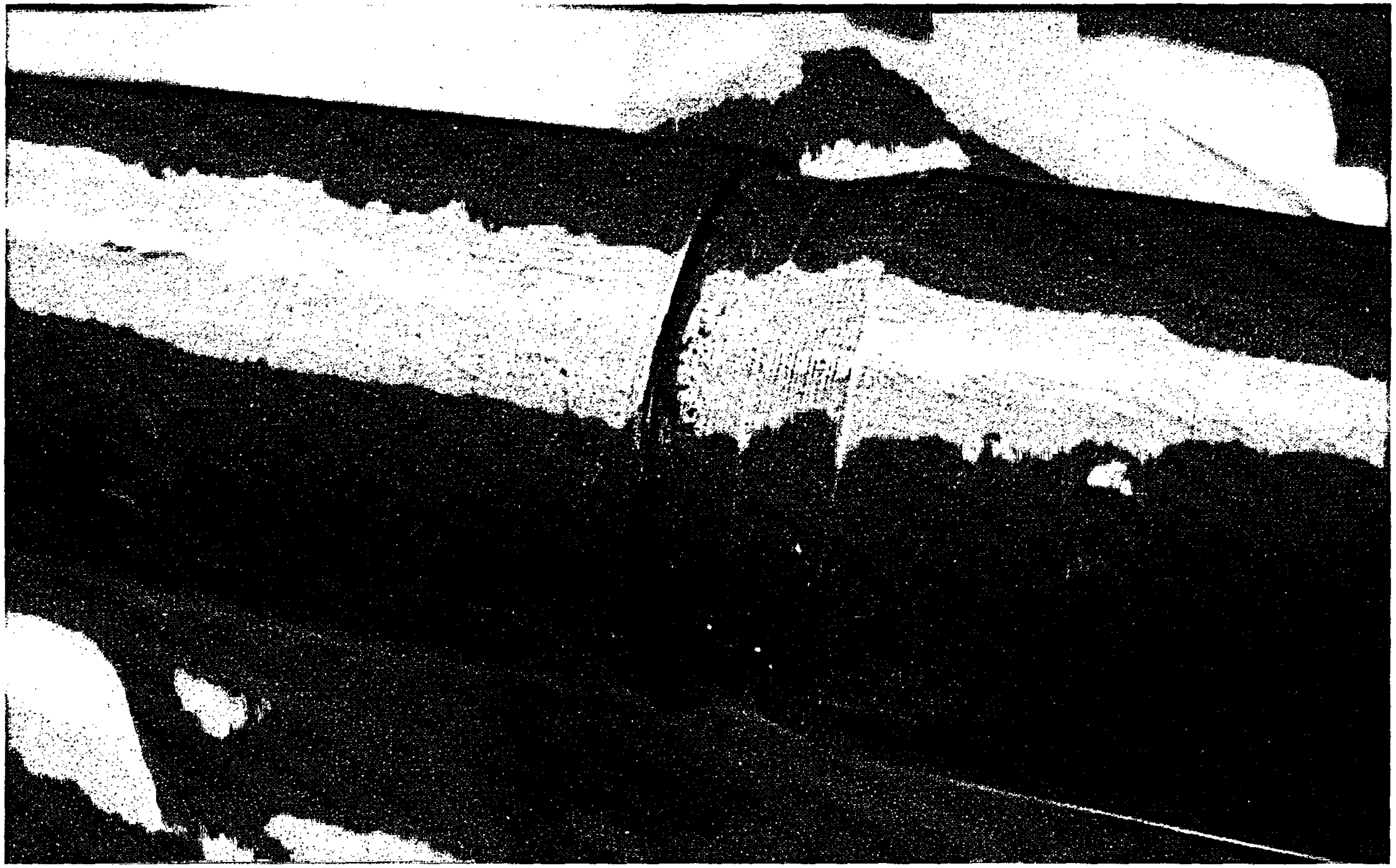

Figure 4.11 Corrosion occurring at index tube notch.

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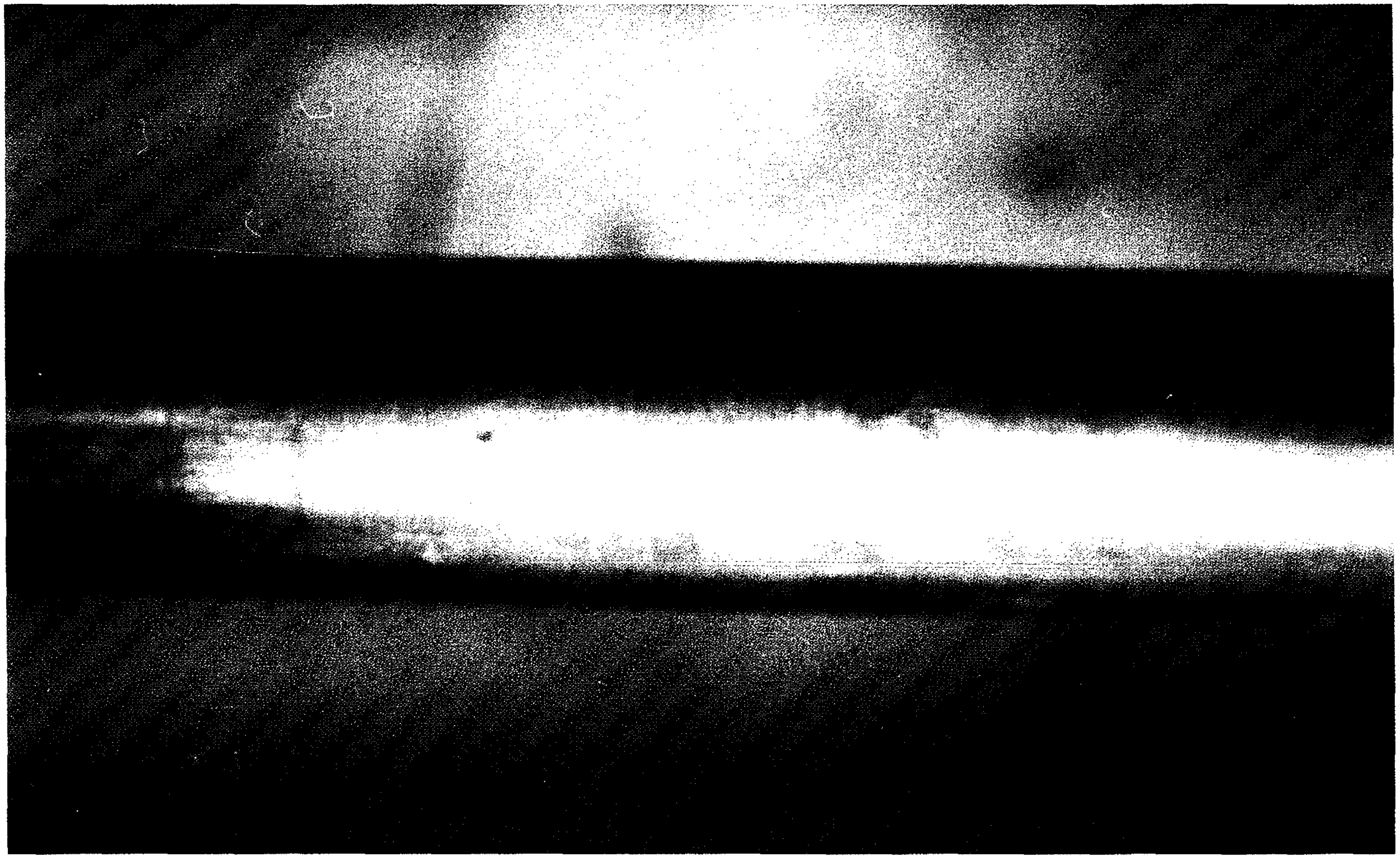

Figure 4.12 Pitting corrosion occurring along the length of a piston tube.

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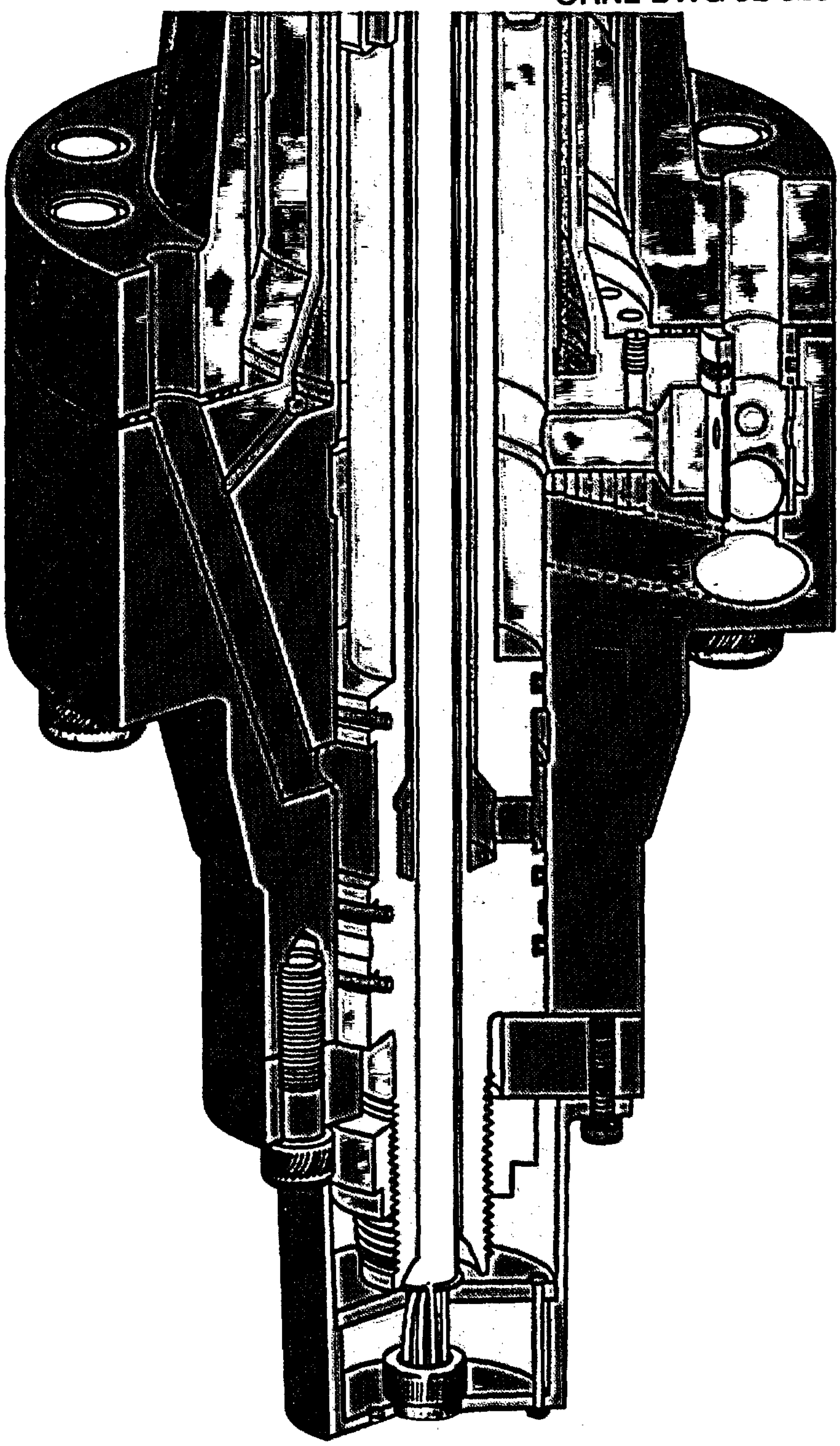

Figure 4.13 Sectioned CRDM flange end.*

**Figure 4.13 provided courtesy of General Electric Nuclear Energy GEZ-4382A* peripheral locations and every 3 to 5 years for central core locations.

Each plant was asked to describe its selection criteria in choosing CRDMs for changeout. Figure 4.14 shows a comparison of individual CRDM selection priorities. Some plants listed several criteria, and others only a few. The most universally used indicator of CRDM performance is "withdrawal" stall flow. This is the amount of water which slips past the collet piston seal rings and the Graphitar stop piston seals in the drive when a withdrawal signal is continuously applied to a fully withdrawn CRDM. A fewer number of plants prefer measurements of the "insert" stall flow (obtained when an insert signal is continuously applied to a fully inserted CRDM during plant shutdown conditions), but the numbers of comparison used throughout the utility industry are very similar: stall flow values higher than 3.5 to 5.0 gpm were indicative of seal wear in the CRDMs (e.g., seal breakage and/or seals fixed and lodged in seal grooves). Other indicators used to select CRDMs for changeout were operational problems (hard to move, requiring increased drive pressures and/or constant HCU valve reconfigurations), high CRDM temperatures [>120°C (>250°F)] along the length of travel, degraded scram times, notching trouble, friction tests (only performed during outages, usually after fuel reloading), and elapsed time since last rebuild.

The questionnaire asked each plant to submit its CRDM changeout history to evaluate if CRDMs simultaneously degraded over time throughout the reactor core. The premise being tested was that CRDMs located toward the center of the core tend to degrade quicker than those located near or at the periphery since drives toward the center (1) undergo more feet of travel in their service life because of higher contributions of their respective CRAs to power shaping, and (2) higher radiation fluxes at the center (as compared to the periphery) might shorten the service life of these CRDMs. The figures provided in Appendix B depict the changeout histories obtained from 21 BWR units. The colors from deep blue to fuchsia respectively indicate a low to high frequency of CRDM changeout for the core location. Only four of these plants had to have the drives changed out five or more times in the same core location, but the overall data suggest that centrally located drives undergo more maintenance than peripheral drives. Although the cause for dissimilar maintenance intervals is uncertain, the lower vessel head geometry probably has a greater influence on the aging rates of CRDMs than the other two scenarios described. Due to the geometry of the lower vessel head, the centrally located drives have more surface area exposed to the inside of the reactor than peripheral drives and may experience more prolonged, higher temperatures along this exposed length (Fig. 4.15). Higher temperatures are known to degrade the long-term performance of the CRDM Graphitar seals (the primary cause of CRDM maintenance). After reviewing the changeout histories of the units presented in Appendix B, attendees at the workshop explained that not all CRDMs that which had been changed out exhibited operational problems, and that, frequently, operational problems had been erroneously attributed to CRDMs that should actually have been directed at the companion HCU.

The selection of CRDMs to be changed out and 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 operational characteristics that would place suspect CRDM into the two categories listed in Tables 4.1 and 4.2. Attendees also stated that when CRDMs began to display operational problems, several of the anomalies listed in Tables 4.1 and 4.2 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 tables and might also include those drives that have a continuous service time of 10 years. Most CRDM operational problems, however, usually have a long lead time and do not suddenly occur without exhibiting characteristic warning signals.

Table 4.1. 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 and "02" scrams
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 cm3/s (5.0 gpm)

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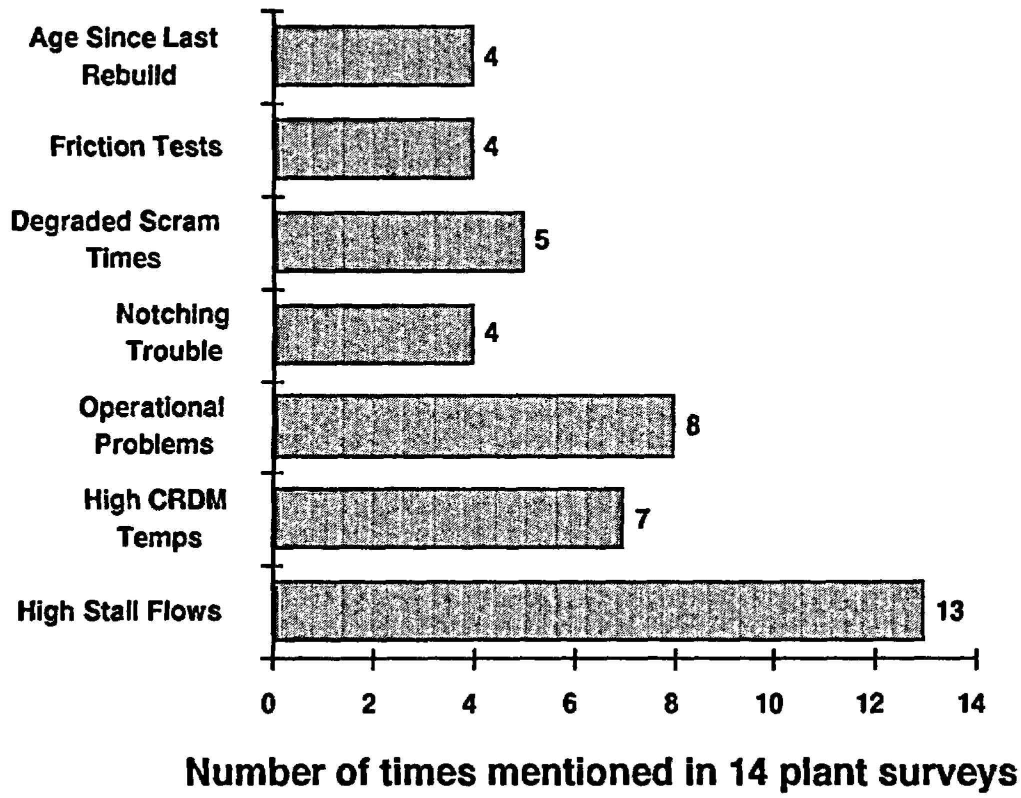

Figure 4.14 Comparison of utility CRDM changeout selection criteria.

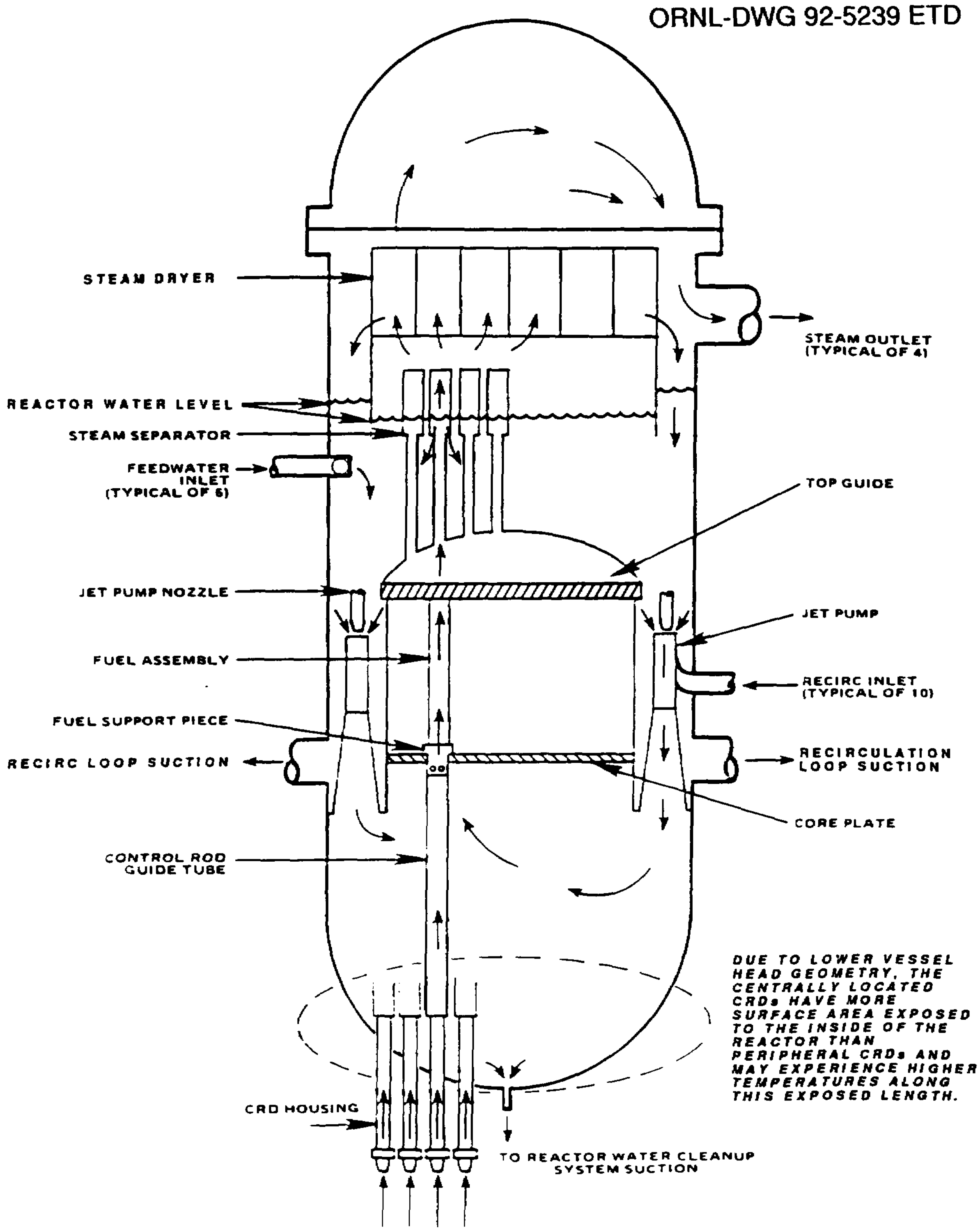

Figure 4.15 Relationship of BWR lower vessel head geometry to CRDM aging.

Table 4.2. Priority 2 CRDMs — Should be exchanged or rebuilt

1. Consistently high temperatures [>177C (350°F)] throughout length of travel
2. Unacceptable withdrawal or insertion times that are unrelated to valve configurations on the HCU
3. Repeated episodes of "double-notching" when moving, or CRDMs that continually require increased drive pressures to move (unrelated to HCU valve configurations)
4. CRDMs with high or abnormal friction traces not attributable to misalignment with fuel assemblies

4.5 CRDM and HCU Degradation

4.5.1 Ranking of Component Degradation

Utilities were asked to rank a list of selected CRDM and HCU components as a primary, occasional, or rare (negligible) contributor to operational problems. The list was developed from failure reports appearing in the NPRDS, GE SILs, and from expert recommendations. From this ranking, the system components that were considered primary contributors to operational problems were the stop and drive piston seals, clogged inner filters, and stop piston bushings. When broadened to include those components considered an occasional contributor to system problems, the list became longer and agreed more with NPRDS results. Figure 4.16 contains the actual results of the rating survey, and Table 4.3 provides a list of those components (in descending order) of their contribution to problems. Components not considered to be a contributing operational problem by 25% or more of the utilities to be a were not included in the table.

Table 4.3. Component contributions to operational problems of CRD system

75%–100% Rating	50%–75% Rating
Worn stop piston seals	Worn or damaged collet fingers
Worn drive piston seals	Worn collet piston
	Worn/damaged collet seal rings
25%–50% Rating	Worn check valve ball
CRDM rebuilding error	Worn drive piston bushings
CRDM installation error	Clogged cooling-water orifice
Clogged outer filter	Worn stop piston bushings
Crushed/flattened strainer	HCU manifold filter clogging
Worn spring washers	HCU water accumulator leakage
HCU isolation valves	
HCU directional control valves	
Collet housing deterioration	
Scram inlet and outlet valves	

4.5.2 CRDM Collet Housing Cracking

CRDM collet housing (or retainer tube) cracking is a type of IGSCC degradation for which every BWR plant should be inspecting in their CRDMs (using dye penetrant methods). GE issued SILs 136, 139 (with five supplements), and 148 on the phenomena, which reported cracks in the region of the flow holes, near the internal section change, and in the vicinity of the attachment weld (see Fig. 4.17). The cracking is generally shallow and occurs predominantly near the area where the tube wall changes thickness. The tube has a very low mechanical loading and the probability of complete failure (the circumferential separation of the CRDM) is very remote.[20] GE attributed this cracking to the thermal cycles occurring during hot scrams, followed by exposure to oxygenated CRD cooling water. The phenomena was first observed in the cylinder, tube, and flange assemblies fabricated from 304 stainless steel (CRDM models A, B, and C). GE changed the material to CF3 (cast 304L) stainless steel in the initial upgrade and subsequent CRDM models, but cracks were later found in two of the first "improved design" collet tubes.[21] General Electric has performed extensive, hot scram testing of all collet retainer tube designs. "The results clearly demonstrate that the lifetime of the drives in which cracking has been already initiated is related to the number of hot scram cycles imposed."[22] "A safety analysis has been conducted to consider the consequences of an inoperable CRD during plant operation. It has been concluded that the CRD collet retainer tube cracking . . . does not materially affect the safety analysis considerations for the CRD system . . ..The following conclusions may be realized from the test results:

1. Weekly surveillance testing (as required per plant technical specifications), when conducted with the reactor at operating pressure, is a valid test to determine collet retainer tube integrity.

2. Successful response of a CRD to a normal withdrawal signal at normal drive operating pressures (reactor pressure plus 250 psi) is a conclusive test of collet retainer tube integrity at all reactor operating conditions.

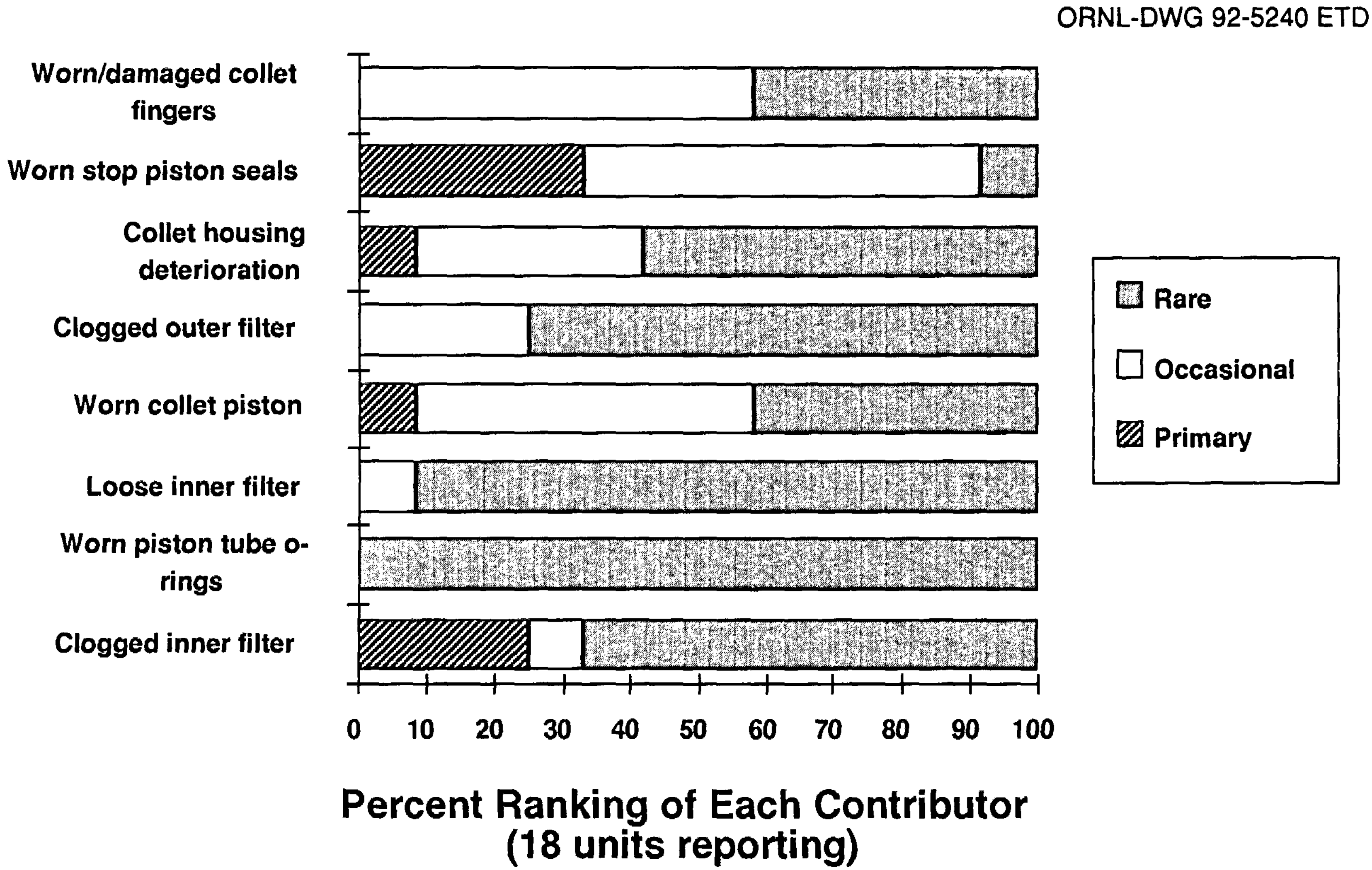

Figure 4.16 Component contributions to operational problems in the CRD system.

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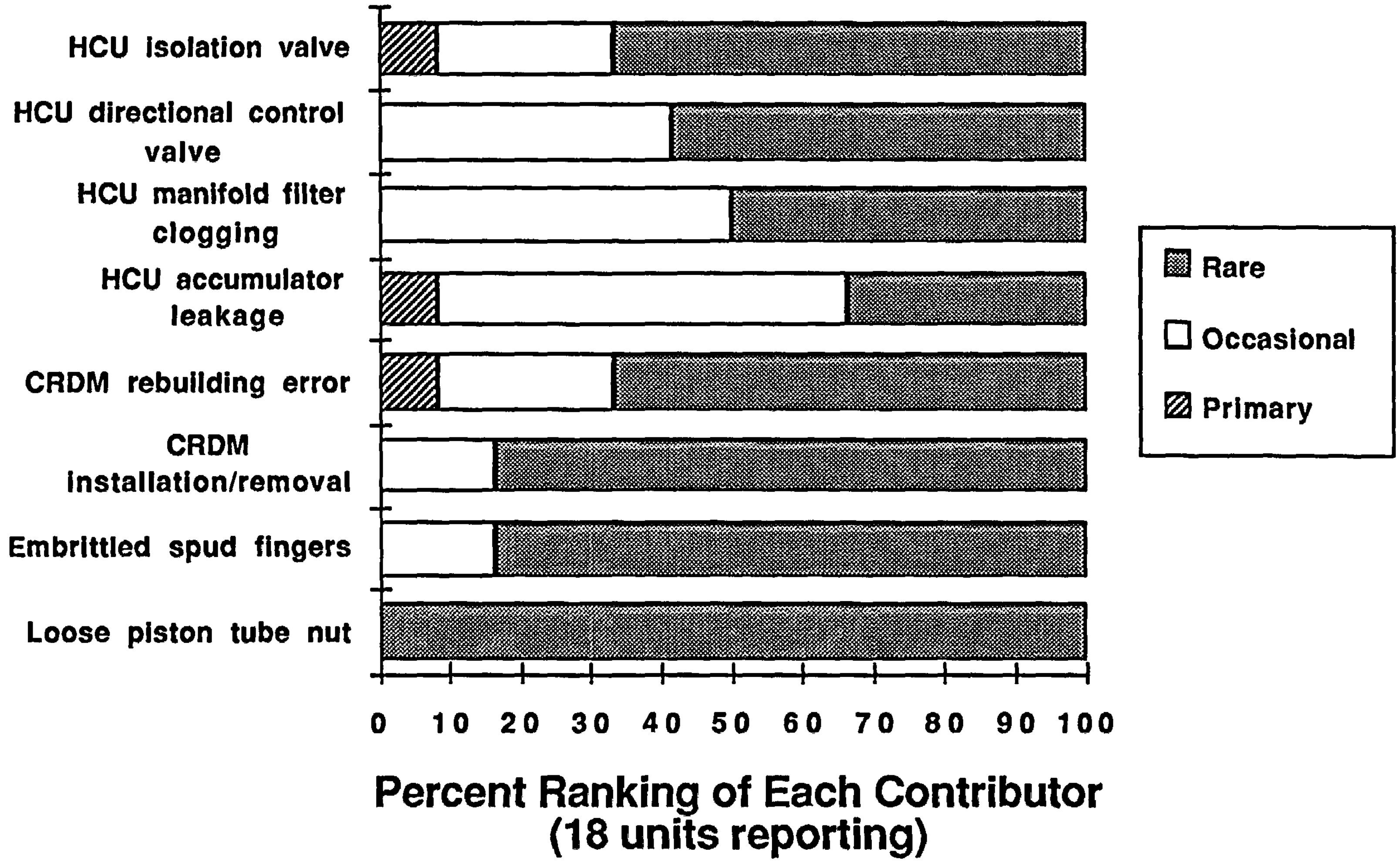

Figure 4.16 (continued)

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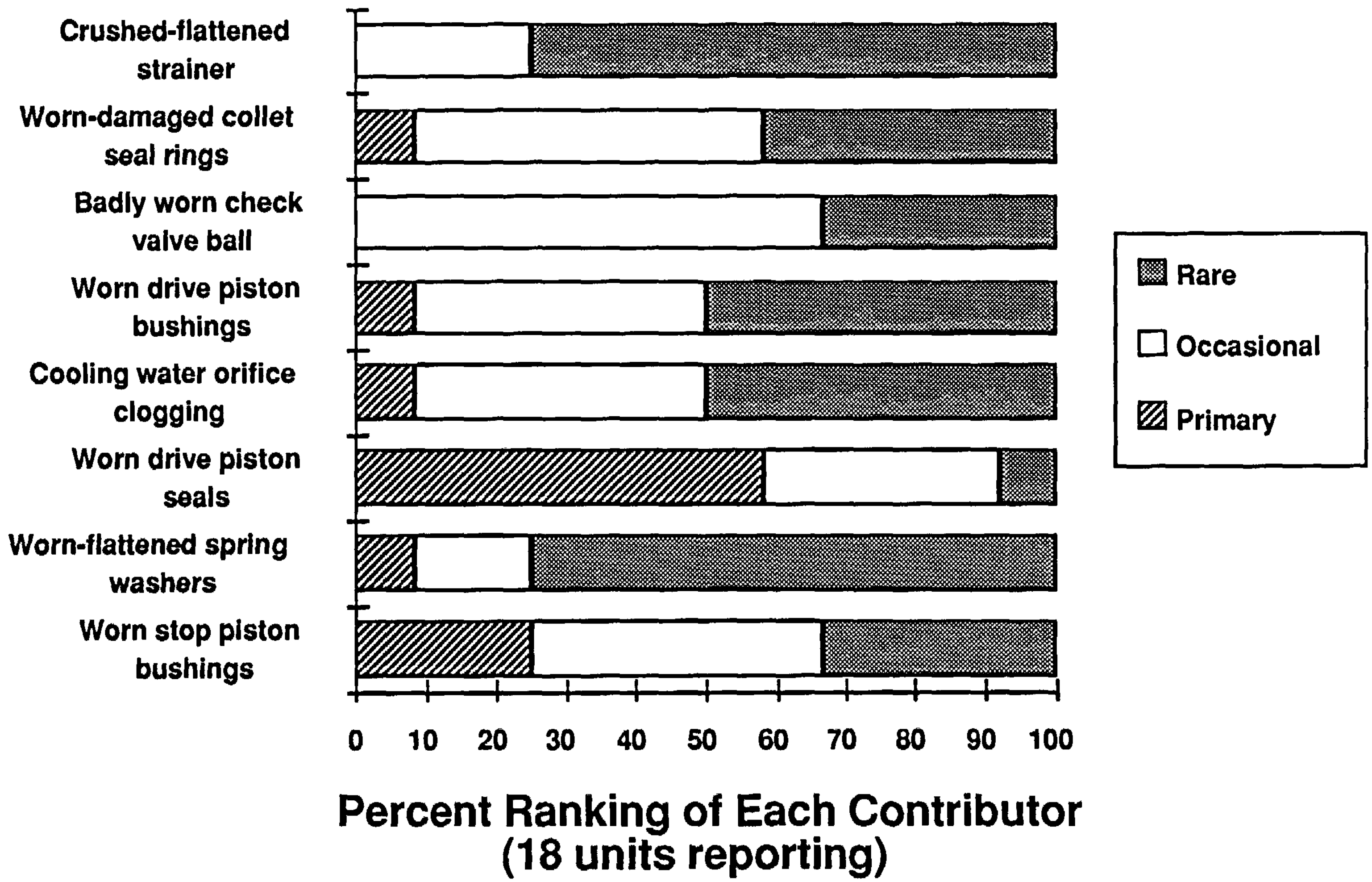

Figure 4.16 (continued)

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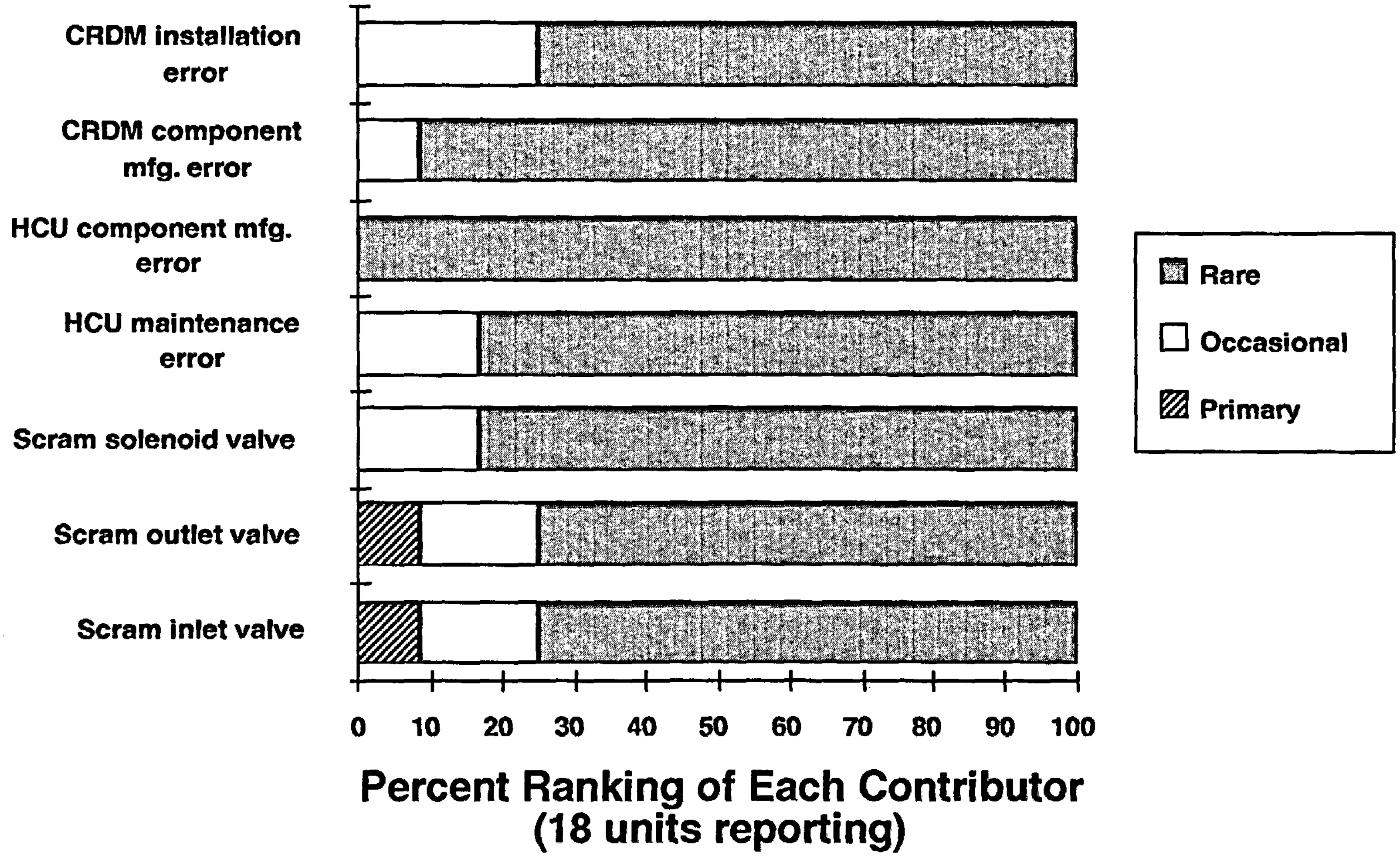

Figure 4.16 (continued)

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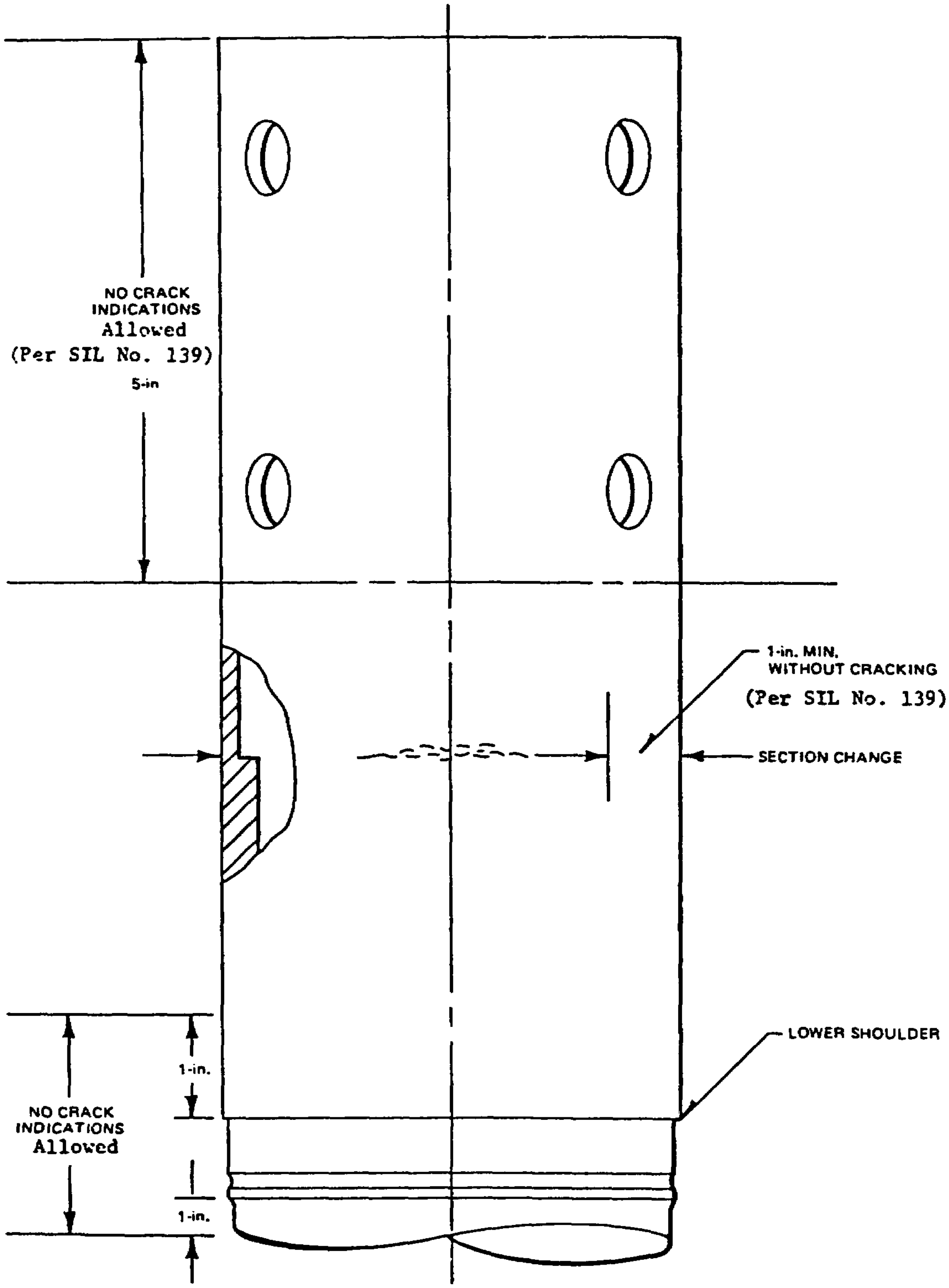

Figure 4.17 CRDM collet retainer tube crack indication restrictions.[20]

3. Successful response to an insert signal at cold, unpressurized reactor conditions is not a conclusive test of collet retainer tube integrity.

4. With the right combination of part displacements and a severed collet retainer tube, application of higher than normal withdrawal pressure can produce an unlatched drive in a cold, unpressurized reactor."[23]

One utility reported at the workshop that it had replaced 46% of its Model C cylinder, tube, and flange (CTF) assemblies because of collet housing cracking. In addition, a two-unit plant site reported in the questionnaire that 65 of its 274 Model A CTF assemblies required replacement due to collet housing cracking.

4.5.3 CRDM Cap Screw Corrosion Cracking

In May 1988, one BWR utility found corrosion cracking in 27% of its 1480 CRDM cap screws on one unit.[24] Circumferential cracking and corrosion pitting in the shank directly below the cap screw head were also observed at three other BWR plants. GE issued SILs 019 and 483 on this phenomenon, and stated that "the cause of cracking is a general corrosion cracking mechanism assisted by a crevice and discontinuity in the fillet region directly below the cap screw head. Crack growth is aggravated by manganese sulfide inclusions in the cap screw material."[25] GE recommended in SIL 483 that BWR owners "visually inspect all CRD cap screws for crack indications either during routine CRD maintenance or within the inspection intervals specified in ASME Section XI code, whichever was more frequent. A liquid penetrant or magnetic particle test should be performed on all suspect cap screws in accordance with ASME Section XI. Defective cap screws should be replaced with new ones."[25]

The cap screws are removed and reinstalled during normal CRDM changeout activities. They should be torqued to ~350 ft-lb during installation. However, there is a large variance between inspection practices among different utilities. During the changeout activities at one plant, the cap screws and washers are sent out in a bag attached to the "old" CRDM, and a bag of inspected and cleaned cap screws with new washers are sent in attached to the "new" CRDM. The necessary cleaning and detailed inspection of the old cap screws are performed later during rebuilding. At another plant, a contract employee informed ORNL research staff that he was given the task of cleaning and visually inspecting the cap screws as he sat underneath the reactor vessel while the changeout crew exchanged CRDMs. Furthermore, other contract employees who have performed CRDM maintenance at several different BWRs assert that there are not good controls on the amount of torque placed on these cap screws, even though limits appear in the procedures. One utility uses certified torque wrenches (calibrated and checked by the plant tool shop before and after the CRDM changeout job) to control the torques placed on these cap screws. To inhibit corrosion (as shown in Fig. 4.18), one plant dips the shanks of the bolts and the bolt heads in two coats of MCG-119 (a corrosive inhibitor) and gives the threads one coat of NIKAL. The low-halogen lubricant, "Nickel Never Seize," is also reported being used.

GE has developed and is distributing an improved CRDM cap screw that uses new materials designed to be resistant to the corrosion cracking phenomena observed at BWRs. ABB-Combustion Engineering is also introducing a new cap screw washer design that allows water drainage (shown in Fig. 4.19) and is currently used at the KKL Leibstadt station in Switzerland.

4.5.4 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 Fig. 4.20) 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.

4.5.5 Other Recurring CRDM Component Abnormalities

Utilities were asked to provide any information they could with regard to unusual yet repeating abnormalties observed in CRDM components replaced during rebuilding activities. These anomalies were openly discussed at the workshop to gain a perspective as to the cause of the problem, how widespread it might be, and actions that other BWRs were taking to solve it.

- *Collet Housing:* The outer seals are flexed, and extra care is needed to carefully install the seal rings into the housing cap. Sometimes, the collet assembly is only removed with great difficulty due to heat stress on the barrel of the collet housing. There were also two reports of "egg-shaped" collet housings.

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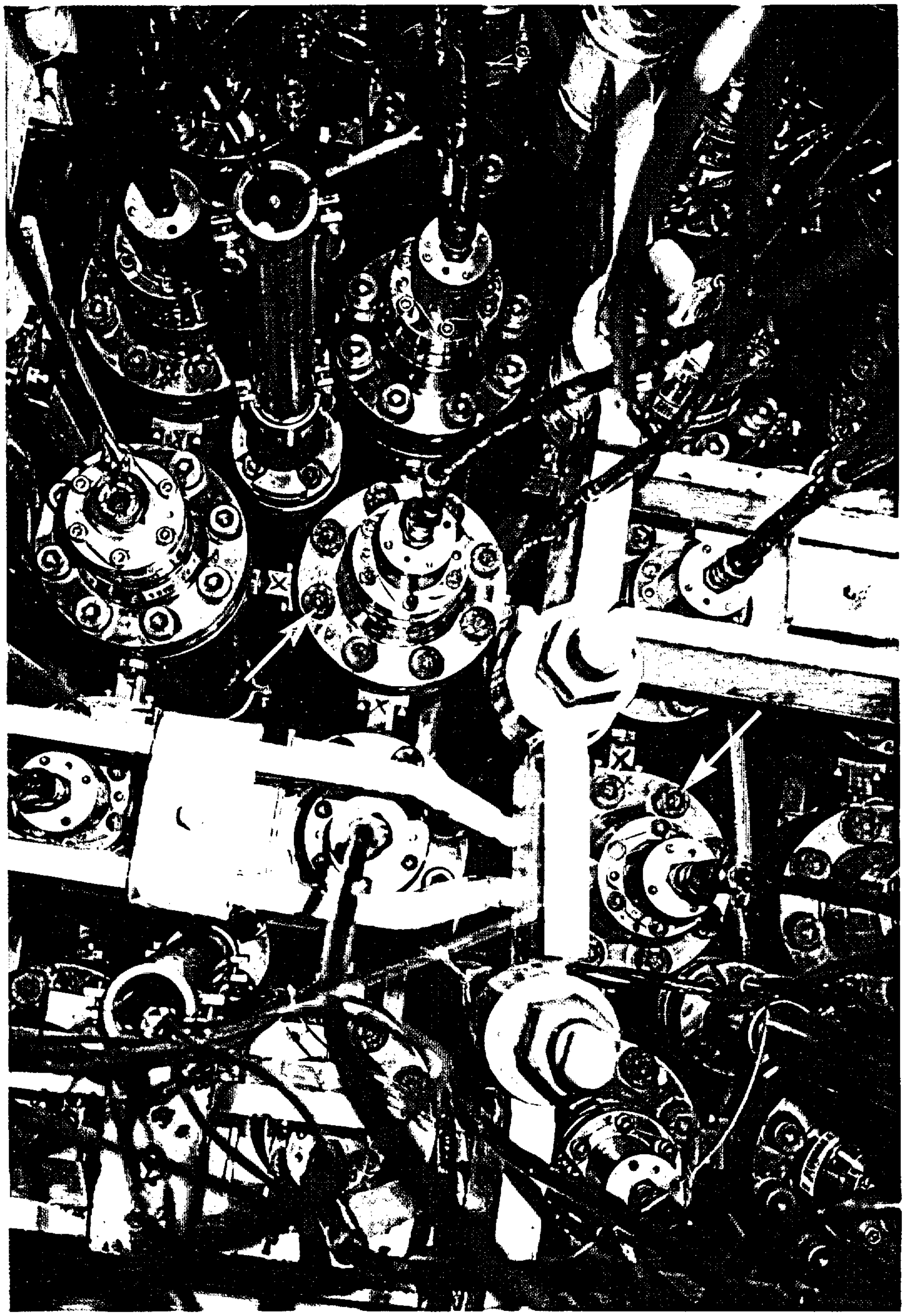

Figure 4.18 CRDM cap screw corrosion.

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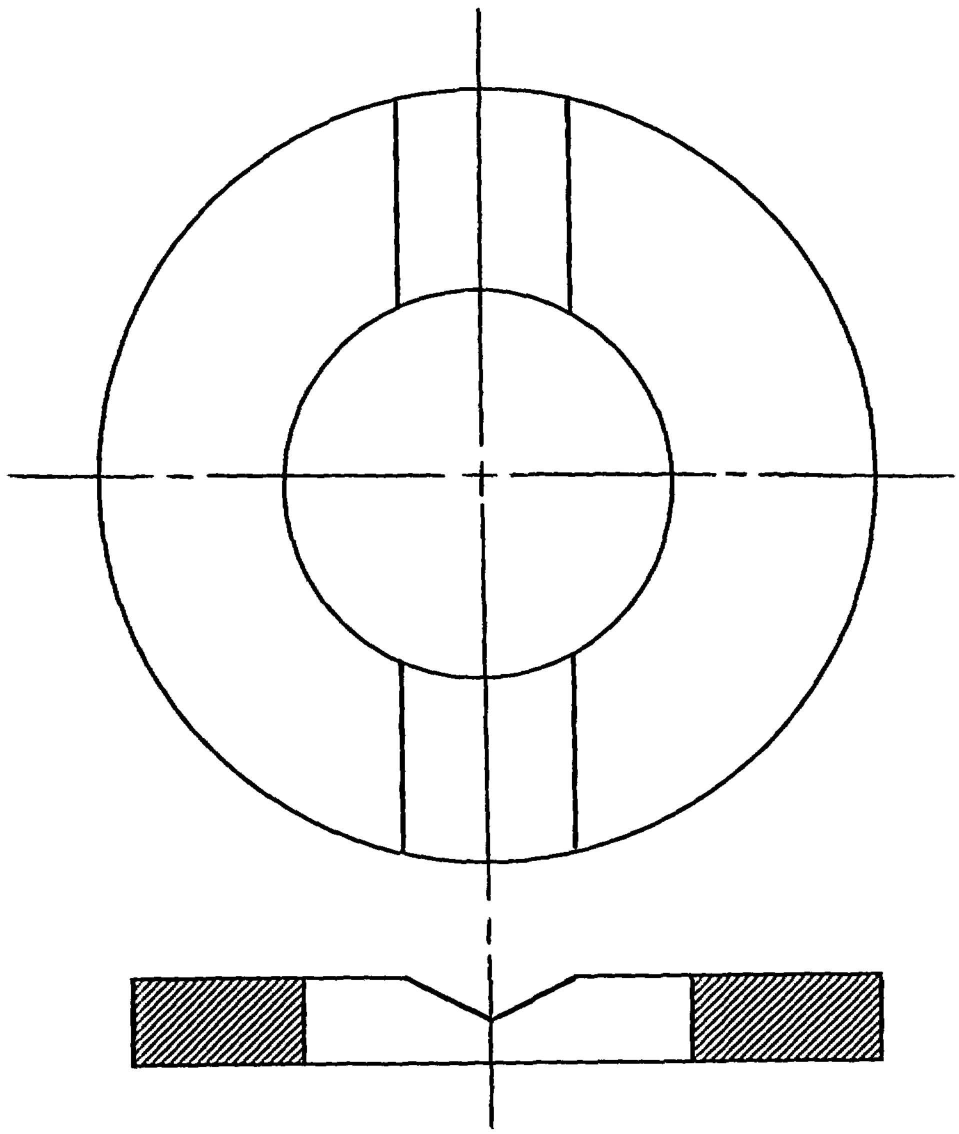

Figure 4.19 New CRDM cap screw washer design.*

**Figure 4.19 provided courtesy of ABB Combustion Engineering Nuclear Power, Inc.*

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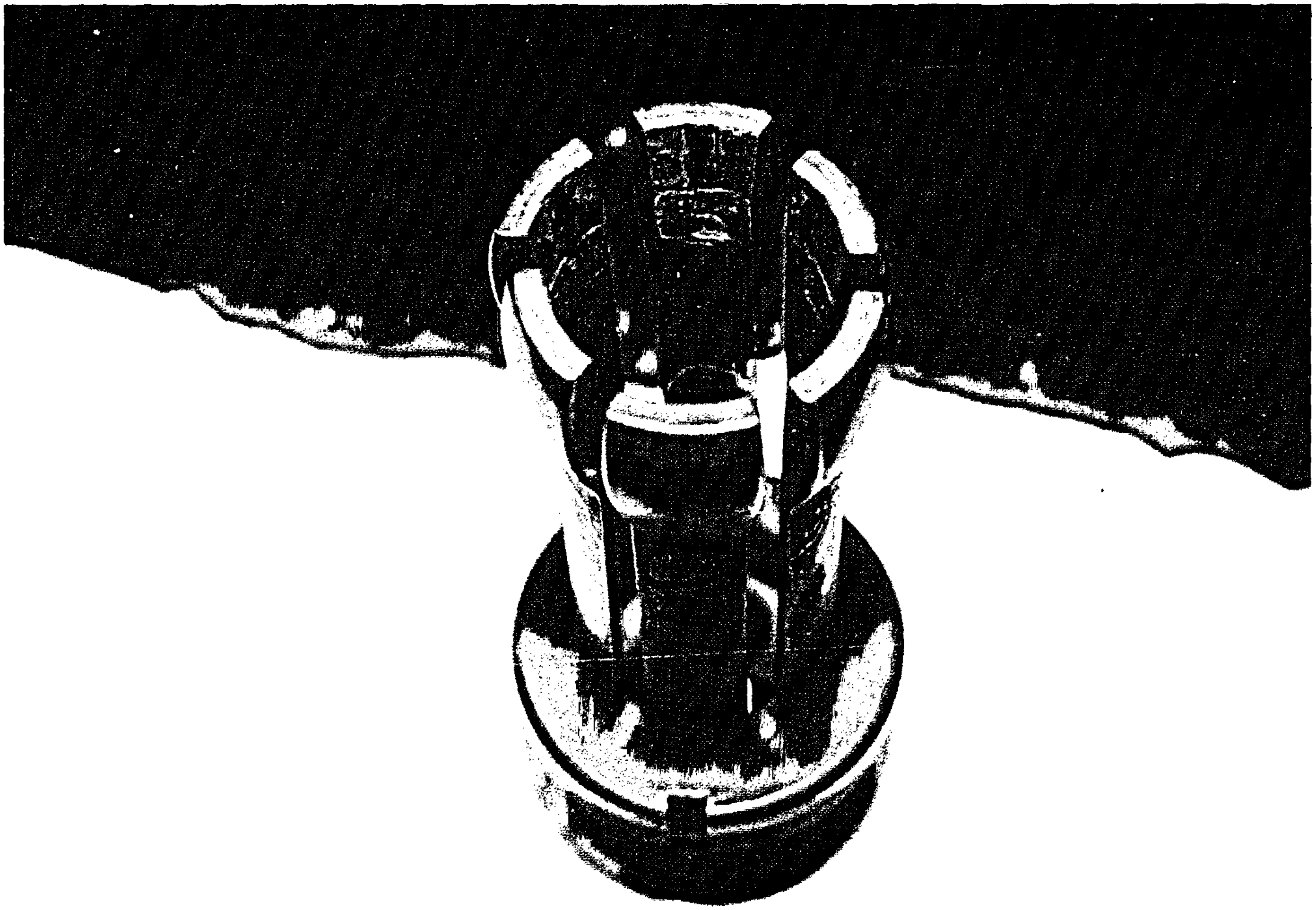

Figure 4.20 Bent CRDM spud fingers.

The collet housing is, perhaps, that part of a CRDM that can be most easily damaged by improper handling, storage, and rebuilding. Any deformation that occurs to the housing during the rebuilding process (e.g., the drive was temporarily laid on the floor and the collet housing supported the weight of the drive and/or someone stepped on it like they had stepped on floor piping) is likely to be amplified when the CRDM is placed back into normal service (which is a high thermal stress environment). Figure 4.21 shows how severe the heat stress can be on the collet retainer tube of a CRDM. In addition, IGSCC was identified on this particular housing.

- *Cooling-water Orifices:* Teflon material has been routinely found "plugged" in these orifices, which are supposed to be clear passages.

  The teflon found in the cooling-water orifice may originate from the seat on the inlet scram valve located on the HCU. The seat erosion could be caused by high flow velocities achieved during a scram. This blockage may cause an increase in the operating temperature of the affected CRDM. The design of the cooling water orifices were later modified by GE, and many utilities have incorporated this enhancement into their CRDMs. GE also issued a "Special CRDM Flushing Procedure" in GE SIL No. 173 (Ref. 14) which helps to loosen entrapped debris. To mitigate water accumulator corrosion, GE modified the design to a stainless steel tank with chromium plating on the inside.

- *Entrapped Crud:* The ball check valve often has to be reseated, and the ball has many scratches on it. The inner filters are clogged and the Graphitar seals are full of crud. Crud is debris (usually a corrosion product) that usually enters the CRDM from the reactor vessel and becomes entrapped in its inner and outer filters and under the Graphitar seal sets. Some plants have more problem with crud in their CRDMs than others. One plant is reducing the amount of crud (an estimated 10%) by vacuuming in and around the guide tubes during refueling outages. Others are trying to improve the quality of water the HCUs receive by increasing the changeout frequency of the filters in the normal supply water (from the condensate storage tank or the condenser hotwell reject line). Crud can also become entrapped in the finger mechanisms of the collet assembly and impede engagement of the fingers with the notches of the index tube, such that the CRDM can be driven but not latched. "BWRs which have operated for a long period of time without scramming and which have accumulated debris in the control rod guide tubes are more prone to this problem."[26]

4.6 Continued Serviceability of CRDM Components

When rebuilding a CRDM, not all utilities will change out the same parts. All CRDM components should be evaluated for service wear, but some parts are always exchanged for new ones. These include the elastomer seals, Graphitar seals, all locking bands, all O-rings, the cotter pin, safety wiring, spring washers, and various screws. Some utilities also require the changeout of the inner and outer filters (from an ALARA standpoint, it may be more beneficial to properly dispose of these rather than clean them), the check valve ball, and the strainer. Due to degradation, many utilities have also reported having to replace components not normally changed out, such as spuds, collet housings, and seal cups.

"The evaluation of 'serviceability'" (of the CRDM components during rebuilding activity) . . ." is generally a subjective decision made by the technicians or the cognizant engineer, with very little comprehensive, definitive information as guidance. In the case of index and piston tubes, especially, minor defects observed in the nitrided surfaces are commonplace, either due to manufacturing anomalies or damage due to improper handling, shipping, or storage. These nitrided surfaces may directly affect the service life of the Graphitar seals and bushings with which they come into contact. When evaluating a defect, the following should be taken into consideration:

1. Depth (is it to the base metal?)
2. Number (isolated or multiple?)
3. Area or size (can it affect seal integrity?)
4. Orientation (circumferential or longitudinal?)
5. Location (affect seal area?)
6. Discoloration (variance in the case thickness?)
7. Thinning (manufacturing flaw?)

In CRDMs which have seen continuous service for greater than 15 years, severe degradation of the nitriding has been observed to the extent that the component no longer provides an adequately smooth, hard surface, but, in fact, has deteriorated to the point where the wear surface is easily and permanently scored (see Fig. 4.22). Thinning of the nitrided surface in some cases has been found to the extent that no wear resistance remains at all. The surface of such a part may be easily and permanently scratched by a soft object, such as a piece of wood. In some cases, the base metal may be clearly visible through the original nitriding, evidenced only a a faint bluish-gray residual coloration."[19]

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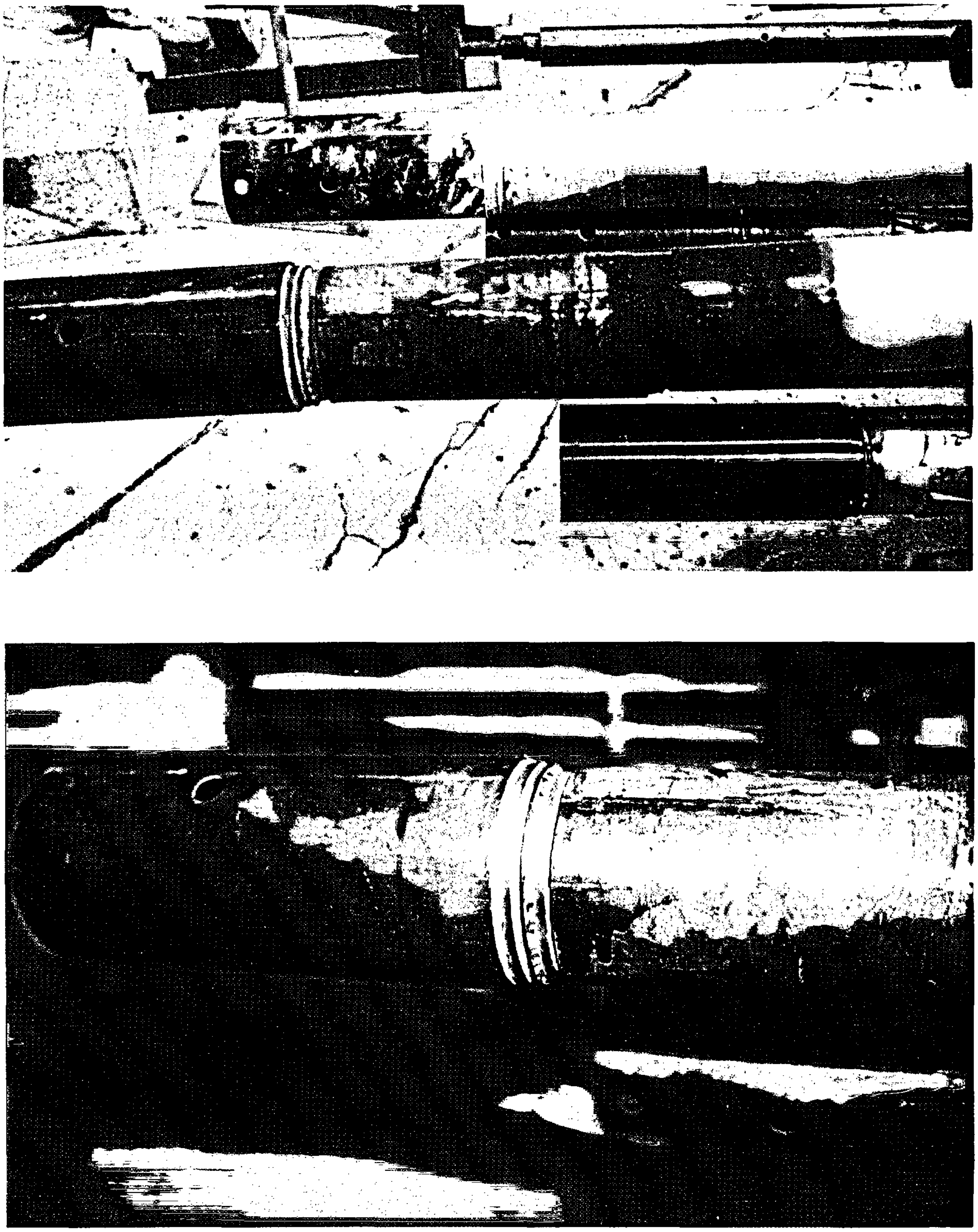

Figure 4.21 CRDM collet retainer tube heat stress.

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Figure 4.22 Index tube surface degradation.

As discussed earlier in Sect. 4.5.4, the spud has shown effects of aging which are thought to be caused by fatigue. The spud fingers have been reported to be easily bent and/or deformed on some parts with excess service time (>15 years). One CRDM specialist described the condition as "the fingers losing their memory." The strength and resilience, which normally typifies parts made of Inconel alloy X-750, no longer remains. If spud fingers become bent, they lose their concentricity. When evaluating the continued serviceability of this part, "special attention should be paid to the concentricity and resilience of the spud fingers in order to avoid a myriad of coupling and uncoupling difficulties."[19] Other CRDM components made of this material include the collet fingers, the collet spring, and the piston seal C-springs. After rebuilding a drive that had >15 years of continuous service, one CRDM specialist commented that the C-springs, as shown in Fig. 4.23, could be broken "like cookie crumbs" (probably caused by IGSCC).

It should be stated that no professional metallurgical evaluations have been performed on the nitrided surfaces or Inconel alloy X-750 components cited in the previous paragraphs. These observations must be considered as "experienced-based speculations" until more comprehensive studies have been completed.

4.7 CRDM Maintenance and Aging Interactions

4.7.1 Description of CRDM Changeout Activities

The maintenance activities that involve CRDM changeout and rebuilding are among the most complicated, physically challenging, and dangerous tasks routinely accomplished by BWR utilities. The working conditions that exist under the vessel during CRDM changeout are cramped, hot, limited in lighting, in a high radiation zone, disorienting, and greatly fatiguing. For the maintenance technician to work in this area, physically confining radiation suits must be worn that have restrictive air hoses and communication wires attached to them. The technician must prepare to work for several hours hunched over in a hot area and be careful not to hit his head on any of the instrumentation that is hanging down all around him. Equally important, he must avoid tripping on the hoses coiled all over the floor. After he maneuvers around the large track floor opening to avoid falling 20 ft into the pit below, he is challenged with the task of identifying the CRDM to be changed out. Since the desired device is one of 100 or more (U.S. BWRs have between 89 and 193 CRDMs), which all look alike and whose serial numbers are obscured by the massive amounts of cabling, CRDM identification is no trivial task. Even vision is hampered if anything gets smeared on the technician's mask or if condensation occurs inside the bubble hood. After the component is finally identified (ideally, by proper tagging), the process of changeout begins.

The CRDM handling equipment must be positioned directly underneath the CRDM. Two opposing bolts are removed, guidepins are inserted into their holes, and the handling device is adjusted to support the weight of the CRDM (about 2000 N or 450 lb). The remaining six bolts are removed, and the CRDM is slowly lowered out of the reactor vessel by operating the handling equipment's mechanical winch or pneumatic elevator. As the CRDM descends, reactor water (about 316 cm^3/s or 5 gpm) continuously spills out on the floor and onto the technicians, who are trying to lower the CRDM without it becoming lodged or misaligned. After the device has been completely lowered out of the reactor vessel (as shown in Fig. 4.24), a lead radiation shield (resembling a small, cylindrical suitcase but called a "pig") is attached to the upper part of the CRDM around the spud region. Unshielded radiation readings at this location can typically range from 20 to 400 R/h. The technicians gradually pivot the CRDM from a vertical to a horizontal position, which is difficult because it is bottom heavy and clearances in the rectangular floor opening are tight. Once horizontal, it is moved along a sliding track out through a drywell portal and onto a CRDM transfer cart. A replacement CRDM arrives through the same portal, and the reverse process commences for CRDM installation. For even the best-trained crew, this procedure can take from 1 to 4 hours per drive if there are no unexpected delays, such as poor communication, tools that do not work, twisted cables and hoses, worker fatigue, etc. With all of these stresses present, coupled with the emotional pressure of knowing that (1) CRDM changeout is critical path work during an outage, (2) the worker has a limited amount of time and allowable dosage to accomplish the job, and (3) a CRDM is a very expensive device, it is understandable how maintenance and handling errors can contribute to CRDM degradation.

Additional complications can also arise during the process of CRDM rebuilding. The 4.7 m (15 1/2-ft) device is usually lifted from the transfer cart and placed onto a rebuilding table or into a long "flush tank" by two or three technicians, who again, must be donned in bulky radiation protective clothing. To be rebuilt, the three long, concentric tubes that comprise the CRDM must be separated. Modern tools and training are the foundation of proper CRDM rebuilding, and this is where human error can easily be manifested. Graphitar seals, which look alike, can be installed backwards. The inner filter, which attaches via a bayonet-type lock, will become loose during CRDM operation if not properly engaged during rebuilding. Spring washers, inherent to the earlier CRDM designs, can be improperly oriented. Cleaning also becomes a complicated procedure when trying to hand wash and scrub tiny parts with thick, cumbersome gloves. Some components can be cleaned with ultrasonic cleaning tanks (if the utility provides them), but most parts must be cleaned by using lint-free, disposable towels, Scotch-brite pads, chemical cleaning solutions, scrubbing brushes, and lots of manual exertion. Again, the technician must perform, without error, a very difficult

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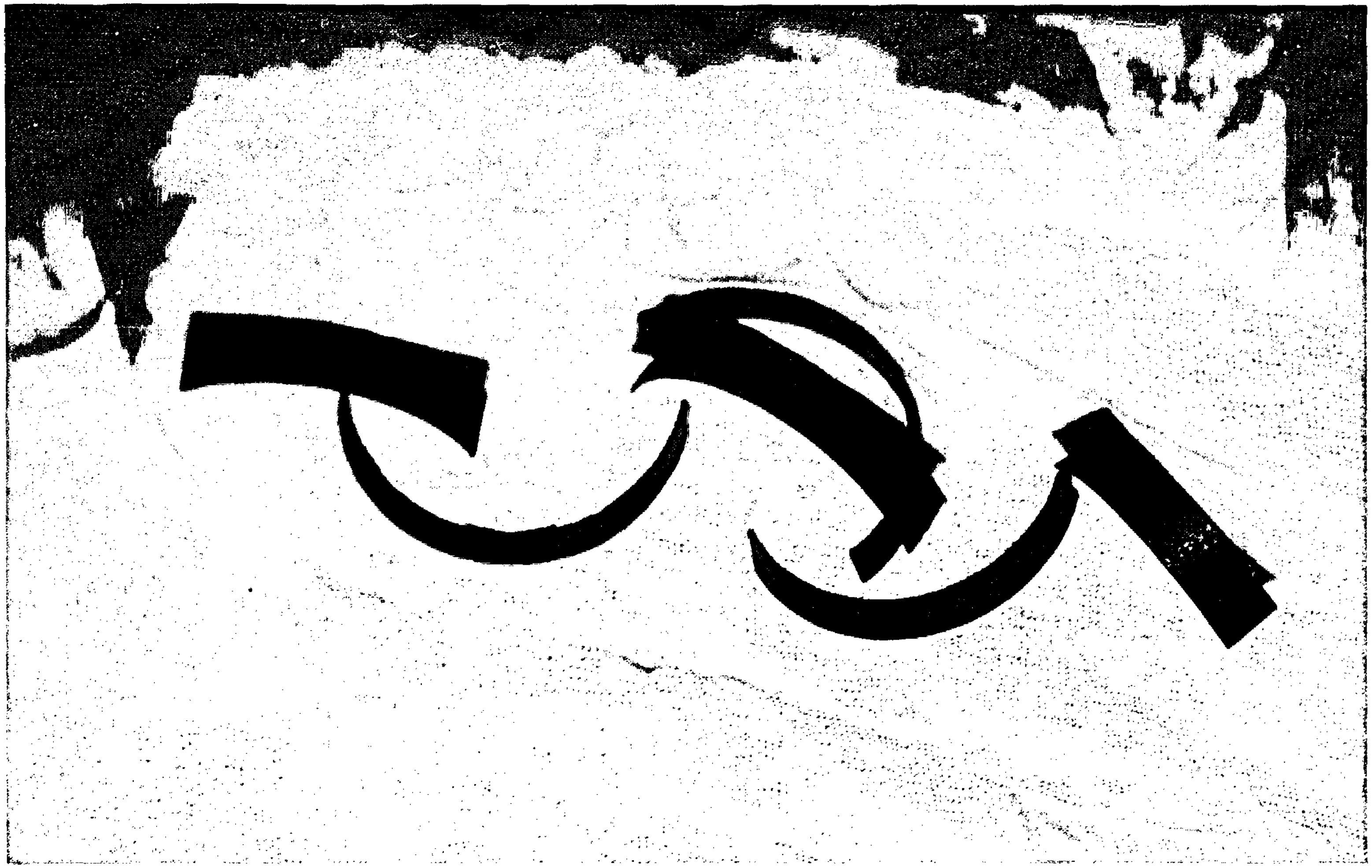

Figure 4.23 Degraded piston seal C-springs.

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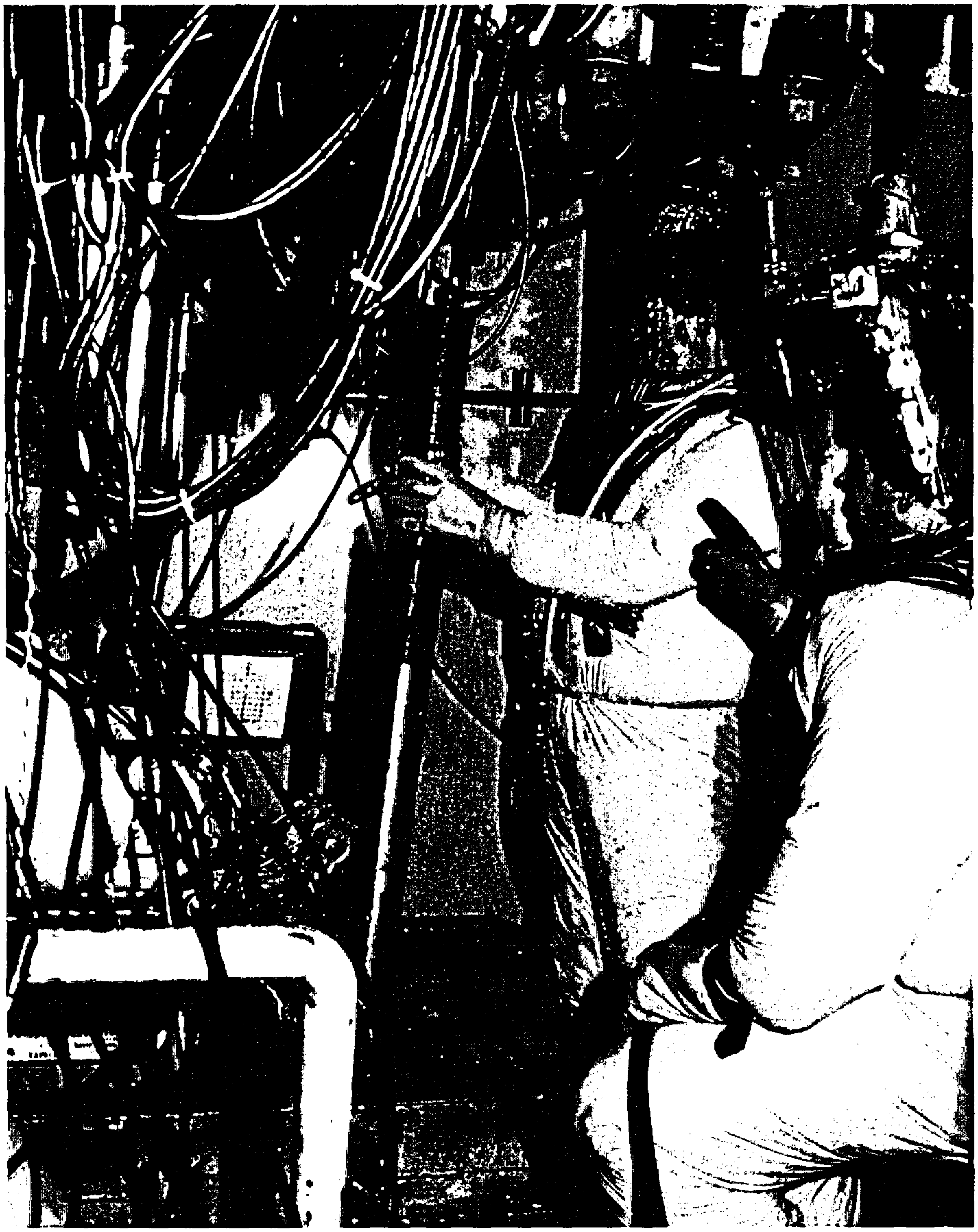

Figure 4.24 The CRDM as completely lowered from reactor vessel.

series of tasks that is complicated by fatigue; hot temperatures; complicated disassembly and reassembly procedures; hampered vision; time constraints; and, in some cases, obsolete tools.

Although most utilities have similarly written procedures regarding CRDM changeout and rebuilding, the previous described CRDM maintenance methods do vary among utilities. The predominant differences occur in how these procedures are implemented with respect to differences in their CRDM design models, individual plant layouts, and available maintenance equipment. Some plants are currently revising and streamlining these changeout and rebuilding procedures to accomodate specialized CRDM maintenance equipment that enables utilities to perform CRDM maintenance more efficiently and, hence, reduce associated costs and ALARA doses.

4.7.2 Human Error Contribution to CRDM Maintenance

When asked what their facility had done to mitigate possible "human errors" during CRDM changeout, utilities responded by identifying bubble suits, temporary lighting, undervessel ID tags, portable air conditioners, advanced CRDM handling tools (like that developed by EPRI[27]), and ALARA shields (these latter two items will be discussed in Sect. 5). Commonwealth Edison and Allstate Industrial personnel cooperated in the development and testing of a one-piece, "Beta-Guard" radiation protection suit that, when used with a bubblehood, helped to promote worker comfort during CRDM maintenance activities (shown in Fig. 4.25). Temporary fluorescent lighting is used extensively by utilities, and some plants keep disposable flashlights under the vessel for the changeout crews.

CRDMs are identified by the manufacturer's serial number tag, which is affixed at the lower flange region. This tag is obscured by the suspended instrumentation cabling, and workers must repeatedly stick their heads up in this high-radiation area under the reactor vessel to find serial numbers and identify the CRDM selected to be changed out. One utility is attaching barcodes to the CRDMs as they are exchanged so a remote barcode reading "gun" (similar to those used in retail stores) can scan the tags at a distance and identify CRDMs. After the CRDM has been identified for changeout, a long fluorescent, lime-green plastic tag is affixed to the piston tube nut (see Fig. 4.26). Under the vessel, these colored tags are easily distinguished by the changeout crew. The green tag goes out with the "old" CRDM, and when a "new" CRDM is delivered for installation in the vessel, it comes with a fluorescent red tag to be placed back on the piston tube nut by the changeout crew. This bar coding and color tagging expedites the identification process and helps the maintenance staff to keep track (at a glance) of the work progress. Figure 4.27 shows the view of lime-green and red tags that the CRDM changeout crew would see at this particular plant. This procedure was developed and implemented at this plant because a maintenance crew made the mistake of changing out the same CRDM location twice (in the same workshift). This error was attributed to CRDM misidentification and worker disorientation.

High temperatures are a normal part of CRDM maintenance. When asked to identify the conditions during CRDM changeout which had the most influence toward improper CRDM maintenance, the majority of those plants responded to the question by citing high temperatures (see Fig. 4.28). Some utilities do have air conditioned drywells, but there are some maintenance activities that prohibit the use of air conditioning (because of airborne radiation concerns) during their performance. For the sake of worker comfort, utilities should schedule CRDM changeout activities during a time when air conditioning can be used. If this scheduling cannot be accomplished, then personal air conditioners should be considered for the changeout crew. Depending on the level of the radiation fields encountered under the vessel, crews may remain in high-temperature conditions for several hours. Physical reactions normally associated with febrile conditions, such as black-outs, weak knees, nausea, and impaired thinking, are common to experienced workers performing changeout tasks.

"In 1980 a study was conducted by a utility on the physiological effects of working in harsh environmental conditions during CRDM exchange. The study involved a registered nurse being stationed outside the drywell access, where, prior to entry and immediately after exit from the drywell, each individual was monitored for body temperature, heart rate, weight, and blood pressure. Testing was stopped by the utility after one shift, with approximately 35% of the crew placed on three days restricted light duty. This restricted duty was a direct result of the physical findings on the personnel exiting the drywell."[28]

Some utilities use contract labor personnel to perform CRDM changeout and rebuilding tasks. The utility is responsible for training these individuals to perform this work, and sometimes this training is also contracted to a specialized services group. Even if the labor personnel are very adept at performing these tasks in training and are prepared for harsh work environments, the characteristic hot temperatures, high doses, cramped workspace, and limited time schedules normally associated with CRDM changeout activities places demanding constraints on even the most experienced personnel. Utilities should recognize that there may be some workers who do not have the personality attributes necessary to efficiently accomplish this job; persons exhibiting claustrophobic tendencies should be considered for less confining work details. Maintenance specialists with good teamwork skills usually adapt best to the uncompromising work environment under the vessel.

4.7.3 CRDM Changeout and Rebuild Maintenance Training

Utilities were asked to describe any training that CRDM changeout crews received and how it might improve CRDM reliability. As shown in Fig. 4.29, undervessel

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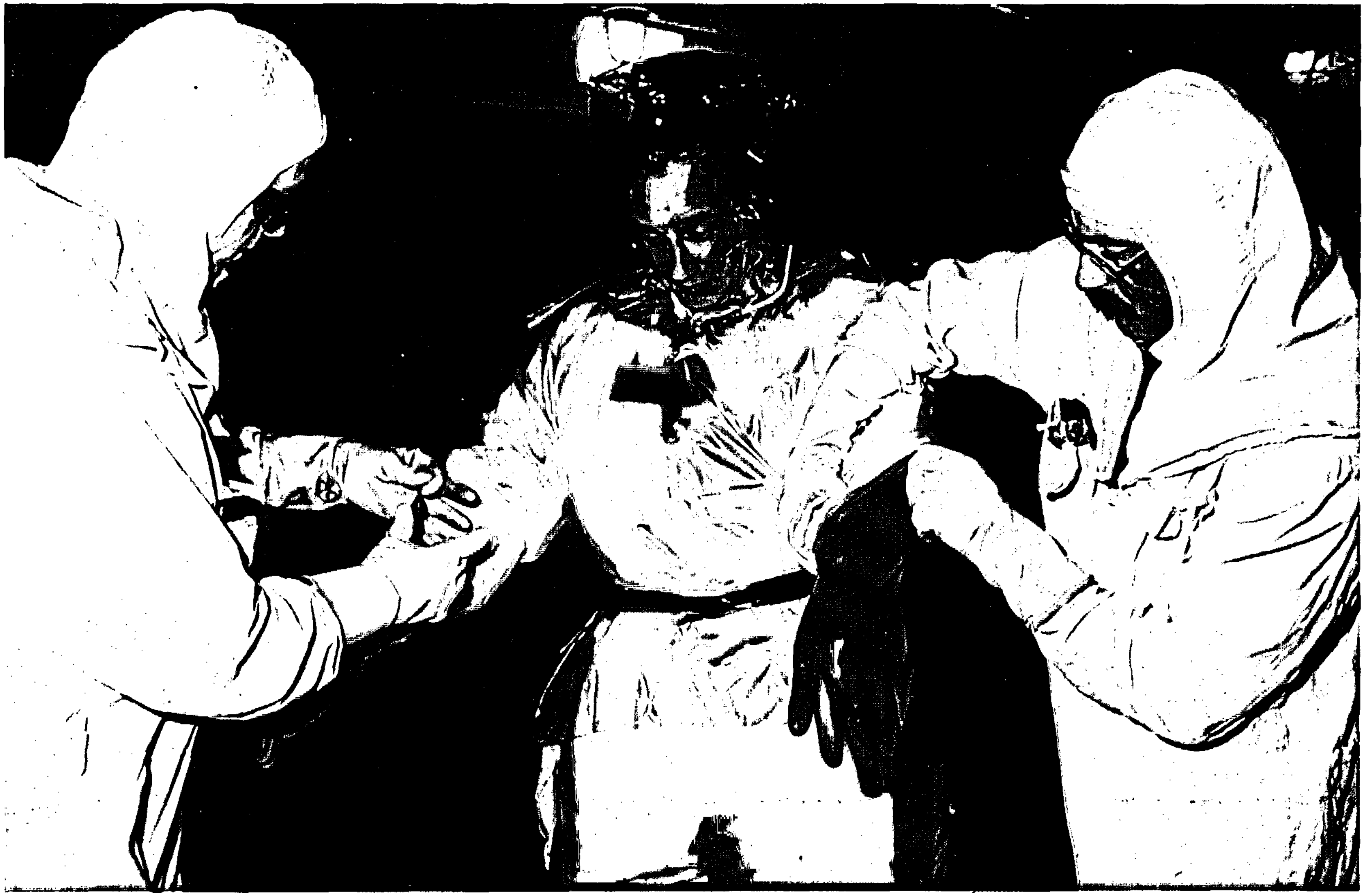

Figure 4.25 CRDM changeout worker donning special one-piece radiation protection suit.

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Figure 4.26 Barcode scanning system for quick identification of CRDMs.

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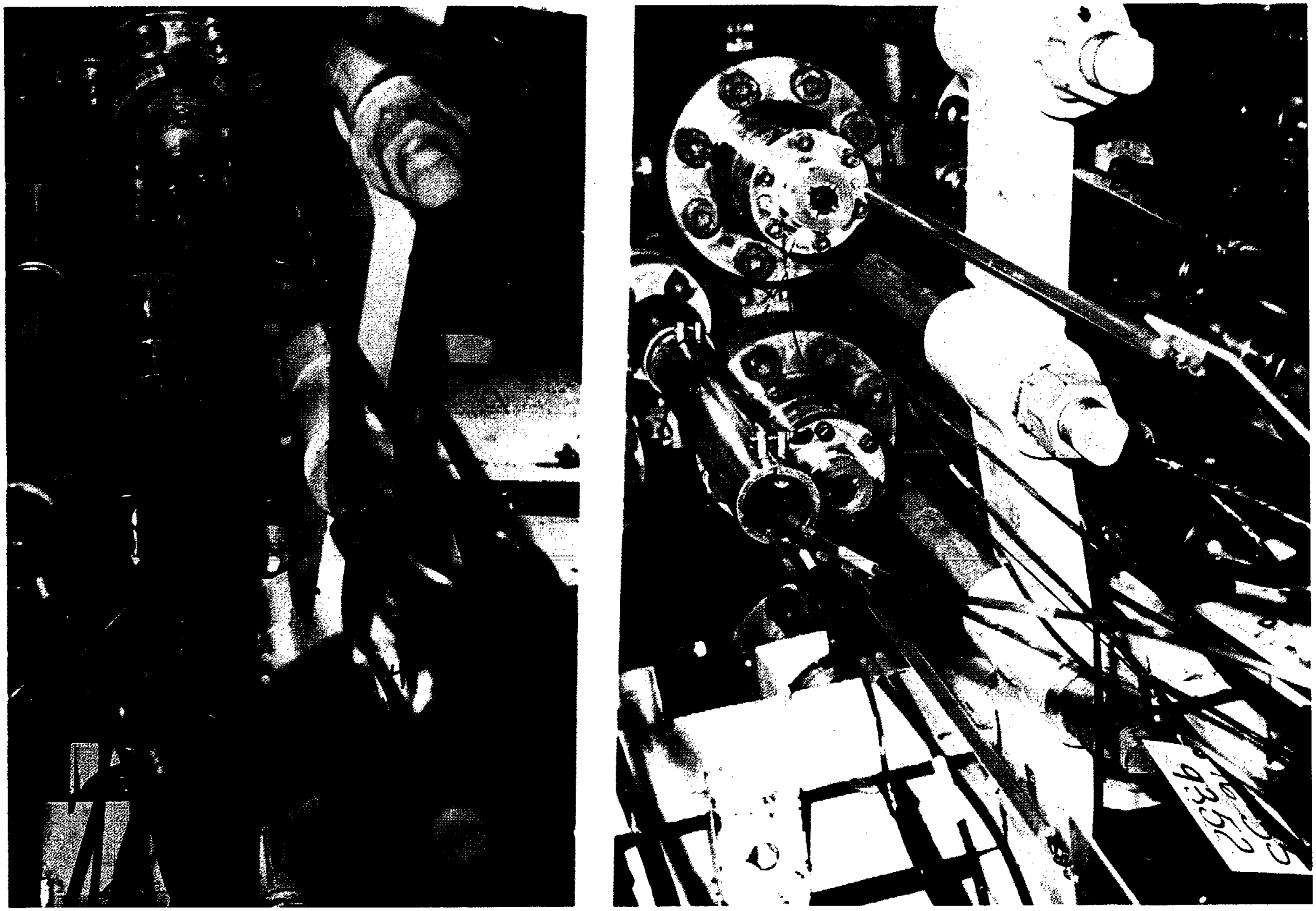

Figure 4.27 Colored CRDM identification tagging expedites location.

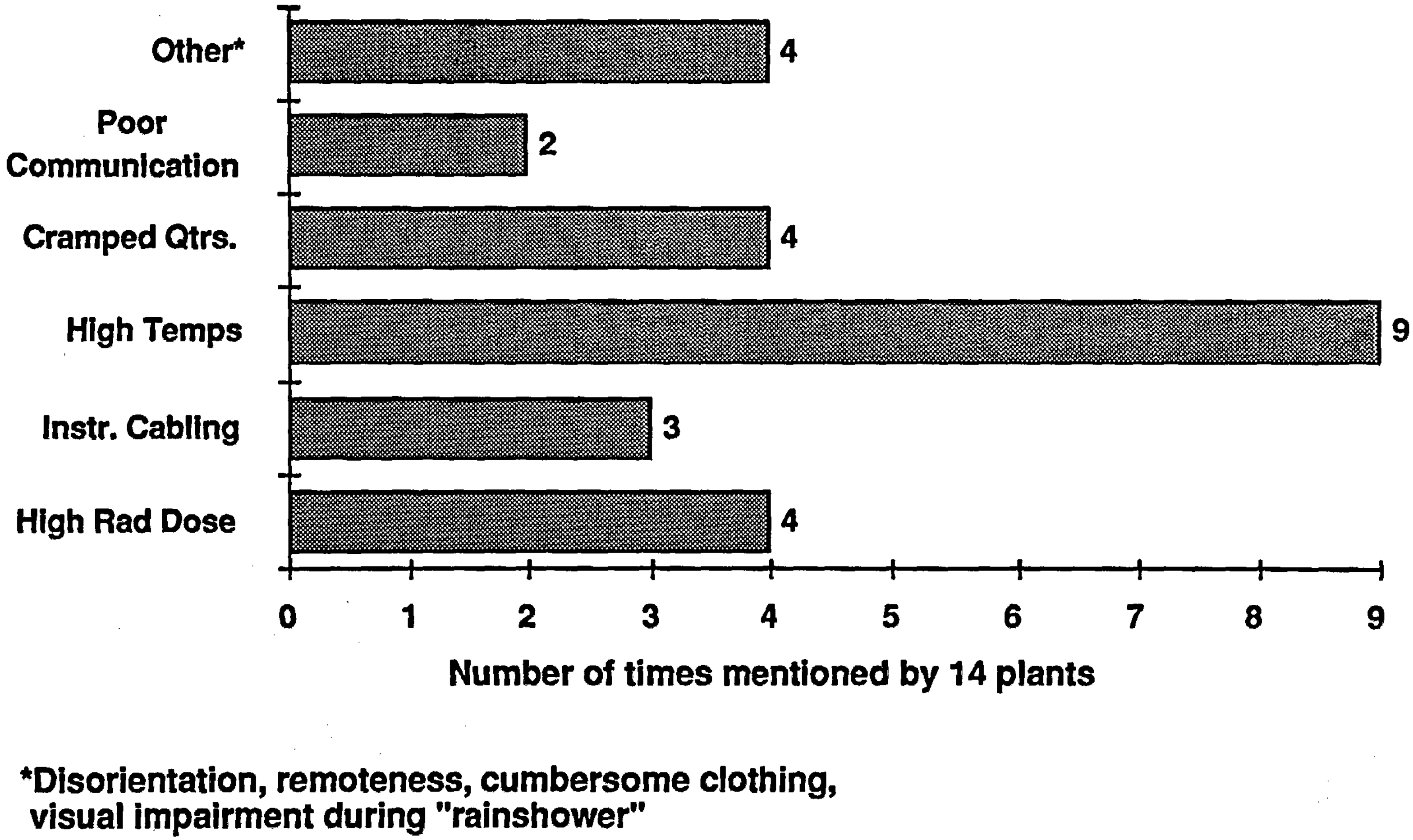

Figure 4.28 Conditions that contribute to improper CRDM maintenance.

NPRDS Data

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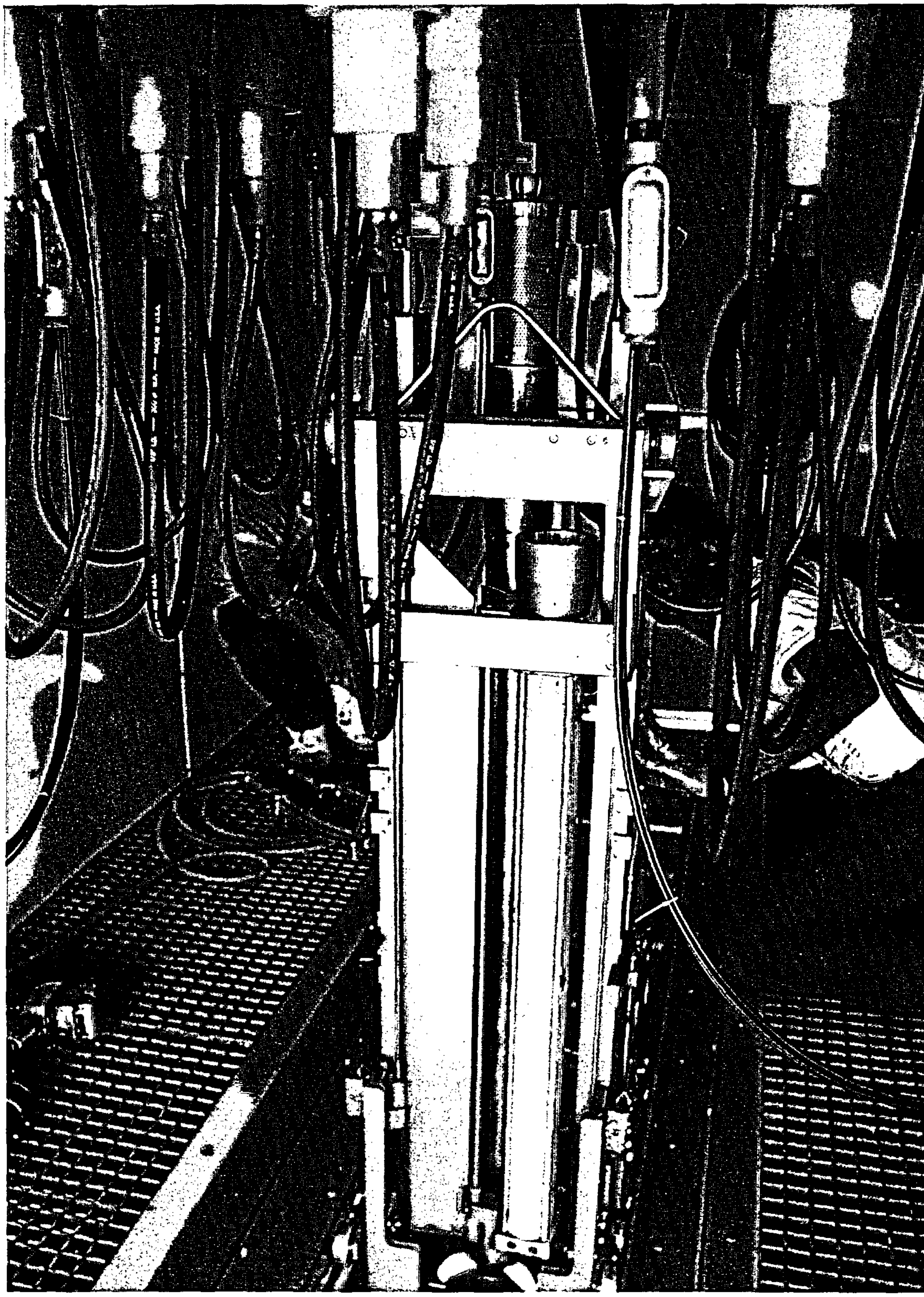

Figure 4.29 CRDM undervessel mock-up using CRD handling device.

mockups are employed at nine sites to implement the training of changeout crews. Several of the utilities stated that the CRDM work was contracted to service organizations whose personnel had completed training that employed these mock-ups. Siemens Nuclear Power Services uses its Mobile CRD Training Simulator to drive a mock-up facility (via a standard 18-wheel transfer truck) to various plant sites that do not have CRDM undervessel mock-ups.[29] There are also utility-oriented training programs, such as that offered at the Barbadoes Training Center,[30] that have on-site mock-ups to instruct maintenance personnel. Nine sites also reported having maintenance practice sessions to help teach workers the complicated process of rebuilding a drive, usually by disassembling and reassembling a decontaminated spare CRDM.

The duration of changeout and rebuilding training varied from 3 to 5 days with shortened "refresher" courses being given to personnel with previous experience. Several utilities stated that their programs also involved individual testing. All of those utilities providing customized instruction or using trained crews also cited in the questionnaire that improvements in job performance were noted. Other benefits mentioned were reductions in radiation doses, worker safety, worker attitude, and fewer rebuilding errors.

INPO offers guidelines for utilities in developing their own training programs. Other instructional tools, such as video tapes, are also being developed by utilities to augment the training process. Video tapes of actual changeout and rebuilding jobs have also been used for "time-and-motion" studies conducted to identify any unnecessary activities, streamline required movements, enhance procedures, and hence, reduce ALARA doses.

4.8 CRDM Testing

Attendees at the workshop were asked to identify the types of tests conducted at their facilities to ensure CRDM operability and system performance. Leak rate and stroke tests are performed during CRDM maintenance activities to verify that drives have been correctly rebuilt and alert the technician to any component problems which may inhibit normal CRDM operation. Insitu testing of the drives (in the reactor vessel) is accomplished according to technical specifications, which require regular notching exercises of individual CRDMs as well as scram time testing. Extended system component testing is further warranted by plant technical specifications to ensure operability of the scram discharge volume vent and drain valves. Optional CRDM testing being conducted at many stations includes insert stall flow testing (conducted only during shutdown conditions) and withdrawal stall flow testing (conducted at rated reactor temperatures and pressures). The results obtained from stall flow testing are often analyzed by plant personnel and used as criteria to select CRDMs for rebuild maintenance. Differential pressure testing (also called "friction" testing because it quantifies CRD drive-line friction) may also be conducted by those stations performing troubleshooting analysis on the hydraulic operations occurring between companion CRDMs and HCUs. The following sections offer brief descriptions of these tests and how utilities are using them to evaluate CRD system performance.

4.8.1 Leak-rate and Stroke Testing

Leak-rate tests are normally performed on all rebuilt and new CRDMs prior to their insertion in the reactor vessel. The test is a measurement of the leakage of the drive fluid (water) past various sets of Graphitar seals, at the check valve, and through the cooling-water orifice in the CRDM. The maintenance manuals for the various CRDM models details what the normal leakage rates should be at various point in the drive. Leakage rates higher than those listed in the maintenance manuals can indicate a rebuild error or component problems.

Figure 4.30 shows a dual leak-rate fixture, which allows both the "P" overport and "P" underport hydraulic paths to be connected to a demineralized water supply for testing. The water is supplied at a specified pressure (200 psi) and the leakage rate is measured at selected points on the drive. Utilities should not perform this test on drives more than 28 days before installation, since it leaves the drive internals wet and subject to corrosion (particularly the nitrided surfaces).

Stroke testing is performed on CRDMs to determine if the CRDM will protract its full length of travel when subjected to normal design pressures. Although conducted as part of normal procedures by some plants, GE does not recommend this test as one routinely performed on a rebuilt CRDM but suggests it be used "when special data is sought or a reassembly defect is suspected."[16] A stroke test that uses inadequate support methods can actually damage CRDM internals from moments that might be placed on the long and heavy concentric tubes within the drive. "In order to preclude the possibility of causing severe damage to CRDMs during pre-installation testing, the following options may be considered:

1. If a full length stroke test is desired, use a stroke test fixture which provides positive mechanical support to the index tube during extension and retraction precluding the undue application of tensile stresses to the guide cap/collet housing assembly or index tube. A relatively simple rail/track support mechanism may be fabricated or procured to fulfill this purpose.

2. If a partial stroke test is acceptable, modify the stroke test procedure to limit extension of the index tube to a maximum of eight notches (position 34) to ensure that undue forces are not exerted on the guide cap/collet housing assembly or index tube. A partial stroke provides an adequate demonstration of operability without risking damage to the CRDM. No support mechanism would be required for a partial stroke limited to 1/3 of full travel.

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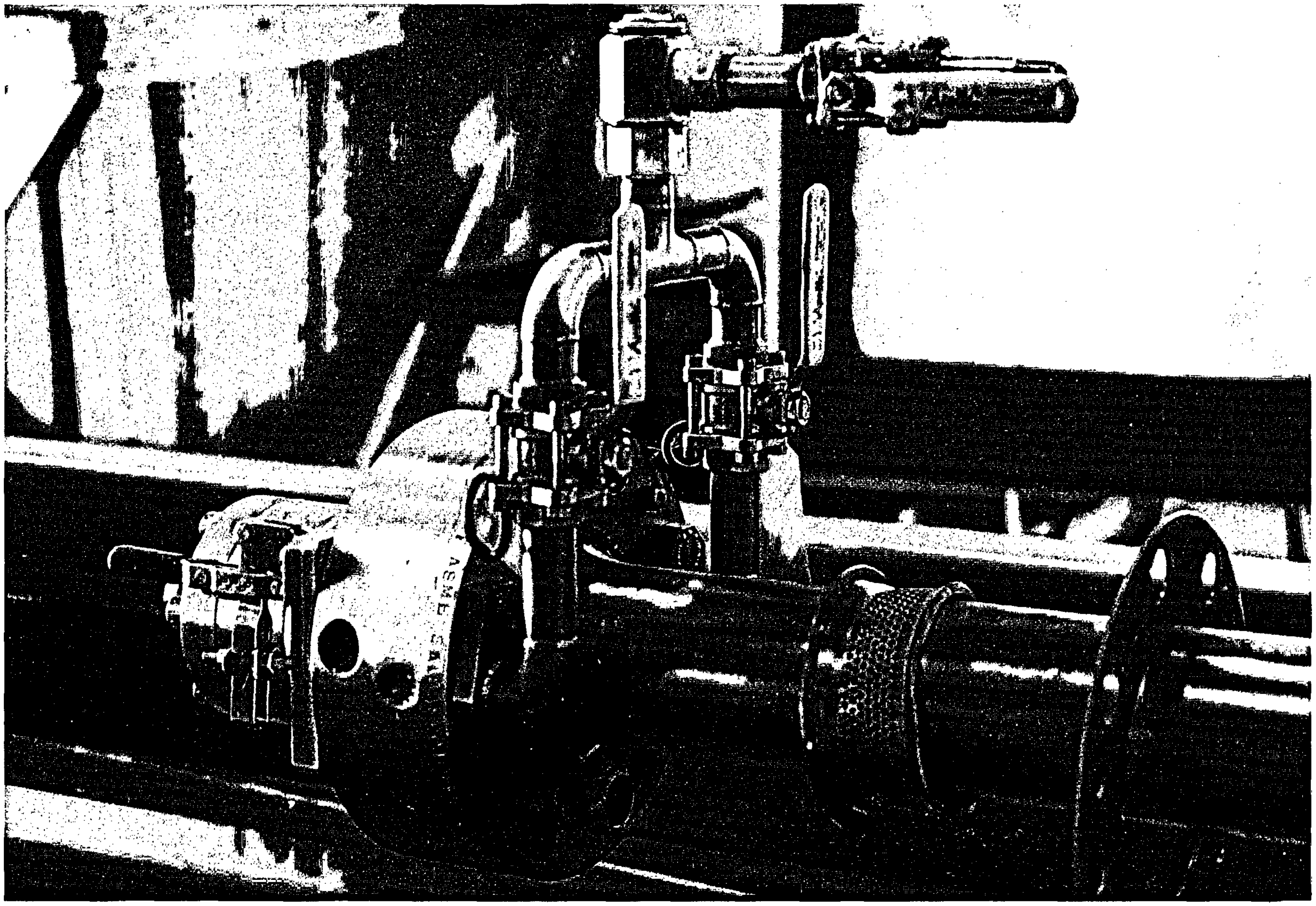

Figure 4.30 CRDM dual leak-rate test fixture.

3. If acceptable, eliminate the stroke test as a procedural requirement but use it instead as on optional confirmatory test employed on an as-needed basis. Partial stroke testing, for instance, may be useful to confirm by direct observation the proper operation of a previously troublesome collet assembly."[19]

4.8.2 CRDM In-situ Testing

After the CRDMs have been reinstalled in the reactor vessel, an insert stall flow test may be conducted to measure the flow of water past the drive's seals. The insert stall flow test is conducted only on drives that are fully inserted, which mandates a shutdown condition. Conversely, the withdrawal stall flow test is conducted only on drives that are fully withdrawn (position '48') with the reactor operating at rated temperatures and pressures. The tests are conducted from the control room and require (at a minimum) the approval of the plant shift supervisor and appropriate reactor operator personnel. On the CRDM control panel, the operator selects the fully inserted (position '00') drive to be tested, and simultaneously depresses the "INSERT" and "IN TIMER SKIP" pushbuttons long enough to obtain and record the insert stall flow rate from the drive flow meter. On the other hand, the withdrawal stall flow rate is obtained from the same meter by simultaneously depressing the "WITHDRAW" AND "CONT WITHDRAW" pushbuttons. Since the measurements are obtained at locations where the CRDM should not be moving further in or out, the name "stall" is given to the test.

Attendees at the workshop related that they had occasionally obtained questionable readings from these tests due to the operator's hurried manner of collecting data. The drive flow rates had not been allowed to stabilize during testing, so the measurement was not a correct indication of the actual stall flow. Many utilities collect withdraw stall flow data on a monthly basis and trend the results to determine CRDM seal degradation. As the seals break due to scram impacts and/or thermally induced embrittlement, increased hydraulic pressures are required to move the drive, which results in greater amounts of water flowing past the seals. Higher stall flows normally indicate greater degrees of seal degradation. Figure 4.31 shows how one plant compares withdraw stall flows with core location, and Fig. 4.32 is a trend of monthly withdraw stall flows recorded for a specific CRDM.

The maximum amount of allowed insert or withdraw stall flows varies among the plants. Figures 4.33 and 4.34 indicate the maximum acceptable insert and withdraw stall flows provided by utilities in response to the CRDM Aging Questionnaire. Some plants do not perform one or both of these tests, and hence, the test was considered "not applicable." Since the withdraw stall flow is, perhaps, the most widely used measure of determining CRDM seal degradation, workshop attendees were asked to define a value which, if used as a criterion, would definitely indicate enough seal degradation to warrant selection for CRDM maintenance. The value agreed upon at the meeting was 5.0 gpm (316 cm^3/s).

Another parameter used to determine seal degradation is CRDM operating temperature. These temperatures normally range between 50° to 120°C (120 to 250°F). GE states that "CRD temperatures above 250°F (120°C) can shorten CRD Graphitar seal life and increase CRD maintenance, and CRD temperatures of 350°F to 550°F (177° to 288°C) will result in a significant reduction in the strength of the Graphitar seals. Higher wear/breakage rates can be anticipated when operating hot drives. Temperatures over 350°F (177°C) may also result in a measurable delay in scram response times. An increase to 400°F (204°C) could result in up to a 0.150-second increase in the 90% insertion time for an otherwise normally-performing CRD. However, this increase should not affect a normally-performing CRD's ability to meet technical specification limits."[14] There are several reported causes of high CRDM temperatures including a leaking scram discharge valve, low cooling-water flow, a defective thermocouple circuit, and a plugged cooling-water orifice. Workshop attendees agreed that a CRDM should be selected for maintenance if temperatures consistently exceeded 177°C (350°F) throughout its length of travel.

Utilities are required by their technical specifications to perform weekly-to-monthly "exercising" of the CRDMs by moving them in and out one notch. The frequency with which these tests are performed may increase with elevations in reactor power, or if a certain number or percentage of the CRDMs are designated as inoperable (either because they are having operational problems or they do not meet scram insertion timing limitations). Required scram insertion times and the schedules for evaluating them are defined in each facility's technical specifications. The scram insertion times are provided in four parts that reflect the amount of time required to insert the control rod from a certain percentage of the fully withdrawn position.

Other operational tests required by plant technical specifications may include monthly tests on the scram discharge volume vent and drain valves and weekly tests to verify that the HCU accumulator pressure and level detectors are not in an alarmed condition.[31] One workshop attendee also indicated that their facility performed a weekly coupling check on all fully withdrawn CRDMs.

4.8.3 Differential Pressure Testing

Defects in HCU valves and excessive CRDM drive-line friction may be determined by the measurement, analysis, and comparison of CRDM piston-over (PO) and piston-under (PU) differential pressures (dP) as a function of time. These dP measurements are obtained through the test ports in the HCU manifold or insert and withdraw line high point vent valves. By using vendor-supplied electronic test equipment (oscilloscope and associated plug-in modules), measurements can be acquired,

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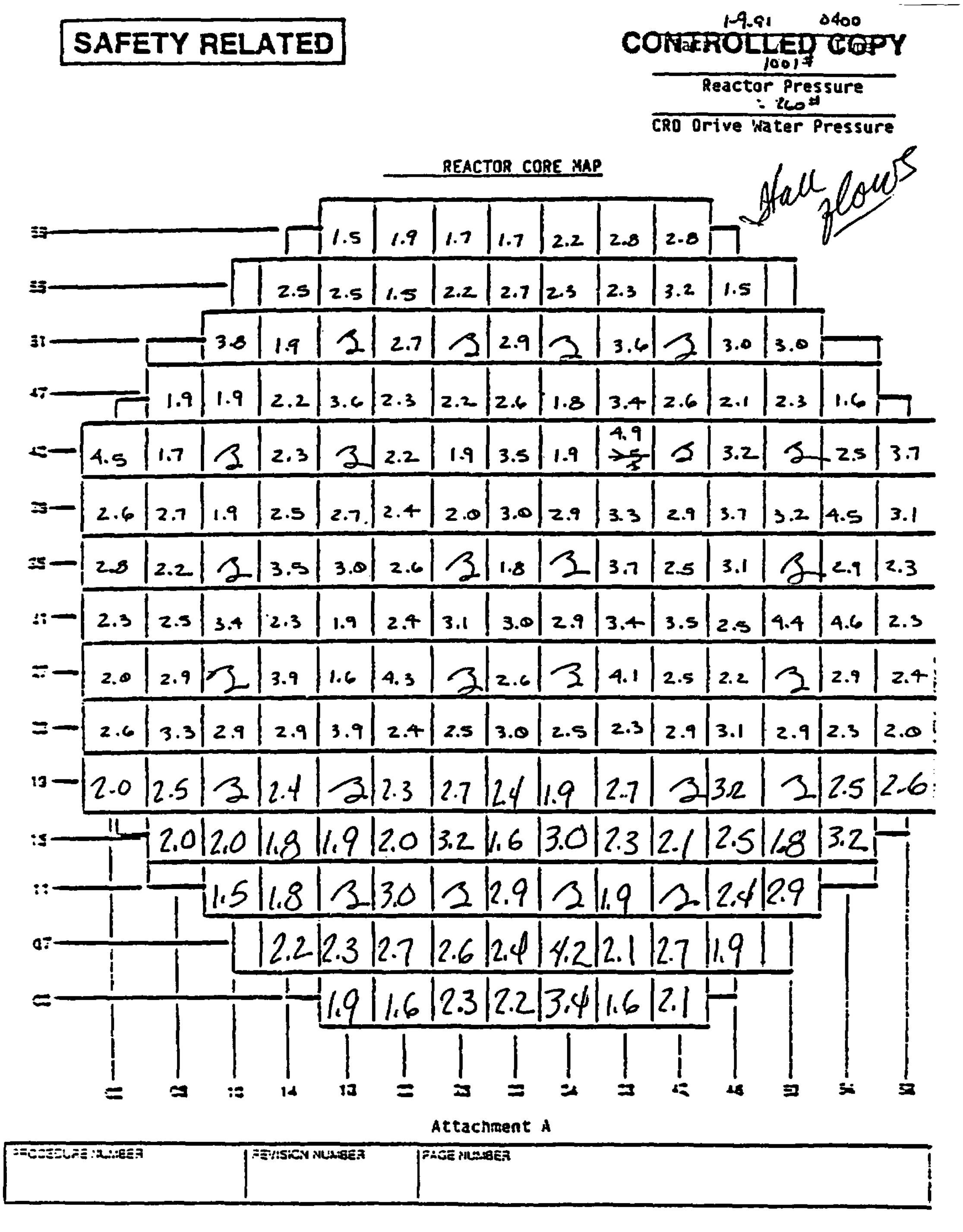

Figure 4.31 CRDM withdrawal stall flows at different core locations.

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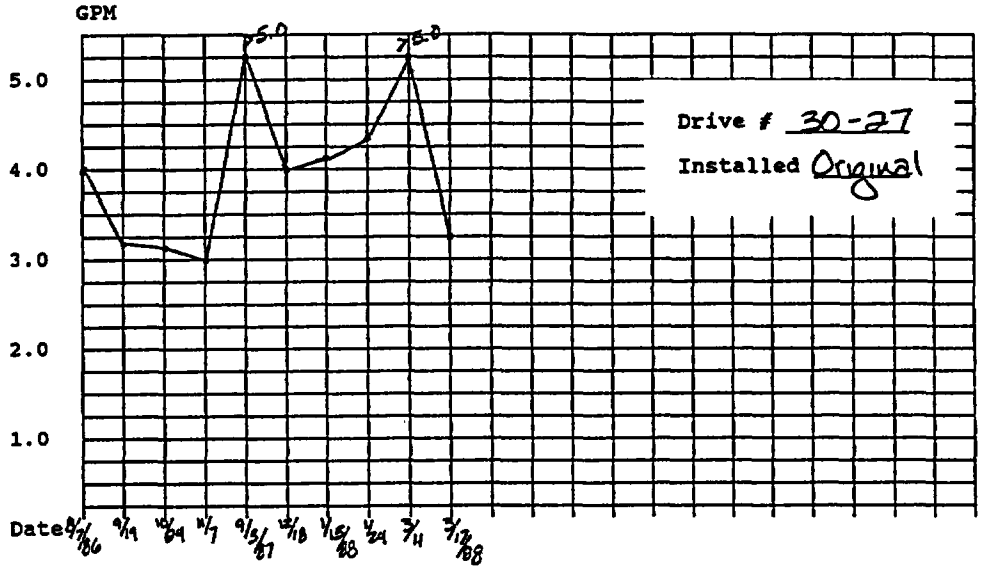
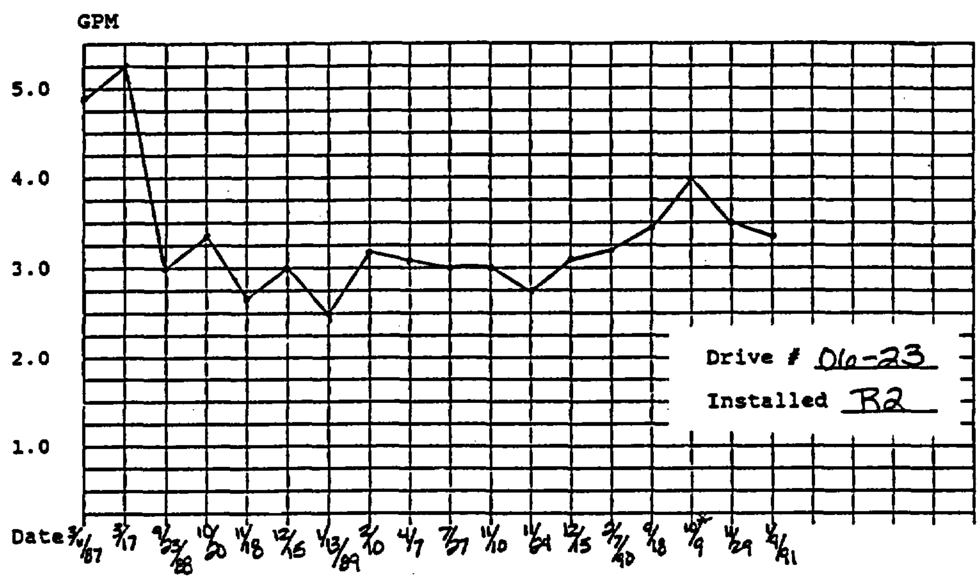


NOTES: Drive selected for maintenance - R3/1988 outage



NOTES: *10/9/90 Ops had to increase d/w pressure to 275# to move the drive back to 48 during CR exercise.

Figure 4.32 Monthly acquired withdrawal stall flows trended to detect CRDM degradation.

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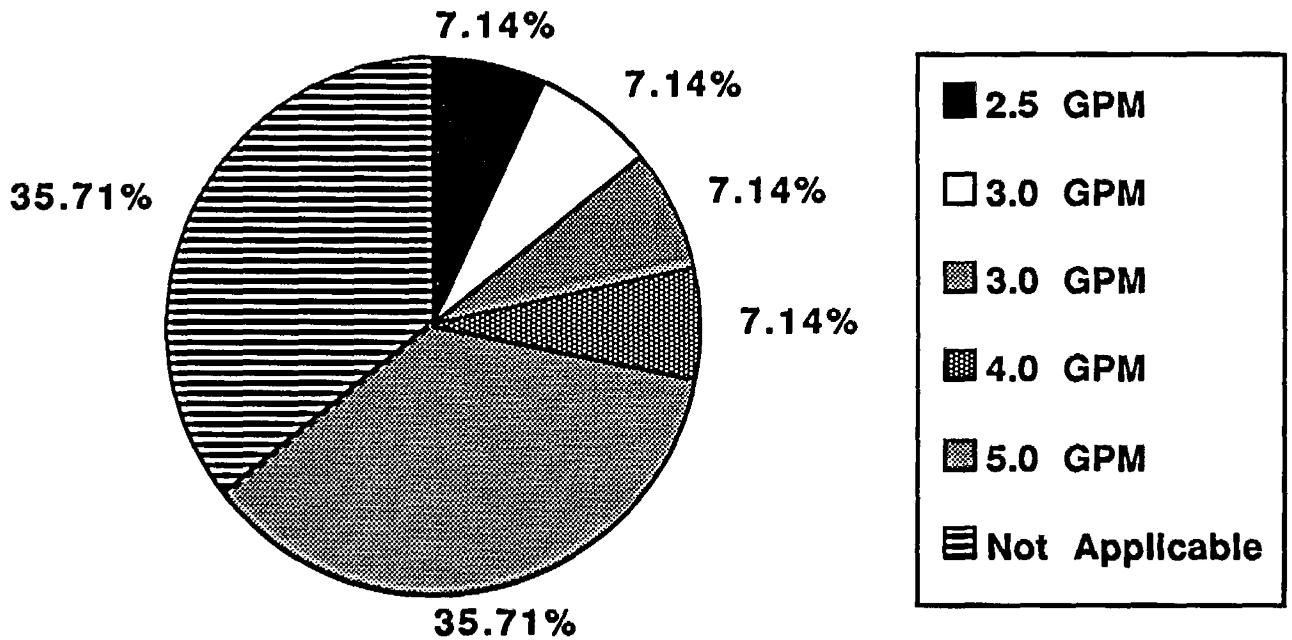

Figure 4.33 Reported CRDM insert stall flow high limits.

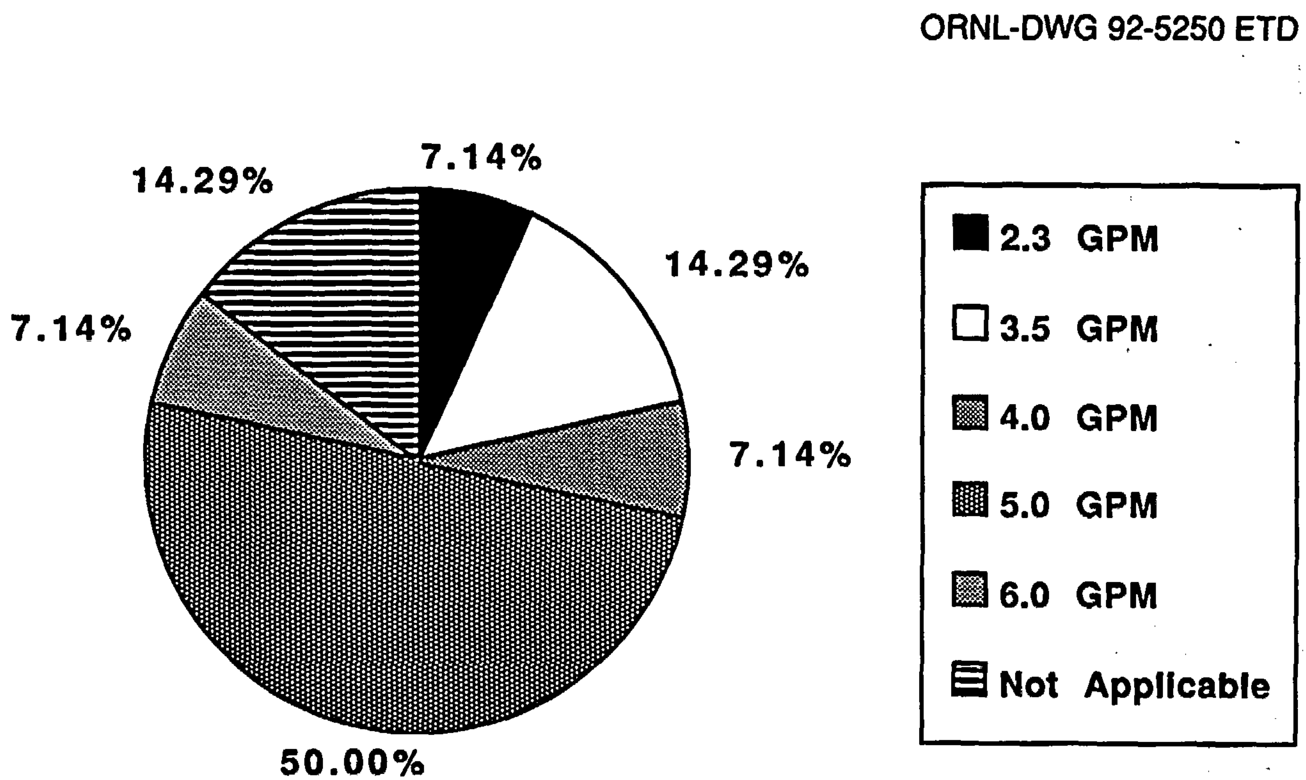

Figure 4.34 Reported CRDM withdrawal stall flow high limits.

photographed, and analyzed for comparison with oscilloscope photographs shown in the HCU maintenance manual (for the respective model), which shows the relationship of PO and PU dP as a function of time for normal hydraulic operations occurring between companion CRDMs and HCUs.[32]

GE has streamlined the efforts required to utilize these diagnostic procedures by introducing an "expert system" computer program named DRIVEX. DRIVEX is an optional part of the site services package offered by GE to utilities and is currently being used at six BWR locations. The diagnostic program consists of three systems, which interface with one another: an interactive expert system, which prompts the user for symptoms and diagnoses CRDM- and HCU-related problems, a data acquisition system, which consists of both the necessary hardware and software needed to collect dP traces from suspect CRDMs, and a data analysis graphics system, which compares the dP traces against a set of standard reference dP traces and also evaluates the acceptability of stroke timing and friction test data. GE states that DRIVEX can be used to determine or verify the cause of a variety of operational problems including CRDM withdrawal, insertion, scram timing, drifting, and non-motion problems, such as high CRDM temperatures.[33] To date, GE is the only company that has developed a computer-based, expert system from a CRDM operational history data base.

5 ALARA Dose Reduction Tools and Techniques

The CRDM Aging Questionnaire asked BWR utility personnel if their plant had purchased any tools and/or equipment specifically designed for CRDM changeout and rebuilding that were not originally provided by the vendor. Many of these new devices were designed not only to augment maintenance activities but to reduce personnel exposures normally obtained from these tasks. As stated earlier, CRDM changeout and rebuilding are the highest dose maintenance activities routinely accomplished by BWR utilities. With the recent revisions in the federal radiological protection regulations set forth in 10 CFR 20, all utilities will be seeking additional ways to lower doses received by plant and contract personnel.

The CRDM can be damaged from mishandling during changeout and rebuilding activities. Some of the tools discussed in this section, such as the CRDM handling and exchange tool, not only help to expedite the maintenance, and hence reduce ALARA doses, but enhance worker safety as well. Their use may simplify required maintenance, reduce the opportunity for human error, and promote proper handling.

5.1 CRDM Changeout and Rebuilding Tools

The following sections describe a few of the tools that are being developed by maintenance technicians to assist them in the exchange and rebuild of CRDMs.

5.1.1 CRDM Handling and Exchange Tools

In 1985, the Electric Power Research Institute (EPRI) sponsored research to develop state-of-the-art equipment and procedures for BWR CRDM replacement.[27] As a direct result of this study, the design of an improved CRDM handling device was made available for prototype development and product licensing. The device replaces the vendor-supplied electrical winch system (Fig. 5.1), which has a history of the following operational problems: "electrical failure due to water getting into the controls, hoist cable breakage due to high stall torques of the electric motors, difficulty with reeving the cables and rigging the hoist systems under the vessel, slipping of the CRDs though the suitcase type clamps, hoist cable fouling due to slack cables, and difficulty with maintenance of the hoist cart since it was not easily removed from the undervessel gallery."[34] In addition, when using this device the maintenance crew "have to be constantly careful not to snag their protective clothing on exposed hoist cables."[34] Operation of the older system requires three workers (two on the undervessel platform and one below), compared with the two workers needed to operate the new device.

The EPRI-designed CRDM handling and exchange tool (Fig. 5.2) is basically a pneumatically operated elevator that holds, lowers, transfers, and raises CRDMs during the exchange process. The system requires very little installation time and can be used without making any modifications to existing undervessel platform structures. One vendor of this tool has also designed an optional drain boot for the device (Fig. 5.3) that captures and directs more than 90% of the initial rush of reactor water.[35] Another company has performed CRDM changeouts employing a design which utilizes a hydraulic operating medium instead of a pneumatic one.[36]

Of the 15 plants responding in the aging survey, 66% of them acknowledged that they had either purchased or used various designs of this tool in their CRDM changeout work. One plant reported personnel radiation exposures for this task reduced by approximately 50%,[34] and two other sites reported reductions of 38 and 56%, respectively.[37] Another facility was so impressed with the device that it has two on-site: one is allocated for changeout activities occurring at either of the station's two units, and the other is dedicated for training in its CRDM mockup.[34] The amount of time required to change out one CRDM using this type of device (barring any unusual complications) has been observed to be 30 to 40 min.

The Toshiba Corporation has developed an automatic CRDM handling machine that is currently being used at 14 BWR units in Japan and one in the United States. It consists of a robotic-type device, which remains stationary under the reactor vessel while it is controlled by an operator (via computer console) in a remote-control room. Video screens on the control console provide the user with a television display of undervessel activities as they occur. Although substantial dose savings could be achieved with this device, significant modifications to the undervessel structures would be required before it could be incorporated into many existing BWRs. The most cost-effective application of this type of handling device would be for existing BWR commercial reactor designs that may be constructed by utilities in the future.

5.1.2 CRDM Flush Tanks

Flush tanks are long, rectangular, metal troughs (Fig. 5.4) that are used for CRDM disassembly, cleaning, inspection, and rebuilding. There are several designs developed for utility use, some of which incorporate particulate filtration and ultrasonic cleaning systems. ALARA dose reduction is easily achieved with flush tanks because they allow the drive to be cleaned under a water shielding medium as opposed to cleaning it on top of a table (Fig. 5.5). Flush tanks are usually a little longer than the drive itself, and offer enough width to accommodate the submerged storage of all three CRDM

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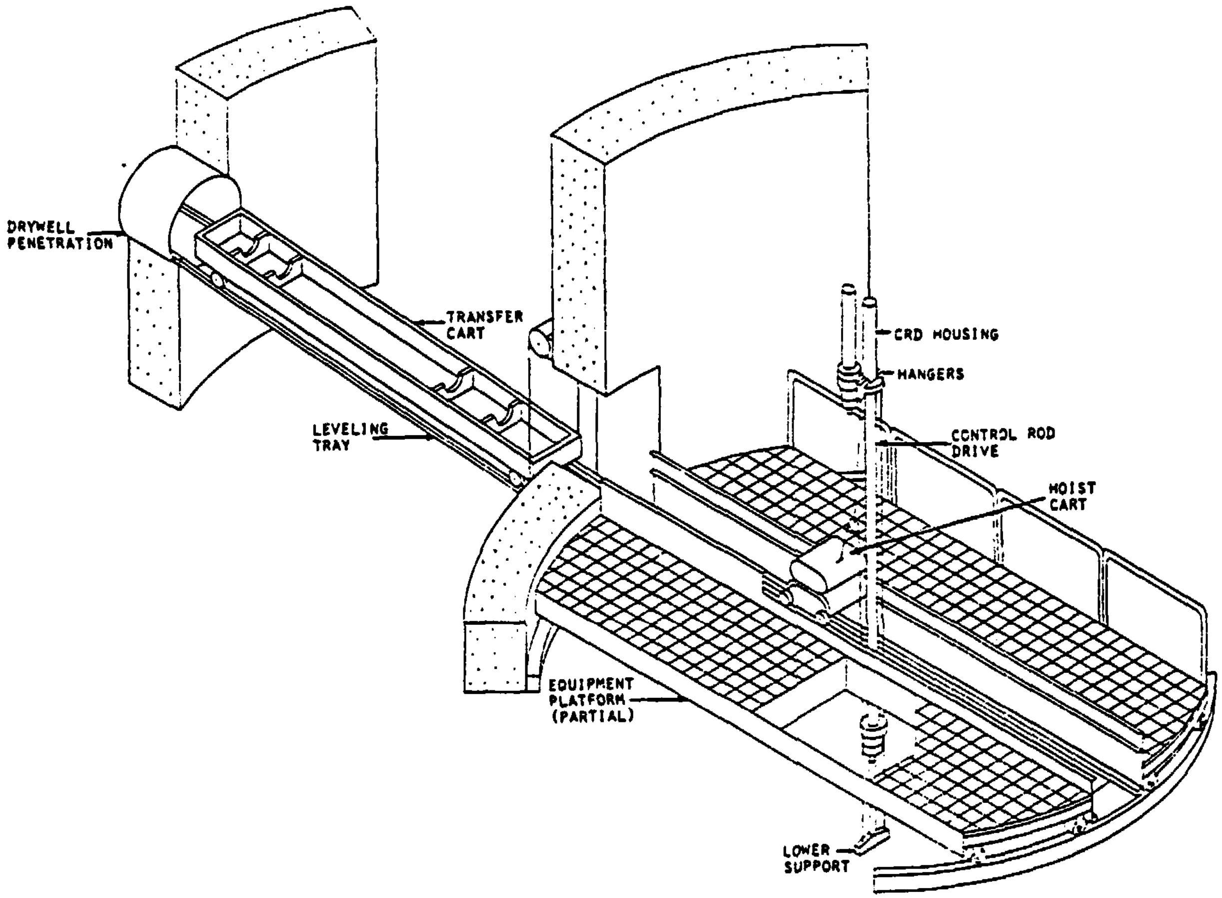

Figure 5.1 Electrical winch system used to changeout CRDMs.[27]

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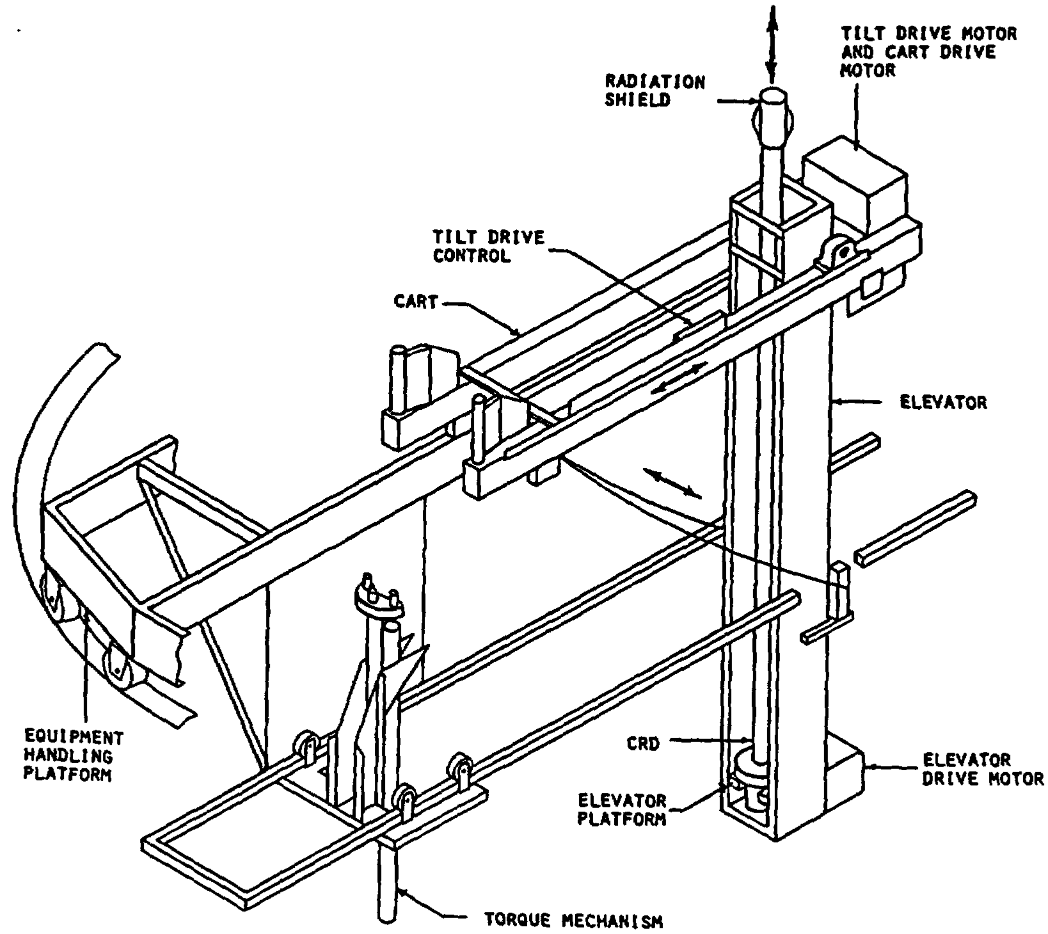

Figure 5.2 CRD handling and exchange device.[27]

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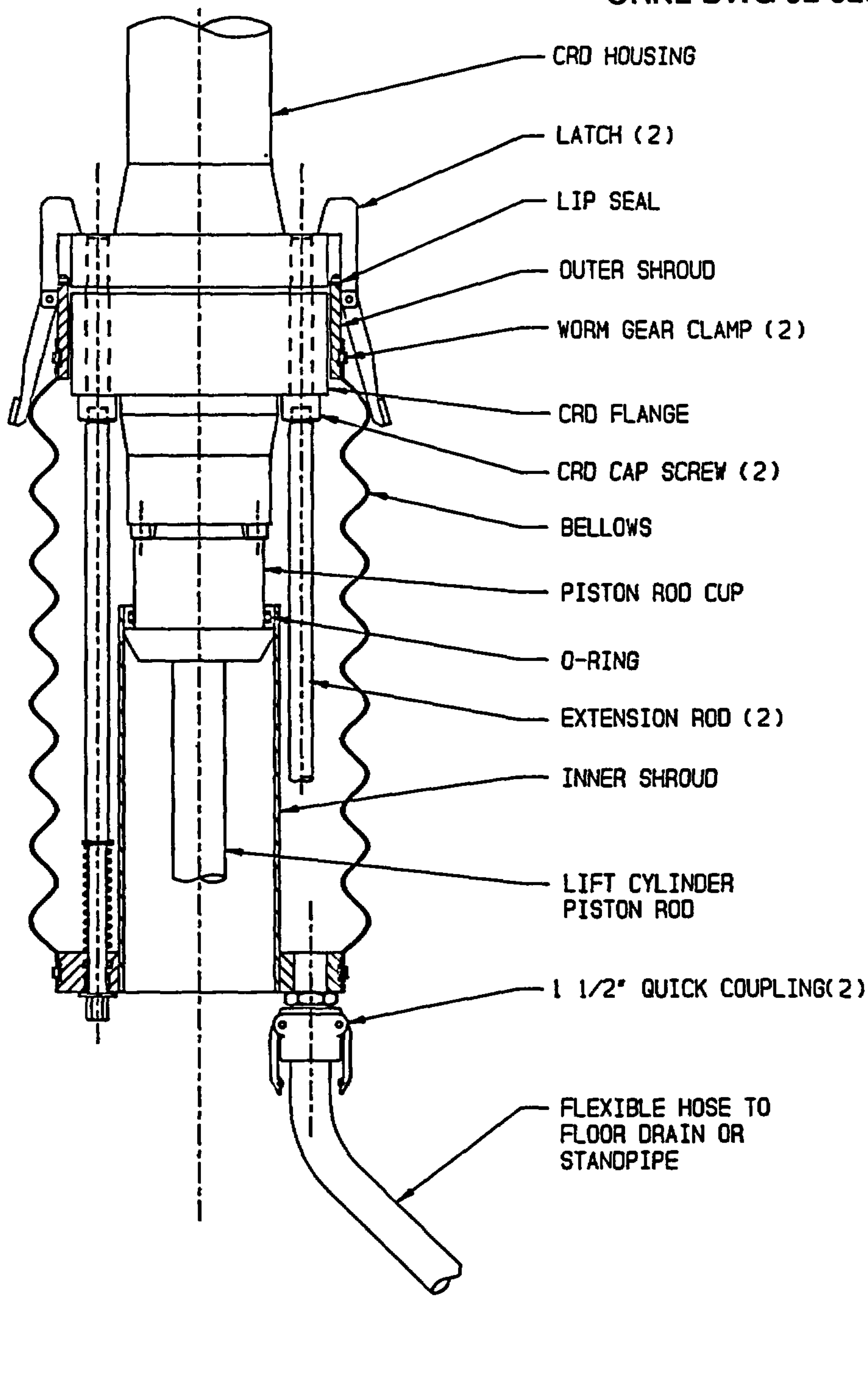

Figure 5.3 CRD handling device drain boot.[34]

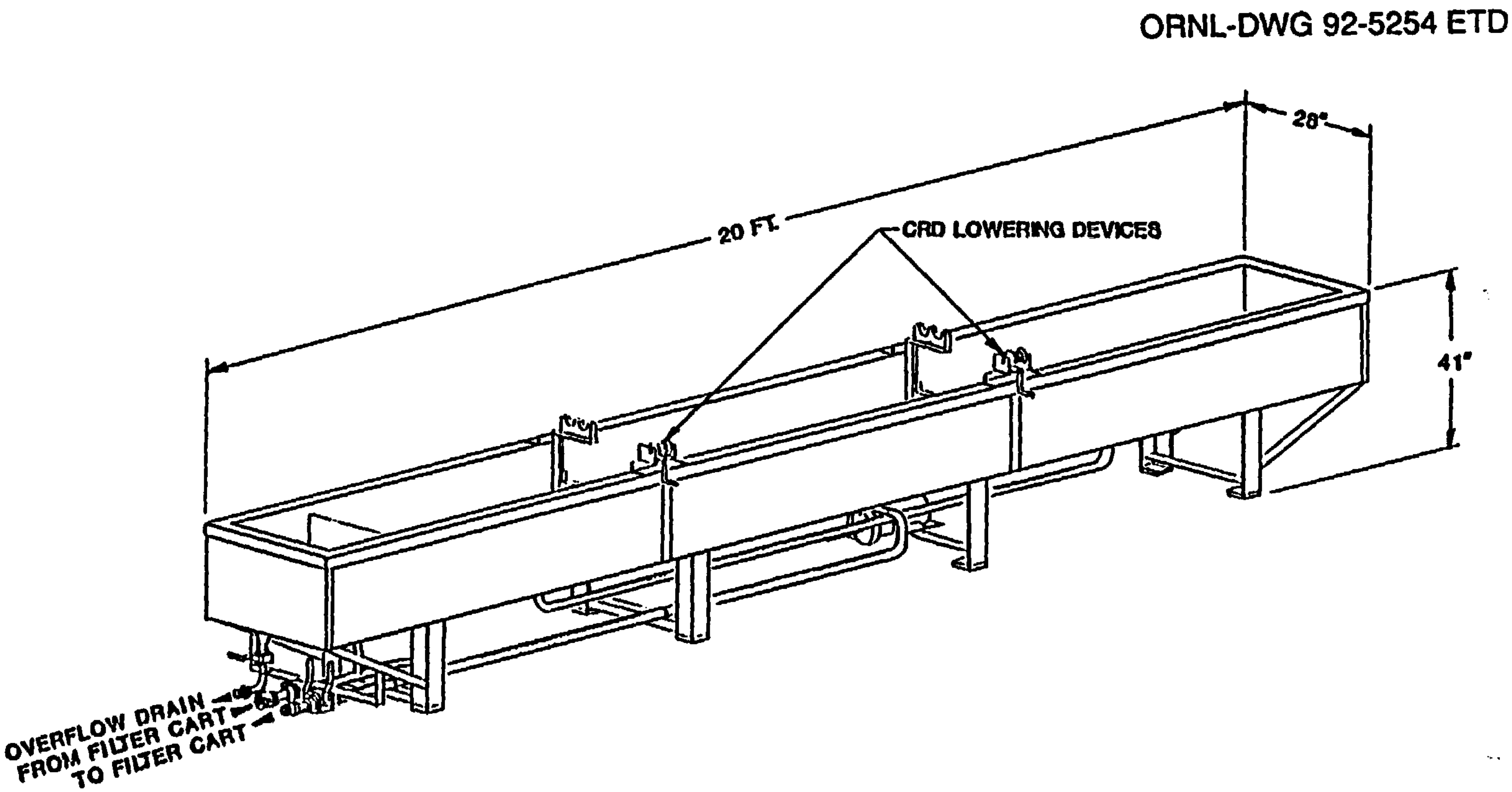

Figure 5.4 CRDM flush tank.[35]

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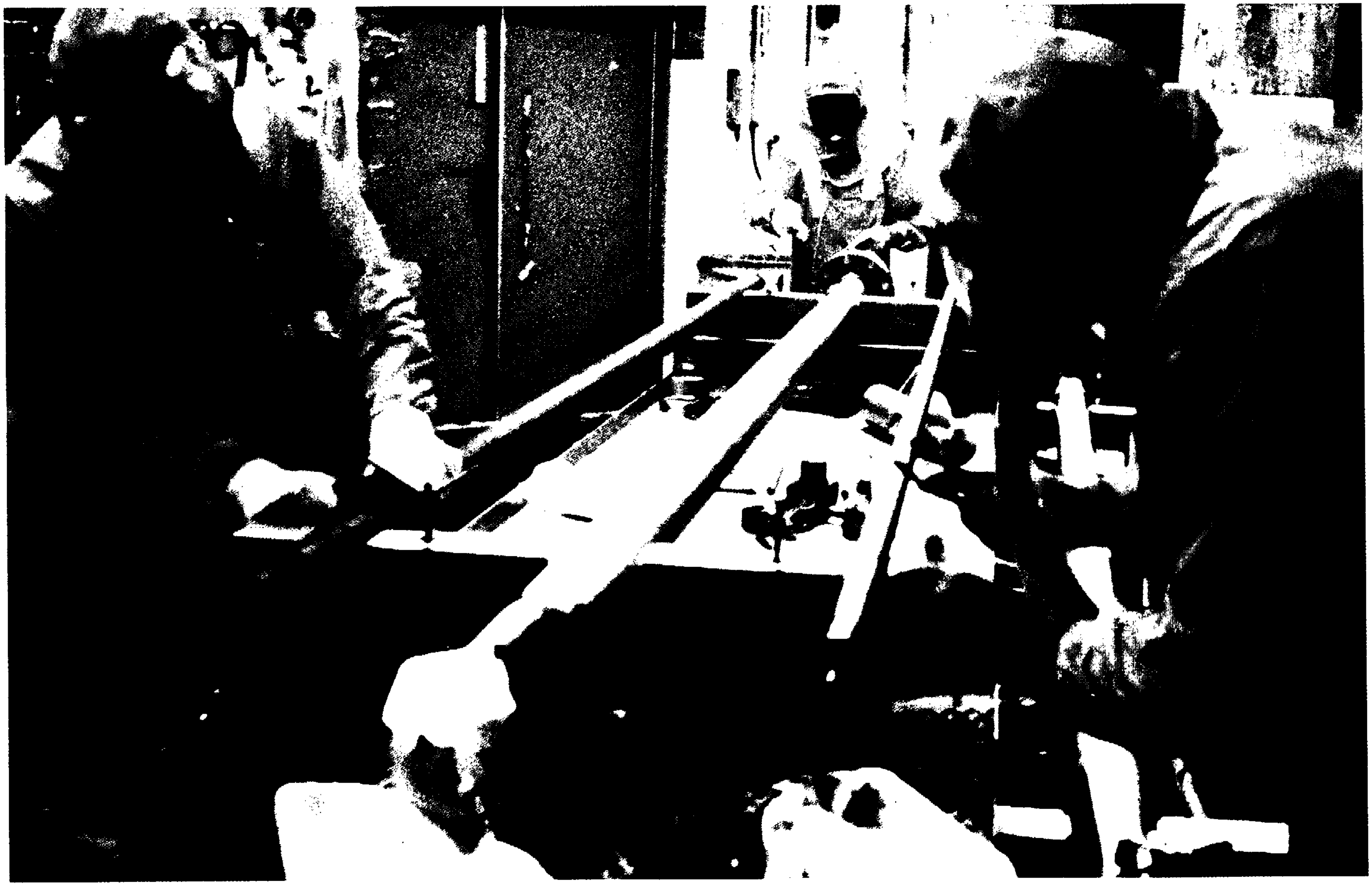

Figure 5.5 Rebuilding a CRDM on a table.

tubes. Other features may include drive supports and lowering devices to accommodate the cleaning and manipulation of various components that comprise the 450 lb, 15 1/2 ft-long CRDM. The primary drawback of flush tanks is their space requirements. Several CRDM Aging Workshop attendees stated they simply did not have enough space in their rebuilding room to accommodate a flush tank. The Toshiba Corporation also has an automatic disassembly and cleaning tank which can be remotely controlled by an operator at a computer console. The device flushes the filters, extracts the index tube, separates the driving piston, and extracts the piston tube all in the same tank. Significant dose reduction could be realized by utilizing this device, but the length requirements for this tank are more than twice that of the other flush tank designs.

5.1.3 Miscellaneous CRDM Maintenance Tools

CRDM maintenance is a high dose, direct-path task, which is performed only during outages, and therefore, it is a job that has visibility for a limited period of time. Daily, weekly, and monthly maintenance activities on plant equipment are likely to take precedence in tooling allocations funded into the plant maintenance budgets. The majority of CRDM rebuilding activities are performed with standard, conventional tools, with the exception of a few specially designed tools provided by the vendor. From a historical perspective, there has been limited advancement and interest directed toward the development of customized CRDM maintenance tools.

To reduce ALARA doses, one utility has decided to advance the state-of-the-art of BWR CRDM maintenance technology. To accomplish this goal, it has reviewed and enhanced maintenance procedures, augmented training and equipment, and also participated in the design and development of a host of tools to be used solely for CRDM installation and rebuilding. Reducing the time required to perform the necessary maintenance is the mandate behind most of these designs. All of the tools have been employed during rebuilding activities at one of the utility's stations, and extended distribution of these devices to its other BWR sites is planned. These tools were also demonstrated at the CRDM Aging Workshop. The following list is not an all-inclusive summary of available specialized tooling but is provided as an example of the measures that some utilities are undertaking to reduce ALARA doses.

- **Precision Super Grip Clamp Wrench**

  As shown in Fig. 5.6, this device replaces the use of the familiar strap wrenches (Fig. 5.7), which have been reported to damage thinly walled components in the CRDM. One workshop attendee also confided "that one time a highly-torqued strap wrench came loose in the technician's wet, gloved hand, its handle spun around and hit the worker in the forehead through the bubble-suit, and knocked him out." The worker recovered fully from the accident, but the scenario demonstrates the precarious nature of CRDM maintenance work, aside from any radiation exposure concerns. The patented thread design features on the Super Grip Clamp Wrench (U.S. patent number 4638994)* provide secure grip-locking capabilities. The clamp is lined with a high coefficient of friction material that will not scratch or damage CRDM parts and uses different color-coded components that match specific CRDM tube diameters.

- **Collet Guide Cap Plug Puller**

  Displayed in Fig. 5.8, this self-centering device pulls plug pins straight out without damaging other CRDM components. After the plug is engaged, the short stroke arms are lowered to obtain its quick removal. The procedure used is very similar to removing a cork from a bottle.

- **Cooling Orifice Screw Driver**

  This device, shown in Fig. 5.9, is designed to be a precision fit to the cooling orifice set screw and capture the screw before it is completely removed. Historically, standard small-head screwdrivers have been used which did not fit the screw head groove well and inadvertently damaged the cooling-water orifice during the screw removal process.

- **Index Tube Removal Tool**

  Historically, the index tube has been pushed out of the CRDM by using a wooden 2-by-4, rope, and a mallet as shown in Fig. 5.10. Maintenance personnel were frustrated by this practice and developed their own pneumatically operated, index tube-removal tube displayed in Fig. 5.11. Not only was the rebuilding job expedited, but the risk of damaging the CRDM internals by repeated mallet strokes was alleviated.

There are also two piston tube nut-removal tools (designed around different principles) that can be used during CRDM changeout and rebuilding activities. CRDM maintenance specialists have said much about the history of damaging undervessel instrumentation during this task, because long-arm wrenches were used to loosen and tighten the nuts in this area of very tight clearances. Either of these two devices can be used to preclude the likelihood of damaging surrounding instrumentation during CRDM changeout.

*Personal Correspondence to R. H. Greene, (Martin Marietta Energy Systems, Oak Ridge Natl. Lab.), from B. J. Gogarty, BGI Tooling, Elgin, Ill., August 10, 1991.

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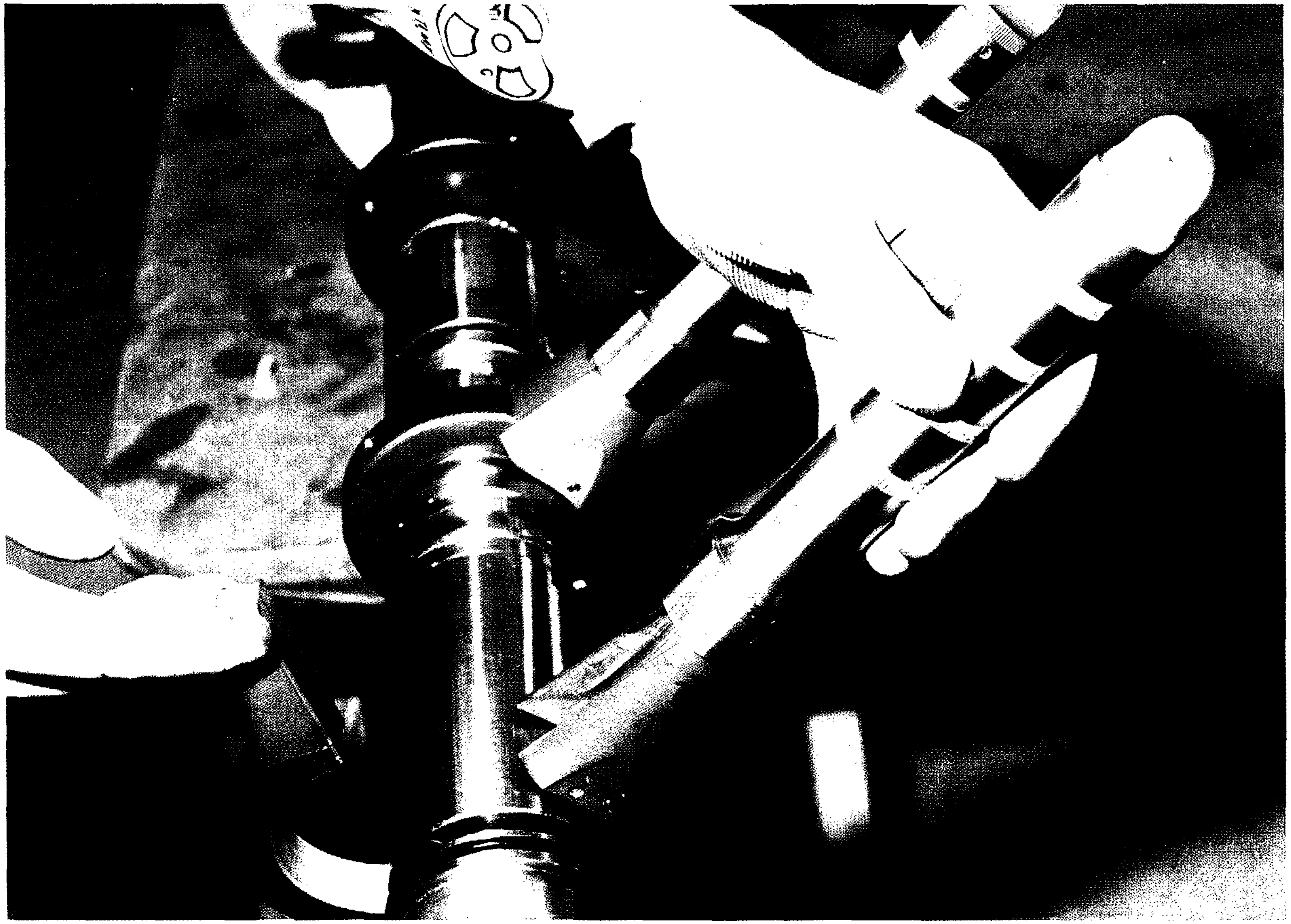

Figure 5.6 CRDM component disassembly using super grip wrench.

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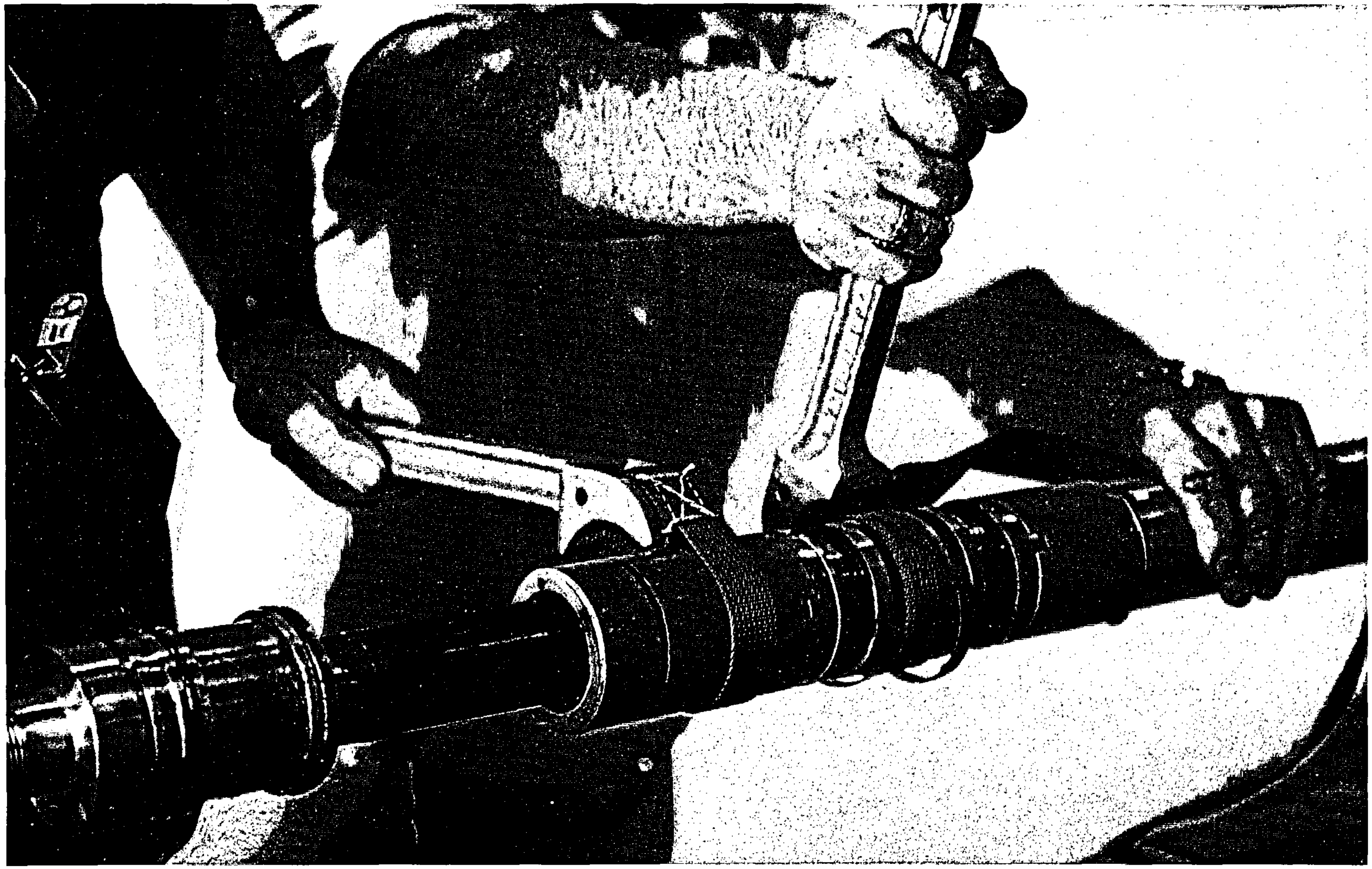

Figure 5.7 CRDM component disassembly using conventional strap wrenches.

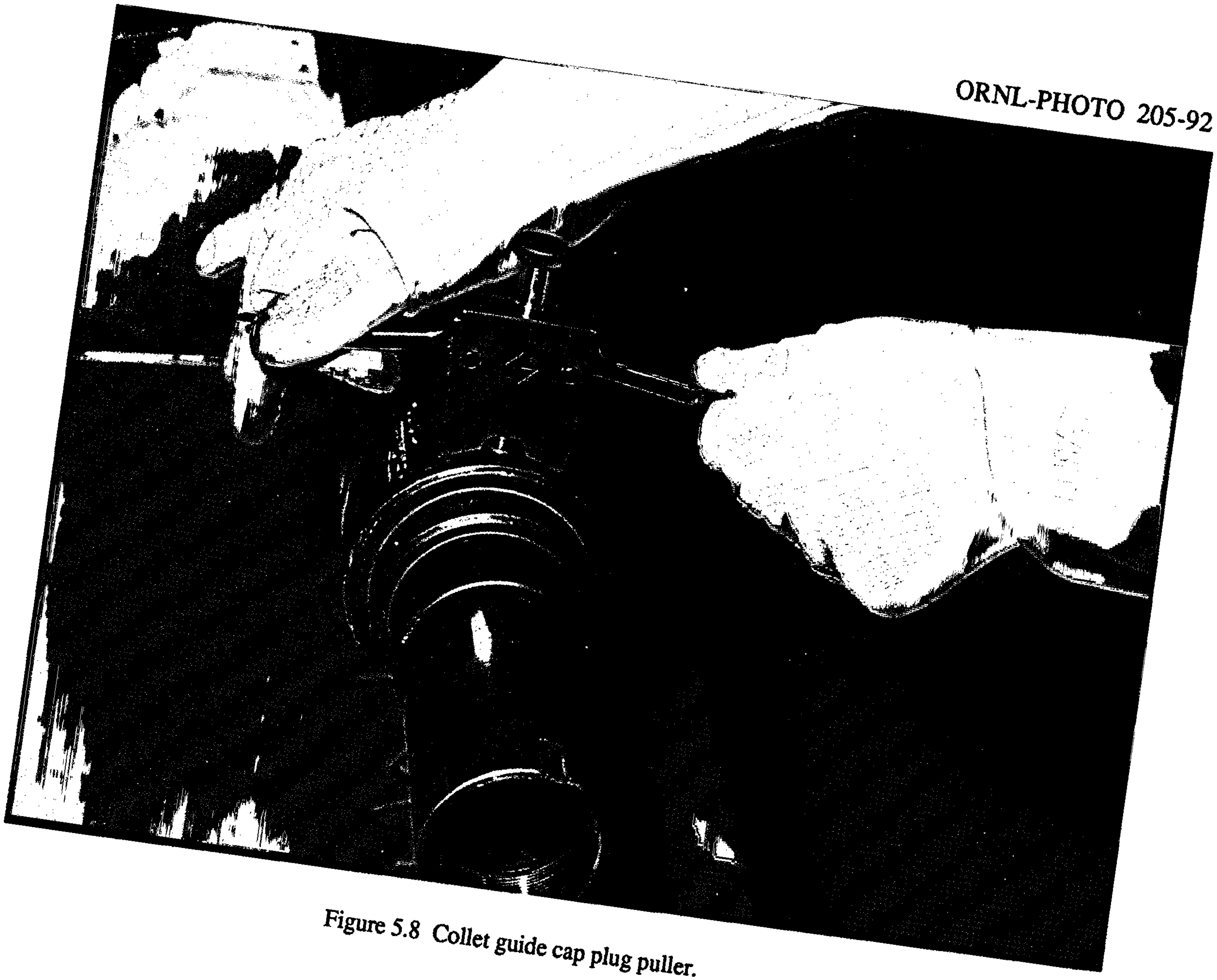

Figure 5.8 Collet guide cap plug puller.

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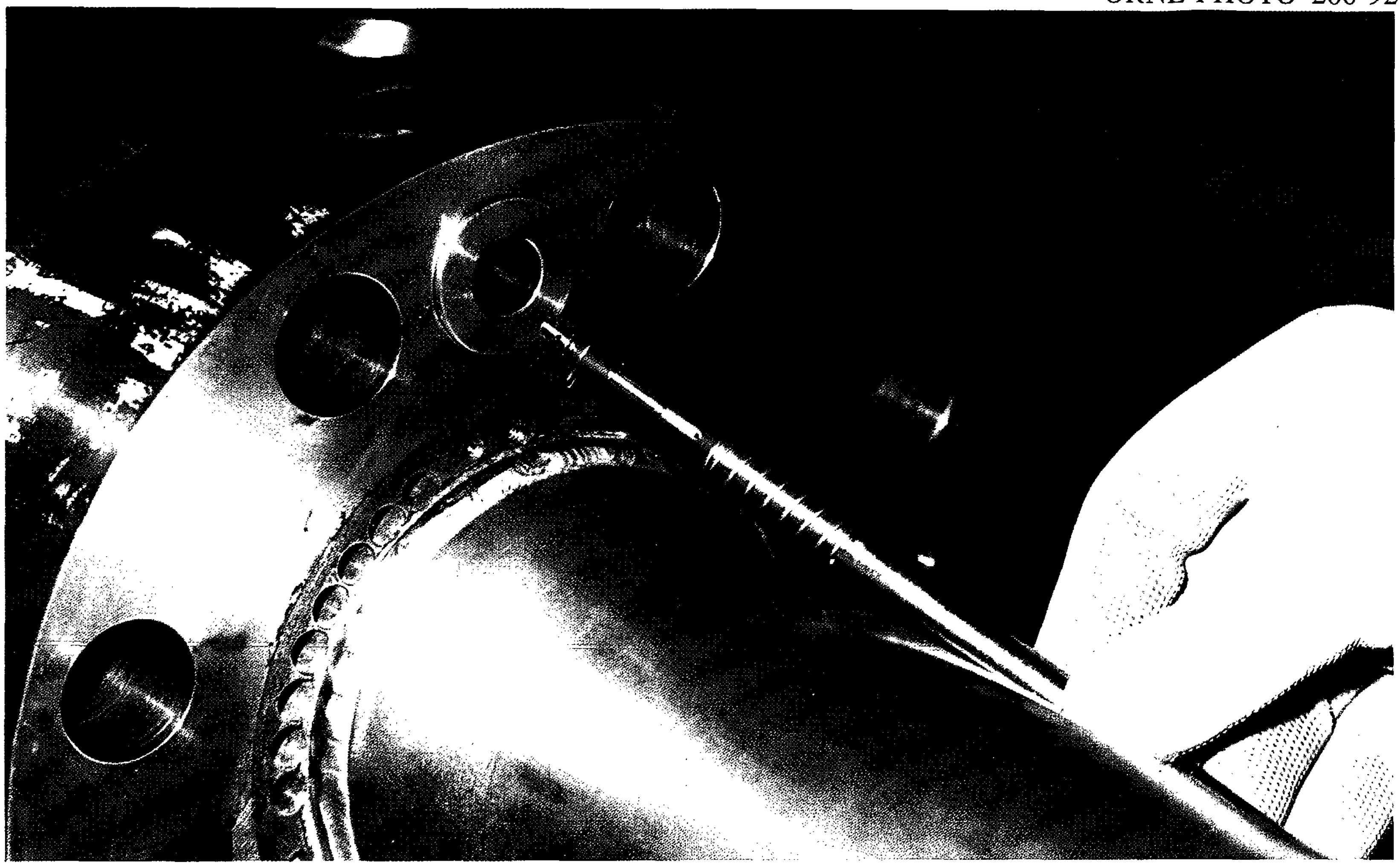

Figure 5.9 Cooling orifice screw driver.

ORNL-PHOTO 207-92

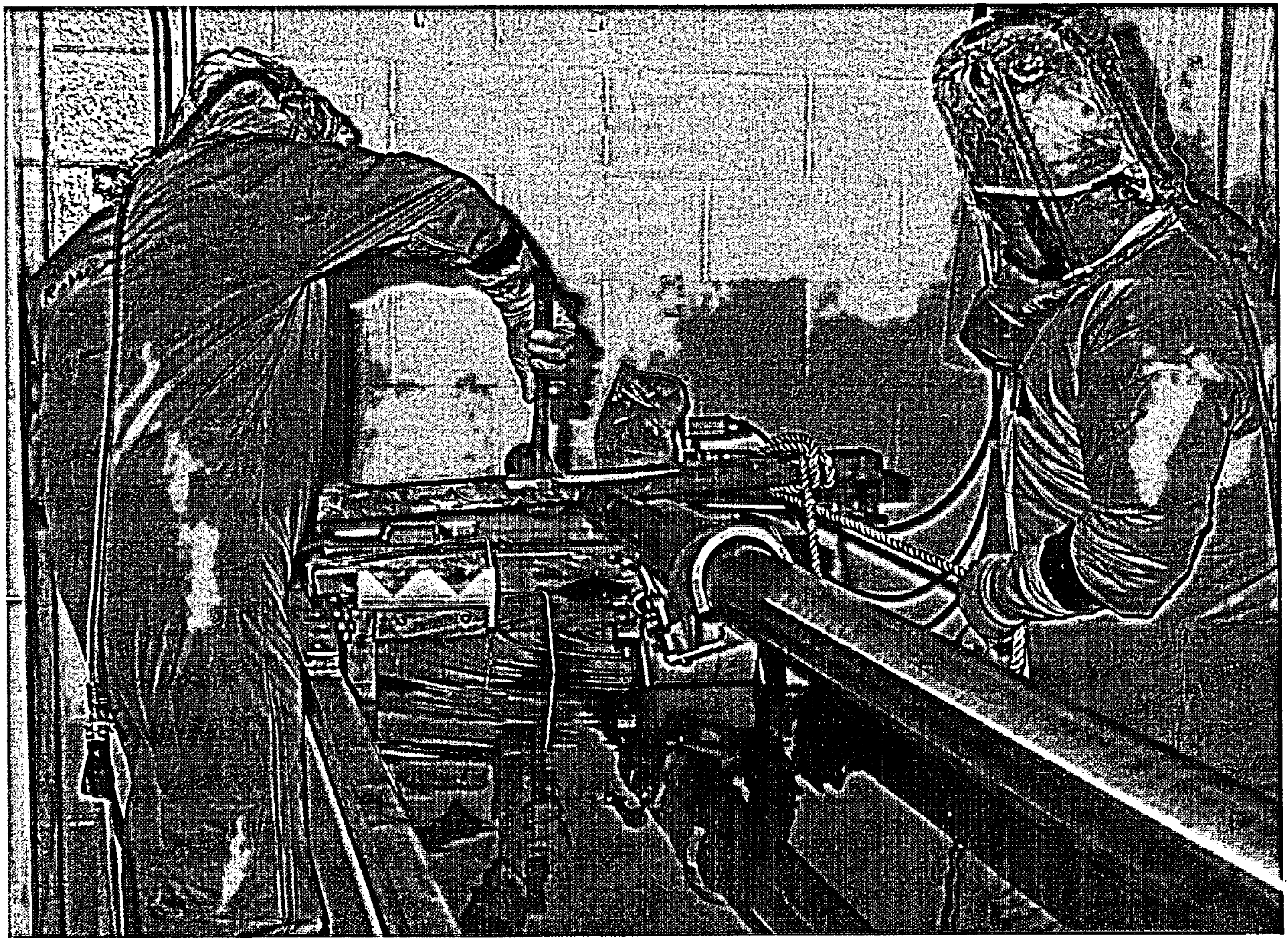

Figure 5.10 Index tube removal using wooden 2 by 4, rope, and mallet .

ORNL-PHOTO 208-92

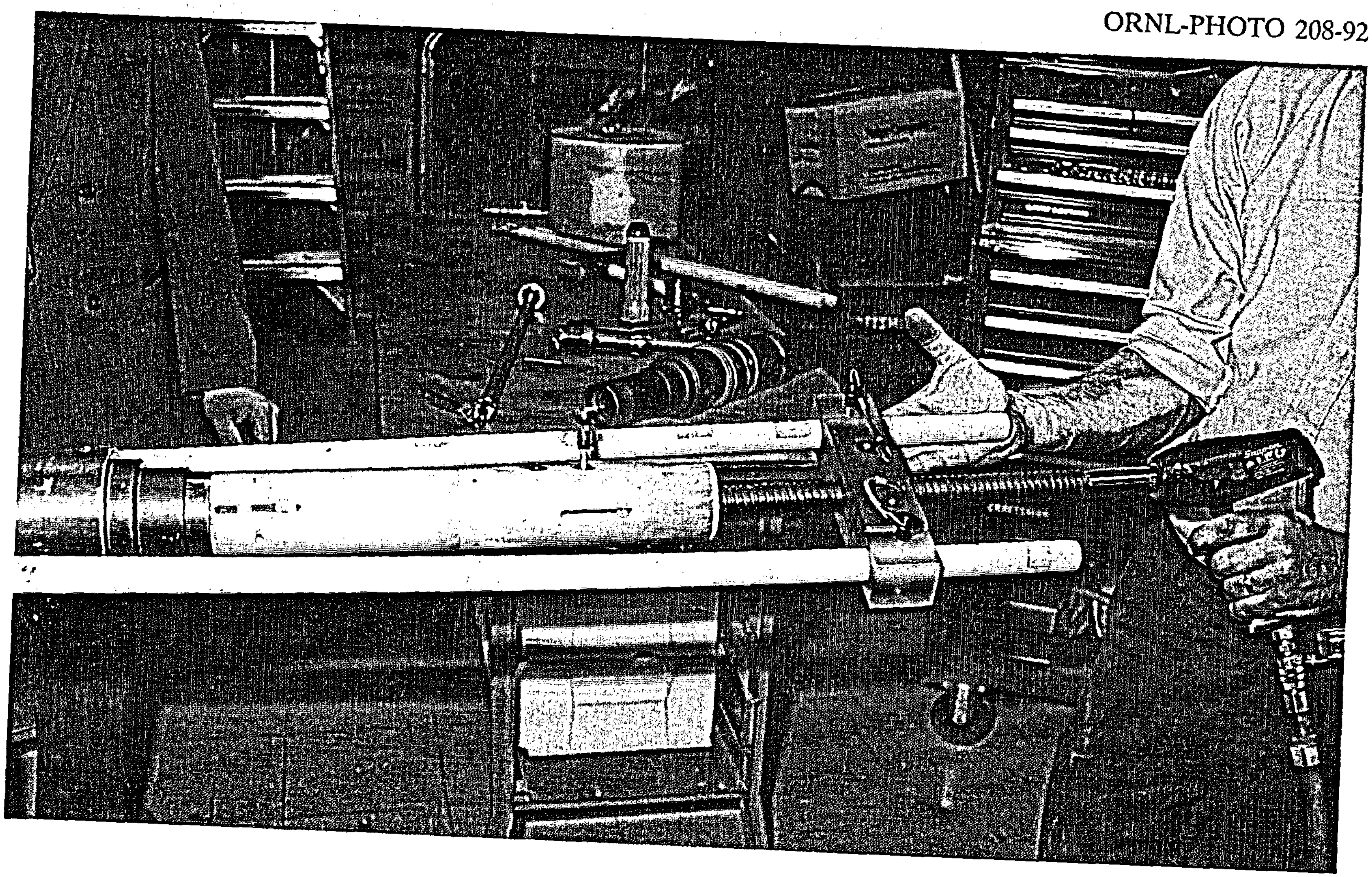

Figure 5.11 Index tube removal tool.

- **Free Wheeler**

  This device, as shown in Fig. 5.12, uses principles of kinetic energy to remove the piston tube nut during CRDM removal and rebuilding. By spinning the wheel with a twist of the hand, the nut can be loosened or tightened. The free wheeler also adapts to a certified torque wrench to measure applied torques. It replaces large, long-arm, openend wrenches, which have been used under the vessel, and due to lack of clearances have also inadvertently damaged undervessel instrumentation.

- **Piston Tube Nut Extension Wrench**

  This long wrench, displayed in Fig. 5.13, can be used undervessel to loosen or tighten the piston tube nut by applying a torque with the lateral handbars. Under the vessel, these handbars are located at a chest-to-waist elevation on the individual using it, thus clearing instrumentation that remains suspended from adjacent CRDMs not being changed out.

5.2 ALARA Shielding and Shielding Tools

ALARA shields are temporarily installed under the vessel area prior to CRDM changeout activities to reduce the dose to the maintenance workers. There have been both positive and negative reports concerning the use of these devices. For those plants regularly handling CRDMs that have unshielded activities in the range of 100 to 200 R/h, the ALARA shields do, on the average, result in a lower received dose for the entire task (the sum of all worker exposures). For those stations that have drives exhibiting much lower activities (and many plants fall into this category), the doses received during the installation and removal of the ALARA shielding might negate any dose benefits realized by an efficient changeout crew. Therefore, CRDM maintenance workers will probably benefit from ALARA shielding only if the undervessel dose rates are considered high.

Along the same principles, some stations are using shielded inner and outer filter-removal tools that have reduced the exposures to the rebuild crews. Shielded CRDM storage centers also have been retrofitted into some plants, because the maintenance staff was receiving doses not only from rebuilding the drives but also from the "hot" drives awaiting maintenance that were also being stored in the rebuild room.

Substantial doses have also been received when the CRD housing support structure (alias "shoot-out steel") is removed from under the vessel prior to CRDM changeout work. One plant has a conveyor system that quickly transports these weighty structures from the drywell and stores them in a location that prevents them from being a continuous source of dose to other workers.

5.3 Health Physics Enhancements

When faced with the task of reducing ALARA, one must remember the general rule, which states that "time, proximity, and source equals dose." One of the benefits of the CRDM aging workshop was the opportunity for attendees to compare ALARA reduction ideas between their plants. Some of the ideas mentioned in the questionnaire and also during conversations at the workshop are presented in the following paragraph.

At least one utility has assigned the radiation monitoring requirements of the CRDM changeout and rebuilding tasks to only those health physics (HP) personnel who have completed the CRDM changeout and rebuilding training. The feedback received from the HP staff was implemented into existing procedures so that the task could be completed in accordance with ALARA dose reduction goals. Furthermore, during the outage activities at one site, the (CRDM-trained) HP supervisor in charge of monitoring changeout activities gave a "pep talk" to workers prior to the job's performance. In an informal setting (which occurred during the worker's meal break), the supervisor discussed the previous day's maintenance activities. He commended certain actions, cautioned about some problem areas, and invited questions from the maintenance crew prior to performing the upcoming tasks. This activity promoted a very beneficial information exchange and also served to establish a comradery between the maintenance workers and HP staff. In addition, several contract workers who had performed CRDM maintenance tasks at various different plants stated that it was not unusual for HP personnel to institute "job holds" during changeout activities that were the result of a lack of understanding about the work that was occurring. In their opinions, these unnecessary delays caused a waste of time, money, and dose.

5.4 Changeout of CRDMs Exhibiting Unusually High Activities

During the changeout activities at one utility, workers encountered some extremely "hot" drives, one of which had an activity of 300 R/h (contact) on the outside of the lead-shielding pig. This high degree of activity is very unusual for normal CRDMs, and it was speculated as to what could cause such high readings. One scenario suggested was that a fuel cladding failure had occurred and released fuel particles that had travelled through the guide tubes and become entrapped into the filters of the drive. Another premise cited the similar entrapment of cobalt-60 particles produced by the activation of stellite components used inside the reactor vessel or in the primary system (e.g., CRA pins and rollers). Stellite removal and reduction techniques will not be addressed in this report, but with either premise in consideration, how can a utility prepare maintenance personnel for work with CRDMs exhibiting unusually high levels of activity?

ORNL-PHOTO 209-92

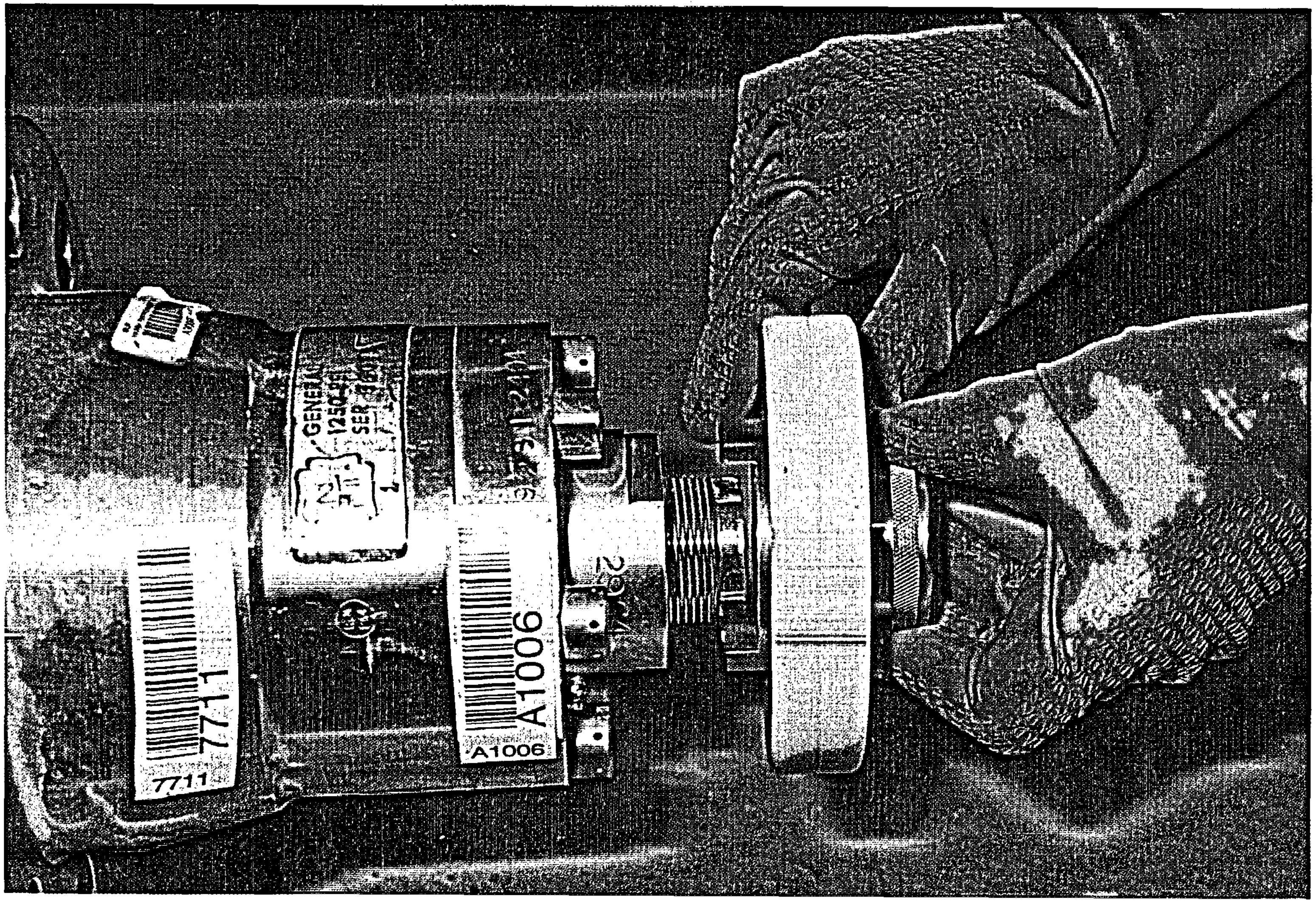

Figure 5.12 Free wheeler piston tube nut removal tool.

ORNL-PHOTO 210-92

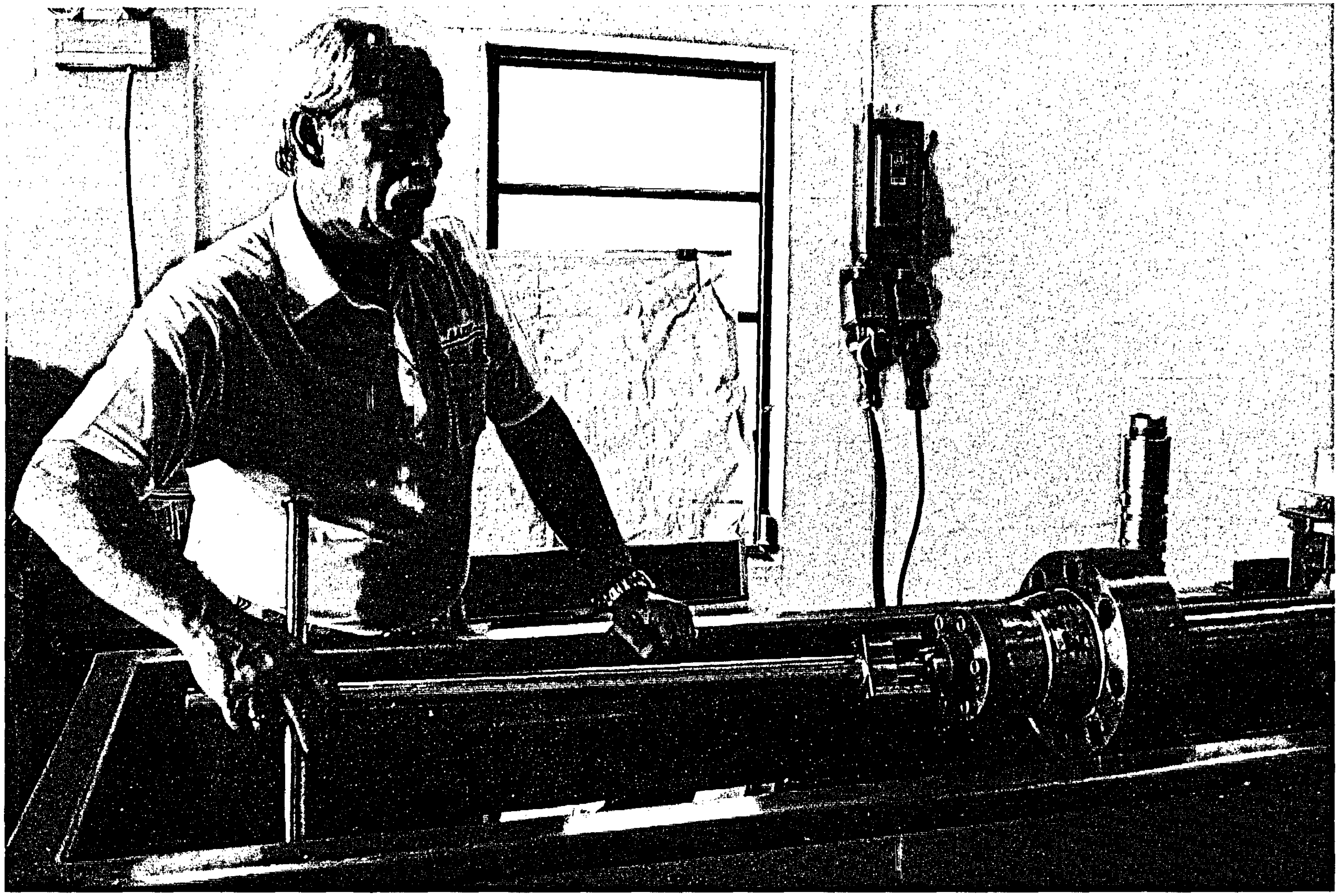

Figure 5.13 Piston tube nut extension wrench.

First, establish a history of fuel failures for the reactor. This information is regularly researched and maintained by utility fuel engineers. This particular utility had experienced 108 fuel failures within a specific nine-year span of operation. During the last cycle, no fuel failures were observed. Any drive that was in service during a cycle that did have a fuel failure could store released fuel particles in its inner and outer filters. These particles would probably remain in the filters until the drive was cleaned and rebuilt. If there have been any fuel failures at a utility, the health physics personnel should also be made aware that it could affect the level of activity normally anticipated during CRDM changeout tasks.

Secondly, health physics personnel should have an auxiliary or backup plan to implement if extremely high CRDM readings are encountered. This particular scenario was described to a health physics supervisor (also trained in CRDM removal) at another utility, which routinely handles some of the more active CRDMs in the industry. He stated that their unshielded reading limit (taken as the CRDM is lowered from the reactor vessel) is 400 R/h. If the reading was higher than that, the CRDM was to be immediately returned to the reactor so that the crew could revise the work plan. However, this procedure may not be feasible if the utility is still using the electric winch system, since it may take more time (and hence more dose) to replace the drive back into the vessel than if the crew had continued the work and removed it as quickly as possible. The health physics supervisor further commented that since their plant had one of the improved CRDM handling devices, it not only expedited maintenance activities but also provided workers with more timely options when encountering unusually high activities during CRDM changeout.

Thirdly, if the CRDM is suspected to contain fuel particles, and since this is "spent fuel," by some degree, it is likely to contain some amount of the transuranic elements normally found in spent fuel. Some of the actinide elements undergo spontaneous fission and generate neutrons, specifically, the isotopes of plutonium (atomic weights of 238, 239, and 240) and curium (atomic weights of 242 and 244). The lead shielding used to block high levels of gamma and beta radiation at the spud end are not effective in blocking neutrons. Furthermore, CRDM maintenance personnel are not required to wear any neutron dosimetry. If the CRDMs contain spent fuel particles, there is also the possibility that workers handling CRDMs are receiving a small neutron dose that is not currently being measured or accounted. Since current monitoring techniques accurately quantify the amount of gamma activity being emitted, a way was sought to reasonably estimate the amount of neutron activity that might exist based on the observed gamma activity.

A neutron-to-gamma dose ratio was sought for spent BWR fuel. Using shielding analysis techniques employed for spent fuel transport casks, a rough estimate of this ratio was calculated using the following information sources:*

1. The analysis was performed with the SAS1 sequence of the SCALE[37] code system.

2. The source terms for the BWR fuel are from a SAS2H/ORIGEN-S depletion analysis.

3. The radiation source in the fuel was calculated for a GE 8- by 8-ft assembly with an average enrichment of 3.0 wt % 235U, burned to 30 GWd/MTU, and cooled (a) 30 days for first case and (b) 10 years for the second case. With these two time intervals, it was hoped to compare the differences in activities observed between fuel failures that might have occurred from recently to as long as 10 years ago.

4. The cask model, which examines the variation in activities along the length of the fuel rod has a smeared fuel region in the cask cavity with 30 mesh intervals.

The average ratios resulting from these two analyses are 1.0×10^{-5} to 1.0×10^{-4} (R/hr) for 30 days and 10 years of cooling time, respectively. These values also include quality factors. The results indicate that if neutron emitting isotopes were responsible for part of activity measured from the filters located at the spud end of a CRDM, the maximum amount of neutron activity of this source might be one ten-thousandth of the measured gamma dose. For the scenario cited above, the CRDM that measured 300R/h (shielded in a lead enclosure) might measure between 1500 to 3000 R/h unshielded, and if it contained spent fuel particles, the maximum continuous neutron dose (since lead does not shield neutrons) is estimated to be 150 to 300 mR/h.

The objective of this analysis was to estimate the amount of neutron dose that might be received by maintenance personnel working with unusually high-activity drives. In addition, it was learned that the lead shielding pig, which shields the ever-present gamma and beta radiation in these devices, will not protect the worker from a possible neutron dose. Since these neutrons may travel many feet, according to their energies, increasing the distance from the source does not always ensure an appreciable lower dose. One simple, preventive measure that utilities could implement to mitigate possible neutron exposure from entrapped fuel particles is the use of a "neutron" pig for shielding: a design that uses an inner, hydrogenous material to thermalize any neutrons (like Plexiglas), permeated with a neutron-capturing material (like boron), which is then surrounded with a lead lining (to shield workers from gamma radiation). Numerous light-weight materials are specifically designed for neutron shielding

*Internal correspondence to R. H. Greene from M. C. Brady, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., July 29, 1991.

that would not add appreciable weight to the current design pigs. Since CRDM changeout requires closeup work performed at "arms length," the use of a "neutron" pig would reduce some of the concerns HP personnel may have if extremely hot drives are encountered during CRDM changeout activities.

6 Conclusions and Recommendations

The overall objectives of the Phase I study on the BWR Control Rod Drive System are to (1) examine the operational histories of BWR CRDMs, (2) determine the predominant modes of aging, (3) evaluate the tests and methodology that utilities employ to determine CRDM degradation, and (4) recommend measures that utilities can implement to mitigate CRD system aging. Table 6.1 and the following discussion summarizes the information compiled on these topics with respect to the CRDM, HCU, and BOCRDS.

6.1 CRDM Aging Summary

Nearly 23% of the NPRDS CRD system component failures were attributed to the CRDM. The predominant course of action taken by a utility to restore this device to service requires the removal of the CRDM from the reactor vessel (during a maintenance outage) and installation of a new or rebuilt CRDM. The CRDM components most often requiring replacement due to age (or service wear) are the Graphitar seals and bushings on the drive and stop pistons. The predominant causes of aging for these seals are mechanical wear and thermally induced embrittlement. CRDM operating temperatures >120°C (250°F) can reduce the service life of the Graphitar seals. In addition, crud that becomes collected between the seal sets can create uneven force distributions at the seal's contact surfaces during scrams and cause the seals to degrade prematurely. To mitigate Graphitar seal aging, utilities should (and in some cases already do) (1) restrict CRDM operating temperatures to <120°C (250°F) and (2) remove excess crud from the reactor vessel by vacuuming in and around the guide tubes during maintenance outages.

Both GE and Toshiba have improved Graphitar seal designs for BWR CRDMs that offer enhanced strength and endurance properties. It is anticipated that using the improved designs instead of the conventional design will extend the service life of a CRDM between rebuild maintenance, but there is no operational data to support this theory. The CRDM changeout histories for U.S. BWRs suggest that service life of a CRDM varies with respect to core location. The service life of a CRDM is reported to be 3 to 5 years for a centrally located CRDM and about 10 to 15 years for a peripherally located drive, depending on water chemistry. Currently, utilities change out an average of 15.6% of their CRDMs per cycle. One measure that utilities could undertake to help distribute any radiation-induced effects of aging due to core location is to implement a simple CRDM rotation scheme: place rebuilt CRDMs in core locations opposite their previous service history. That is, if a CRDM had been in a central core location, the next time it is placed in service (after rebuilding), assign it to a core location closer to the periphery. This practice may not always be possible, but if the utility has the option, the service locations of their CRDMs should be rotated.

Another CRDM component that might have a service life limitation are the cylinder, tube, and flange assembly made from wrought type 304 stainless steel. IGSCC has been found in the collet housing of the pre-BWR/6 designs (CRDM models A, B, and C). GE attributed this cracking to the thermal cycles occurring during hot scrams, followed by exposure to oxygenated CRDM cooling water. In its subsequent CRDM model designs, GE used cast 304L stainless steel in the CTF assemblies, and to date, has received no reports of IGSCC. There have also been reports of IGSCC in the eight cap screws that secure the CRDM to the housing flange. GE has recently released an improved design cap screw that is made from materials resistant to IGSCC.

Other CRDM components exhibiting aging-related degradation are the spud, C-springs, and those tubes having nitrided surfaces (piston and index tubes). The spud and C-springs are made from Inconel alloy X-750. The C-springs are normally replaced during rebuilding activities, but the spud is usually not replaced. Reports of the spud fingers becoming somewhat soft and easily bent are not uncommon on CRDMs having a service history of about 15 years. Although there have been no metallurgical examinations performed on an affected spud, the cause of degradation is probably metal fatigue resulting from an extended length of service. There are also reports from CRDM service specialists of nitrided parts not being reusable because of questionable surface conditions. Corrosion on nitrided surfaces is not uncommon, but there are also indications of the surface thinning and being easily scored with a relatively soft object, such as a piece of wood. Both of these effects are not understood, and metallurgical studies could be conducted on both the CRDM's Inconel alloy X-750 parts and nitrided components to accurately assess and determine the causes of degradation.

6.2 HCU Aging Summary

More than 59% of the NPRDS CRD system failures were attributed to the HCU. This device is a gallery of valves, and the valve components normally subject to aging, such as packing, seals, discs, seats, stems, diaphragms, etc., are also degrading in the HCU. The HCU valves requiring the most maintenance in the NPRDS are the accumulator nitrogen charging cartridge valve (111), the scram discharge riser isolation valve (112), the inlet and outlet scram valves (126 and 127), and the scram pilot valve assemblies and their solenoids (117 and 118). Since the latter two are safety system solenoids that are normally energized, it has been recommended that the solenoid temperatures be routinely monitored and trended by using an industrial pyrometer. Solenoid coil degradation may be indicated by changes in operating temperatures. In addition, the Buna-N disc material in the pilot valves is known to have a limited service life, and GE has

Table 6.1 Summary of predominant BWR CRDM system degradation sites and mechanisms.

DEGRADATION SITE	STRESSORS	DEGRADATION MECHANISMS	POTENTIAL FAILURE MODES	APPLICABLE MONITORING METHODS/RESPONSES
CRD system pumps	Bearing failure due to oil contaminants and normal service wear	Mechanical wear, mechanical loading, impeller erosion, and seal wear	Loss of pump redundancy in the CRD cooling water supply system	Historical trending of vibration analysis data acquired at bearing location on CRD pump housing to assess anticipated service wear
CRDM collet housing (pre-BWR/6 designs)	Thermal transients to wrought 304 stainless steel housing caused by numerous hot scrams	Shallow cracking of the metal caused by IGSCC	Circumferential separation of the CRDM.	Dye-penetrant methods during CRDM rebuilding using GE SIL 139 specifications
CRDM stop & drive piston Graphitar seals	Thermal transients, prolonged operating temperatures >250°F, entrapped debris, scram impacts	Thermally induced embrittlement, mechanical wear, cracking & breakage	Hard-to-move drives requiring repeated increases in drive pressure, double-notching of rods, "02" scrams	Routine collection & trending of CRDM operational data to determine possible degradation. Compare data with Tables 4-1 and 4-2 in NUREG/CR-5699 to assist with the selection of CRDMs for rebuilding.
CRDM spud	Fatigue from mechanical loading from repeated scrams occurring during a prolonged service history (usually 10 to 15 years)	Low-cycle fatigue causing spud fingers to lose their resiliency (over 10 to 15 years of continuous service)	Uncoupling of control rod assembly	Repeated uncoupling history problem with individual CRDM which has not been rebuilt in several years; visual inspection during rebuilding showing bent, non-concentric spud fingers
CRDM Graphitar seal C-springs	Preloading from prolonged service (usually 10 to 15 yrs) and corrosive water	IGSCC, breakage	Improper Graphitar seal seating causing hard-to-move rods	Withdrawal and insert stall flows exceeding 5 gpm, history of increased drive pressures required to move the rod
CRDM cap screw hold-down bolts	Mechanical loading, entrapped, corrosive moisture when CRDM installed, overtorquing of bolts (>350 ft-lbs) during installation	Stress corrosion aggravated by MnS inclusion in cap screw material	Cracked bolts, measurable leakage of reactor water from lower vessel head during startup operations	Dye-penetrant testing is the most accurate method. Visual inspection methods vary and are subject to error. Affected bolts can be upgraded to new IGSCC resistant bolts

Table 6.1 Summary of predominant BWR CRDM system degradation sites and mechanisms (cont.).

DEGRADATION SITE	STRESSORS	DEGRADATION MECHANISMS	POTENTIAL FAILURE MODES	APPLICABLE MONITORING METHODS/RESPONSES
HCU scram water accumulator	Low pH, high chloride water conditions causing corrosion of the carbon steel tank which, in turn, causes blistering and flaking of the tank's inner chromium plating	Corrosion of carbon steel tank; corrosion flakes collecting on inlet scram valve Teflon seat causing leakage; corrosion flakes also plugging the cooling water orifice and negating CRDM coolant flows	Repeated high water level alarms; unplanned individual rod insertion; elevation in CRDM temperatures	Upgrade to stainless steel design tank when HCU operational problems require that the HCU accumulator be maintenanced
HCU accumulator nitrogen charging cartridge valve (equipment part number 111)	Worn valve packing due to normal service wear and or misinstallation	Mechanical wear	Leakage resulting in repeated low accumulator pressure alarms in the control room	Preventive maintenance program requiring scheduled replacement of U-cup packing due to normal service wear (requiring strict adherence to vendor recommended installation guidelines)
HCU inlet and outlet scram valves (equipment parts 126 and 127)	Erosion of Teflon seat from high accumulator flow during scrams; normal aging of Buna-N diaphragm	Erosion, wear of valve seat; cracking of Buna-N diaphragm causing leakage	Improper valve seating and/or cracking of Buna-N diaphragm causing unplanned rod movement	Preventive maintenance program requiring scheduled replacement of diaphragms due to known service life limitation of Buna-N material
HCU scram pilot valves and solenoids (equipment parts 117 and 118)	Thermal degradation & cracking of Buna-N disks, oil and water contaminants in instrument air supply prematurely degrading Buna-N disks. Normal aging of the solenoid coils since they are normally energized.	Cracking of Buna-N diaphragm causing leakage. Normal wear of solenoid coils.	Unplanned rod movement, unplanned scrams, or delay in scram times	Tech. Spec. scram timing, preventive maintenance program requiring scheduled replacement of scram pilot solenoid valve assemblies due to known service life limitation of Buna-N material. Trending solenoid coil surface temperatures to detect sudden increases that foretell imminent coil failure
Scram discharge volume vent and drain valves	Entrapped debris in valve seat causing valve to "stick" when actuated	Erosion, wear of valve seat	Sticking valves may cause reactor water leakage	Routine scram discharge volume valves cycling and timing

recommended their routine replacement in plant preventive maintenance programs.

The scram water accumulators (125) that had tanks made from carbon steel have experienced a large amount of corrosion due to low pH water conditions at various plants. This degradation is exhibited by repeated high accumulator water level alarms in the control room. Many utilities are replacing these carbon steel accumulators with the improved stainless steel design on an as-needed basis.

6.3 BOCRDS Aging Summary

About 18% of the CRD system failure reports in the NPRDS were attributed to components that were not located in the CRDM or the HCU. There were 44 failure reports on valves associated with the scram discharge volume, and 27% of these reports cited entrapped debris as the cause of failure. One utility blamed a prolonged shutdown for the dirt and corrosion products accumulated on the seat of a drain valve. Utilities should trend the results of scram discharge volume valve actuation tests that are conducted to determine any buildup of debris that may cause these valves to stick.

The CRD system pumps and pump components had 54 and 63 failure reports, respectively, in the NPRDS. The causes of component degradation are mechanical wear (for the bearings), erosion (for piping and impeller wear), and service wear (pump seals). Vibration measurement programs that incorporate frequency analysis techniques that characterize misalignment, looseness, bearing problems, and other operation anomalies can be employed to detect the degradation of the CRD system pumps as well as other plant rotating equipment.

Of the entire 3432 component failures reported to the NPRDS on the CRD system, there were 207 reports on electrical components and 79 reports on instrumentation. The primary cause of failure reported for these two groups of components was normal service wear.

6.4 Recommended Component Design Enhancements

The CRDM has a good service history at the U.S. BWR plants. The majority of the problems that have been experienced by this component, the HCU, and the BOCRDS have been addressed by the vendor through its service information letters. There is, however, one problem that has been encountered in CRDM operational history that could be alleviated through a design change. The attachment configuration of the inner filter to the stop piston is a precarious connection that is easily defeated if misassembled. If the inner filter becomes disengaged, it can cause control rod uncoupling. The Toshiba Corporation has already instituted a design change in the inner filter base configuration to circumvent this problem, and it is recommended that GE investigate a similar course of action.

With ALARA dose reduction goals taking a increased emphasis due to 10 CFR 20 changes, this study recommends that a "neutron" shielding pig be designed to adequately protect maintenance workers from any neutron dose that may be emitted from spent fuel particles entrapped in the CRDM filters. Currently, neutron dosimetry is not required for CRDM maintenance crews. The estimated neutron dose, even for high gamma activities, is limited. Unless the CRDM and its filters are placed under water (such as in a flush tank), the neutrons are not shielded, and the workers receive an unnecessary dose. Neutron shielding is off-the-shelf technology, which could easily be incorporated into an improved "pig" design.

6.5 Recommended Analysis Practices

Most utilities completing the CRDM aging questionnaire felt that the current battery of tests conducted to verify the operability of the CRD system did adequately forewarn them of any system or component degradation. This opinion is substantiated by the NPRDS analysis, which indicates that 72% of the reported system component failures were discovered by scheduled testing or routine observation. There was, however, a great deal of interest from workshop attendees regarding the need to automatically maintain a historical trend of some of the routinely acquired data, such as CRDM operating temperatures and stall flows, to determine component degradation. Most of this information is currently trended manually or, in a few cases, not at all.

The computer industry offers a host of various data base management software that can be readily used with a personal computer. The NPRDS analysis was performed with this kind of software. Data are easily incorporated into these data bases. Many of these programs also provide graphics packages that can be used to display and trend these operational performance data. These capabilities can augment any systems analyst's ability to organize and readily retrieve data for diagnostic purposes.

6.6 Training and Maintenance

Because CRDM maintenance is performed under some the most limiting and compromising conditions for workers in the nuclear industry, enhanced training is the most important step a utility can undertake to reduce the human error contributions to CRDM changeout and rebuilding. Increasing the level of comfort of the maintenance crew is also a recognized contributor to reducing maintenance mistakes. CRDM undervessel mock-ups are very beneficial to adequately training workers with the changeout environments. Enhanced maintenance equipment, such as the EPRI design CRDM handling and exchange tool, not only expedite work schedules but offer health physics staff options for dealing with high activity CRDMs that might not be feasible with the electrical winch equipment. CRDM flush tanks can also augment maintenance activities by reducing doses and making components easier to handle during rebuilding. Tools that are customized for CRDM rebuilding can reduce not only ALARA doses but can also prevent some of the damage that might occur to CRDM components during disassembly.

The primary cause for CRDM maintenance is the normal wear and aging of the Graphitar seals. In January 1992, GE made improved Graphitar seals (with greater strength and durability properties) available in the form of a replacement seal kit, but the vast majority of BWR utilities are still using the original design Graphitar seals in their CRDM rebuilding programs. If the new seals do perform in the field according to laboratory test results, the increased service life should translate to less radiation exposures by reducing the amount of required CRDM maintenance. By reviewing the CRDM changeout history of each BWR unit, utilities can easily determine which core locations have required the most maintenance. These locations, which are usually centrally located and are assumed to have the most challenging operational environments, are good candidates for replacement with CRDMs that have the improved Graphitar seals.

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Appendix A. BWR CRDM Aging Questionnaire

Nuclear Plant Aging Research Questionnaire on BWR Control Rod Drive Mechanisms

Instructions: Please fill out this form with data that is as accurate as possible. Send the complete form along with any attachments to: R. H. Greene, Oak Ridge National Laboratory, P. O. Box 2009, Oak Ridge, TN 37831-8063.

The intent of the following questions is to obtain data that will identify any significant aging trends that affect CRDM operation and performance. Several questions may require that you use attachments in order to provide all the necessary information. Feel free to do this, however, please identify each attachment with the number of the question to which it pertains.

General Information

1. Please fill in the following information regarding the CRDMs and HCUs at your facility where it is applicable:

CRDM Model Number	Number Currently Installed	Approximate Date of Installation	Number of Spares	Number Retired from Service
7RDB144A				
7RDB144B				
7RDB144C				
7RDB144D				
7RDB144E				
7RDB144F				
7RDB144G				
HCU Model Number				
237E918				
729E950				
761E500				
767E800				
Other:				

2. Please indicate the approximate number of CRDMs at your plant that have operated continuously without refurbishment or replacement: 1 - 5 yrs ______, 6 - 10 yrs _____, 11 - 15 yrs _____, 16 - 20 yrs _____, greater than 20 yrs _____ (the sum of all the answers should total to the number of CRDMs currently in the reactor).

3. Please describe the storage environment of the spare CRDMs and how they are supported in storage. Provide sketches if necessary.

____

____

____

____

Degradation & Failure Experience

4. Does your utility have a regular practice of changing out a minimum percentage of CRDMs during each outage? If yes, please provide the percentage and explain why this number is used:

____

____

____

5. Please describe the selection criteria normally used at your facility to determine which CRDMs will be serviced or replaced during an outage.

____

____

____

6. If *time* is the *only consideration*, how many years or months do you think a CRDM should be operated (assuming its performance is acceptable) before it is rebuilt and why?

____

____

____

____

7. Please review the following list of CRDM and HCU components along with related degra-dation mechanisms. Assign one of the following ranks to describe the importance of their contribution to CRDM or HCU deterioration and/or failure that has been observed at your plant.

1 - Primary contributor to CRDM or HCU operational problems
2 - Occasional contributor to CRDM or HCU operational problems
3 - Rare or negligible source of CRDM or HCU operational problems

Clogged inner filter	______	Worn piston tube o-rings	______
Loose inner filter	______	Worn collet piston rings	______
Clogged outer filter	______	Collet housing deterioration	______
Worn stop piston seals	______	Worn/damaged collet fingers	______
Worn stop piston bushings	______	Worn/flattened spring washers	______
Worn drive piston seals	______	Cooling water orifice clogging	______
Worn drive piston bushings	______	Badly worn check valve ball	______
Worn/damaged collet seal rings	______	Crushed/flattened strainer	______
Loose piston tube nut (before removal)	______	Embrittled spud fingers	______
CRDM installation/removal error	______	CRDM rebuilding error	______

HCU accumulator leakage	______	HCU manifold filter clogging	______
HCU dir. control valve failure/leakage	______	HCU iso. valve failure/leakage	______
Scram inlet valve failure/leakage	______	HCU maintenance error	______
Scram outlet valve failure/leakage	______	HCU component mfg. error	______
Scram solenoid valve failure/leakage	______	CRDM component mfg. error	______
CRDM installation error	______	Other: ______	______
Corrosion (identify parts)	______		______
Embrittlement (identify parts)	______		______

8. What standard components (e.g., seals, bushings, o-rings, etc.) are always replaced during CRDM rebuilding? Please provide a copy of your plant's CRDM disassembly and reassembly checklist procedure. ______

9. In general, what is the condition of the graphitar seals that are removed from a CRDM? (i.e., are they intact, chipped, cracked, badly scratched, ground on the sides, or broken). ______

10. Please describe any unusual yet repeating abnormalities present in any of the parts normally replaced during CRDM rebuilding: ______

11. What steps, if any, has your facility taken to mitigate stress corrosion cracking that can occur in the eight cap screws that secure the CRDM to the housing flange? ______

12. Have you ever had to "scrap" a CRDM because its inoperability could not be repaired? If yes, please give the CRDM ID, core location, and reason(s) for non-acceptance. ______

13. Have you ever had to replace an entire HCU? If yes, please describe the circumstances. ______

14. Does your facility currently or plan to employ the use of hydrogen water chemistry in order to mitigate corrosion activities throughout the plant? If yes, do you think that it is or will make a contribution to improved CRDM performance and why? ____________________

____

____

15. In the CRD system as a whole, are there any particular piping locations that have shown recurring problems from stress corrosion cracking, corrosion, and cyclical fatigue failures that you believe are due to aging, and if yes, please describe them. ____________________

____

____

16. CRDMs which operate around the center of the core are used more often than others to control the power profile. Because of their core location, they undergo more "feet of travel", higher fluxes, and may have a greater rate of failure. For the purpose of vali-dating or invalidating this theory, please provide the number of times, at each core loca-tion, that the CRDMs that been replaced during outages that have occurred throughout your plant's operational history. Use the format below to tally the data. Please attach a core map of each operating unit with the questionnaire. Use additional sheets as needed.

LOCATION: ______ TIMES ______ LOCATION: ______ TIMES ______

LOCATION: ______ TIMES ______ LOCATION: ______ TIMES ______

LOCATION: ______ TIMES ______ LOCATION: ______ TIMES ______

LOCATION: ______ TIMES ______ LOCATION: ______ TIMES ______

LOCATION: ______ TIMES ______ LOCATION: ______ TIMES ______

LOCATION: ______ TIMES ______ LOCATION: ______ TIMES ______

LOCATION: ______ TIMES ______ LOCATION: ______ TIMES ______

LOCATION: ______ TIMES ______ LOCATION: ______ TIMES ______

Maintenance & Aging Interactions

17. Difficult working conditions under the reactor vessel during CRDM changeout may contribute a "human factors" component to CRDM aging. In your opinion, which conditions, e.g., elevated temperatures, high radiation exposure rates, low lighting, disorientation, etc., have the most influence toward improper CRDM maintenance, and has your facility determined any steps that could be taken to mitigate the possible "human error" effects of these conditions?

____

____

____

____

18. Please describe any training that CRDM changeout crews receive prior to the outage. Do you believe that simulated "changeout rehearsals" improve CRDM reliability and why?

____

____

____

____

19. Please describe any training CRDM rebuild crews receive prior to the outage. Do you believe that simulated "rebuilding rehearsals" improve CRDM reliability and why?

____

____

____

____

20. Briefly describe the cleaning methods used for CRDM components that will not be replaced with new ones. Does your facility use ultrasonic cleaning methods for any of the CRDM components, and if yes, can you attribute better CRDM performance to them?

____

____

____

____

21. If your plant has purchased any tools and/or equipment specifically for CRDM changeout and rebuilding that were not originally provided by the vendor, please list. How has each device improved CRDM maintenance activities and/or operational reliability of CRDMs?

____

____

____

22. After a CRDM has been pulled from the vessel, how much time elapses (days, weeks,) before it is rebuilt? ______ Please describe the storage conditions of a CRDM waiting to be rebuilt, including support methods. If you have observed any adverse effects on CRDMs causing by extended storage times prior to rebuilding, please describe them.

____

____

____

23. Do you think that the CRDM strainer, outer filter, and inner filter do an effective job in protecting the drive mechanism from crud in the reactor water? _______ If no, can you make any design or operational recommendation either to the CRDM or reactor water cleanup system that would reduce the amount of vessel crud delivered to the CRDM?

____

24. How has excessive crud in the CRDM affected its performance at your plant? ______________________

____

____

25. Does your facility vacuum the bottom head and/or the guide tubes during outages and, if yes, do you think this procedure has effectively reduced the amount of crud in CRDMs?

____

____

26. Some CRD engineers have observed that BWR CRDMs are becoming more radioactively contaminated with increasing plant age. Have you observed this phenomenon at your facility, and if yes, which CRDM components have experienced this problem? Have you identified the specific radioactive isotopes causing the increased radiation as plants age?

____

____

____

27. In reference to the previous question, how has your facility modified CRDM changeout and rebuilding activities to accommodate the increased exposure rates of older CRDMs? Which modifications were most and least effective?

____

____

CRDM Testing

28. Does your plant perform CRDM leak rate testing and, if yes, when? ______________________

29. Does your plant perform CRDM stroking tests and, if yes, when? ______________________

30. Does your plant perform CRDM friction testing and, if yes, when? ______________________

31. What acceptance criteria must be met before returning a rebuilt CRDM to service at your plant, e.g., are the index tubes tested for sag or "bowed shape?" Describe below:

____

____

32. Does your facility perform any tests prior to installation on rebuilt CRDMs that have been in storage to ensure that the CRDM has not degraded in storage? If yes, which tests?

____

____

____

33. How often do the reactor operators "exercise" the control rods at your plant during normal plant operations? Please describe the surveillance procedure used:

____

____

34. What tests (other than scram and exercise tests) are regularly performed by the reactor operators to ensure that the CRDM is functioning properly? Please provide a copy of each test procedure along with the testing schedule.

____

____

____

35. Do you trend individual CRD stall flow rates and/or CRD temperatures in order to determine if the drive is functioning properly? _________ What are desired values or ranges for these and any other trended parameters at your plant?

High "Insert" Stall Flow Rate _________ High "Withdrawal" Stall Flow Rate ____________________
High CRD Temperature ____________ CRDM Scram Time: __________________________

36. Do you feel that the tests described in the previous questions do an adequate job of predicting CRDM degradation? ____________________ If no, are there any new tests or modifications to current tests that you think would do a better job of determining CRDM degradation? Please describe below:

____

____

____

____

37. Have you observed *any* trends that lead to abnormal operation or premature failure of a CRDM? _____ If yes, please describe the cause and effect relationships that you believe exists and steps that, in your opinion, could be taken to totally avoid or lessen the undesirable effects. Please include any suggestions with regard to design, testing, and maintenance.

____

____

____

The answers you provide to the previous questions will be held in strict confidence by members of the Nuclear Plant Aging Research Program at ORNL. The NUREG research report by ORNL which documents the CRDM aging study efforts will not associate any information contained in this questionnaire with a specific utility, nuclear plant, employee or representative thereof.

Plant Name: ____________________________________

Mailing Address ____________________________________

Plant Contact(s): __________________ Phone: _____________ Yrs. in this position ______

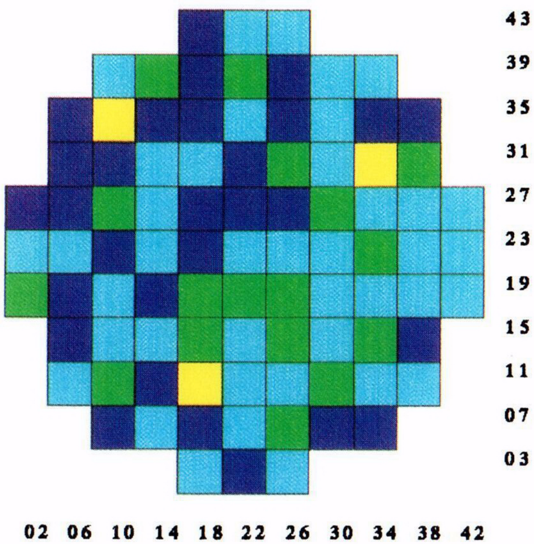
__________________________ Phone: _____________ Yrs. in this position ______

Thank you for your participation in this survey!

Appendix B. BWR CRDM Changeout Histories

Unit A

CRD Changeout History



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3 times
4 times
5 times
6 times

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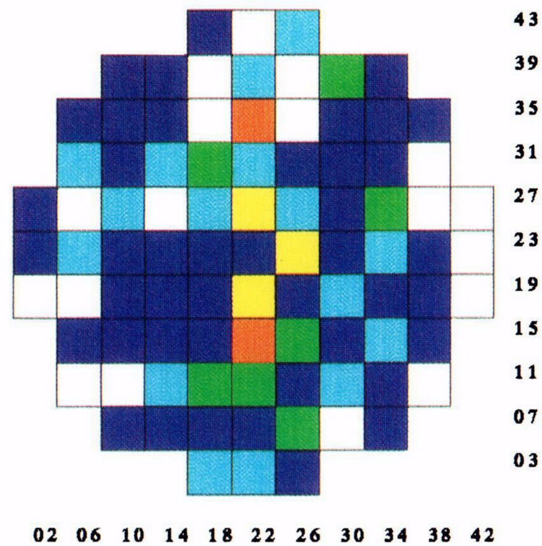
ornl

Unit B

CRD Changeout History



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4 times
5 times
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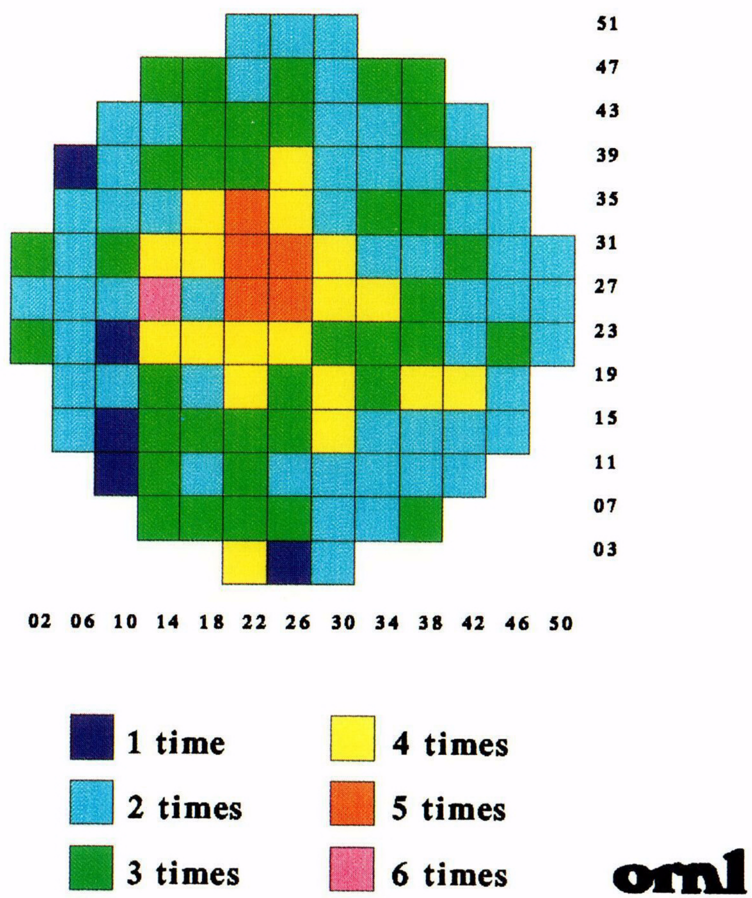
C01

Unit C

CRD Changeout History



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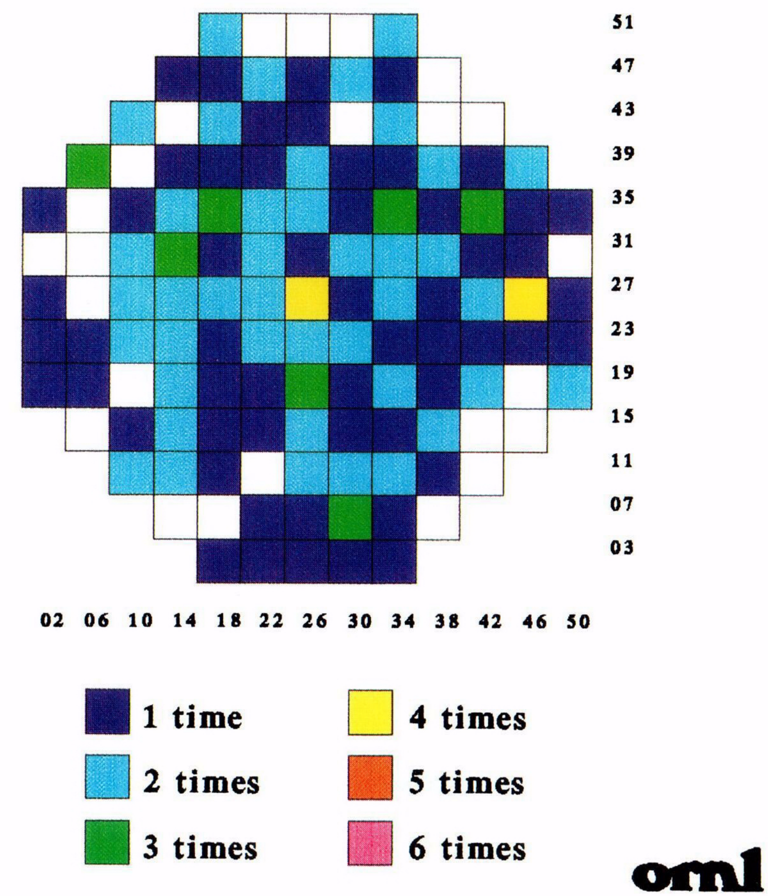
CRD Changeout History



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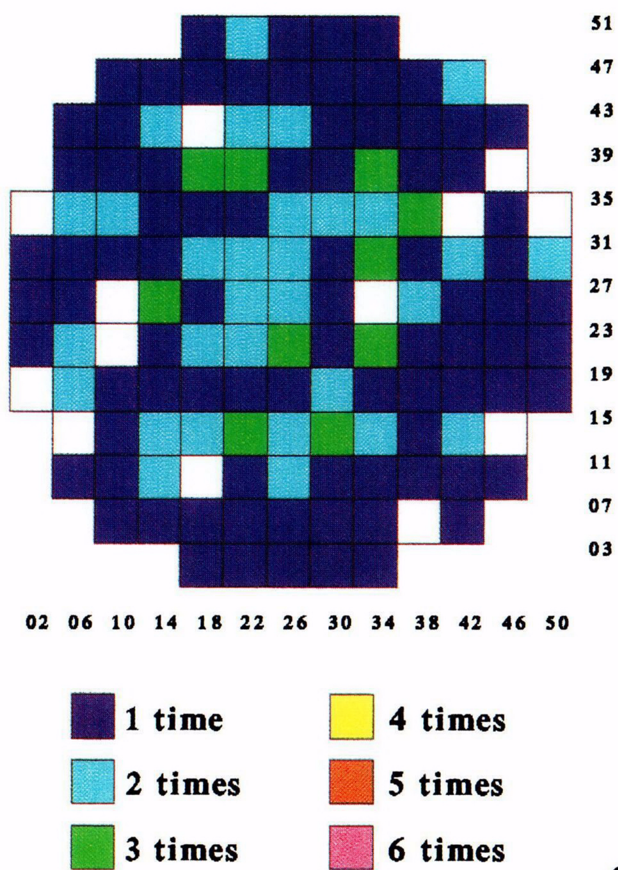
Unit E

CRD Changeout History



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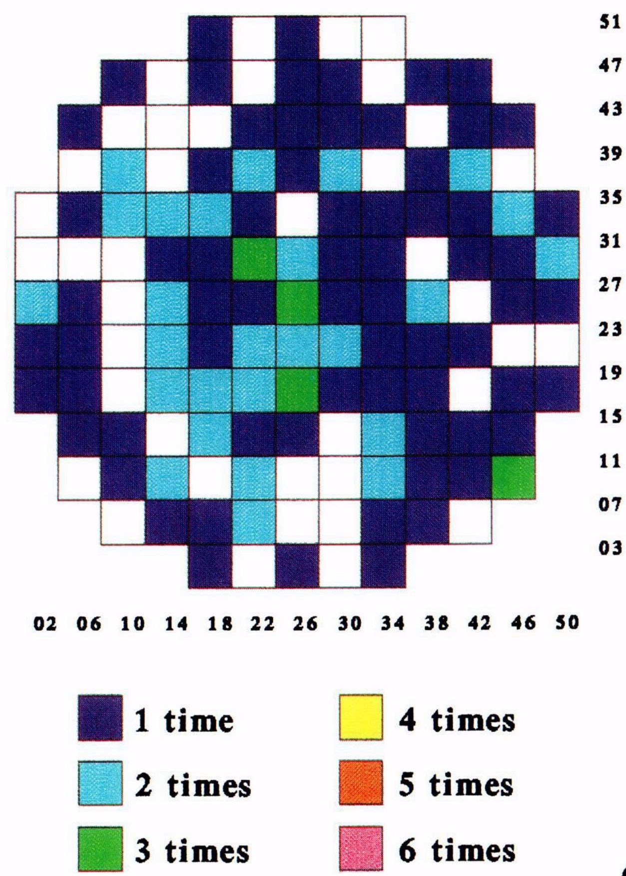
Unit F

CRD Changeout History



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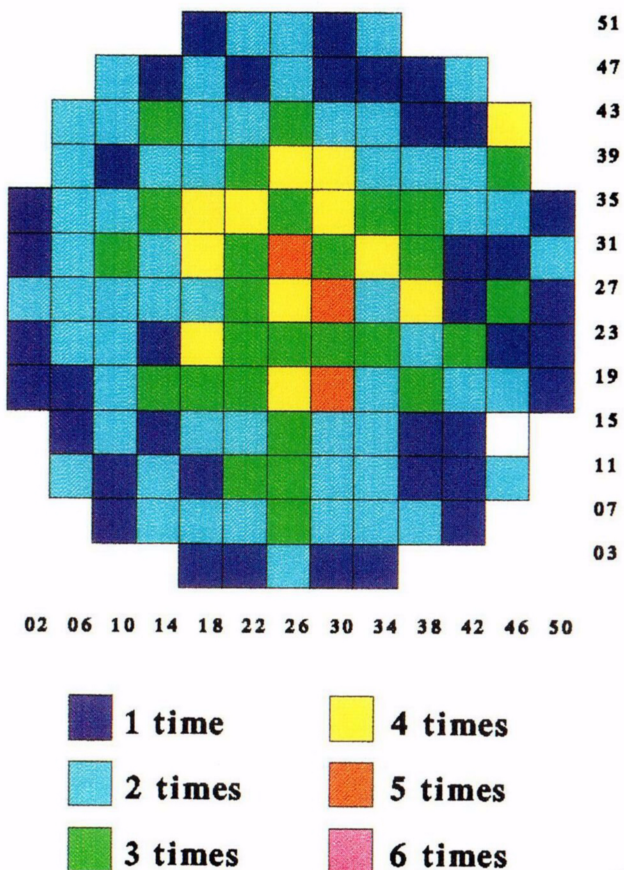
C03

Unit G

CRD Changeout History



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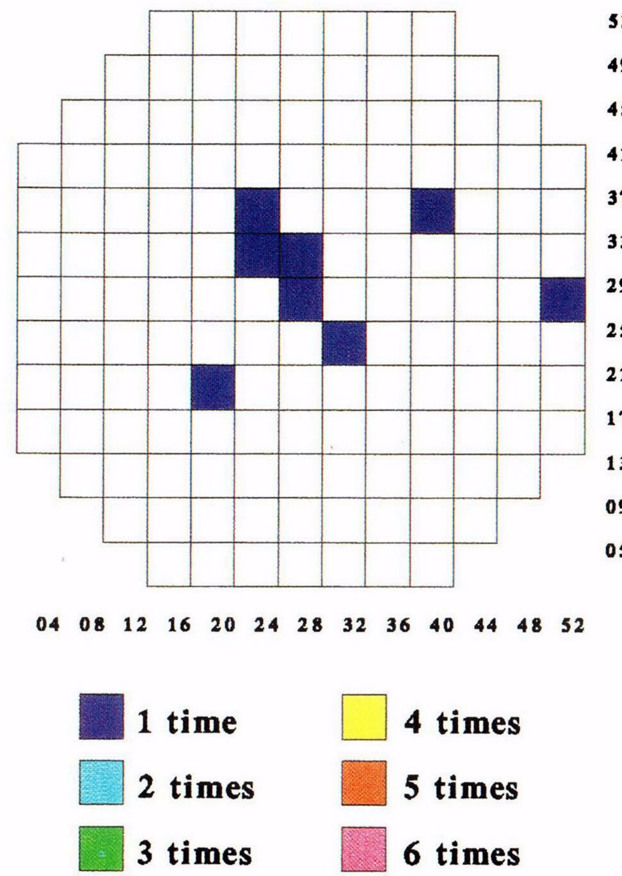
Unit H

CRD Changeout History



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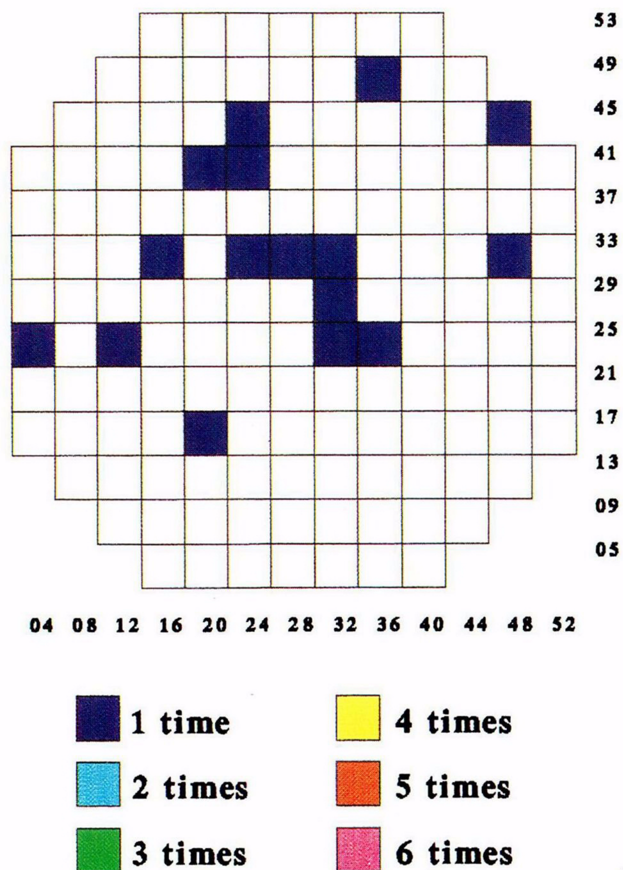
C04

Unit I

CRD Changeout History



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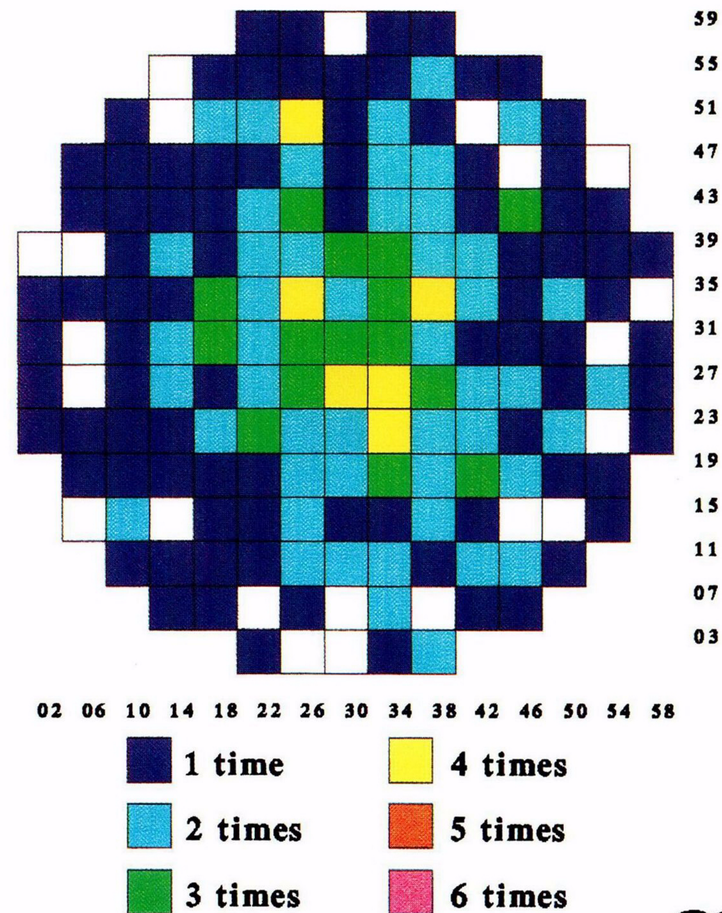
Unit J

CRD Changeout History



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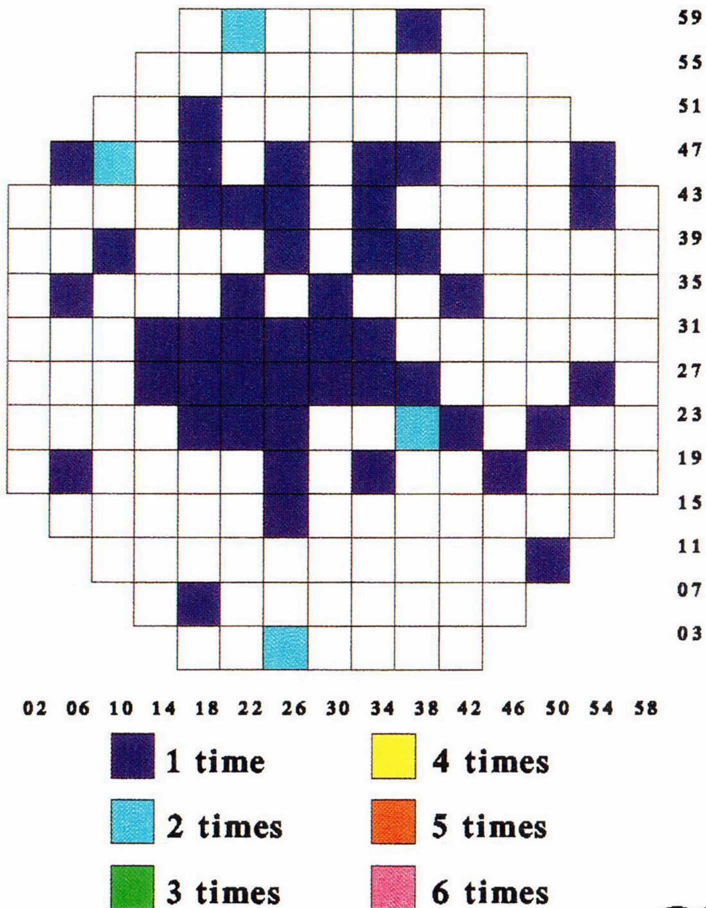
Unit K

CRD Changeout History



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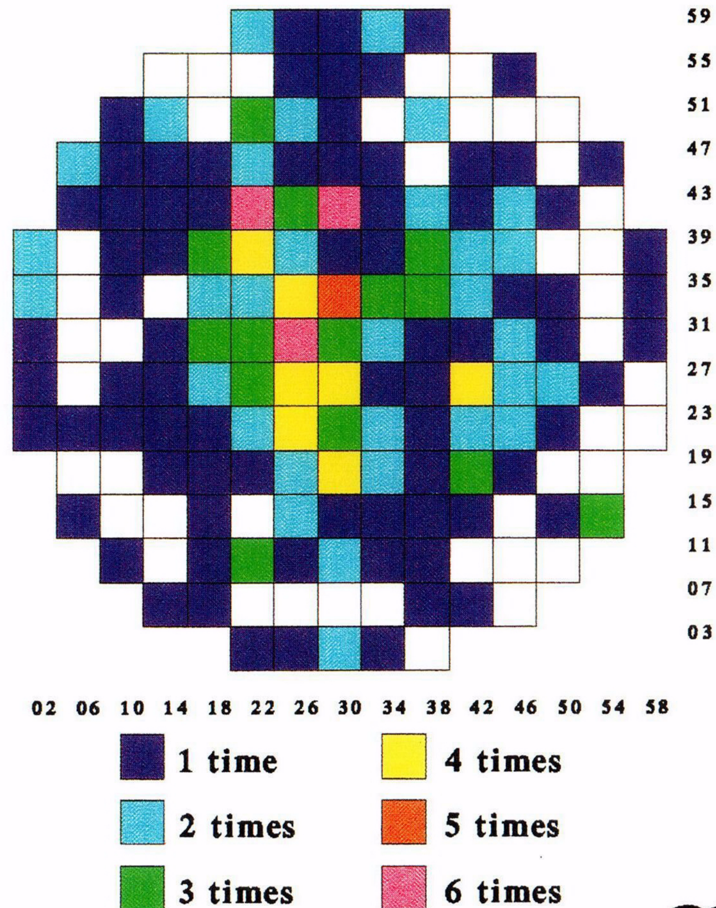
Unit L

CRD Changeout History



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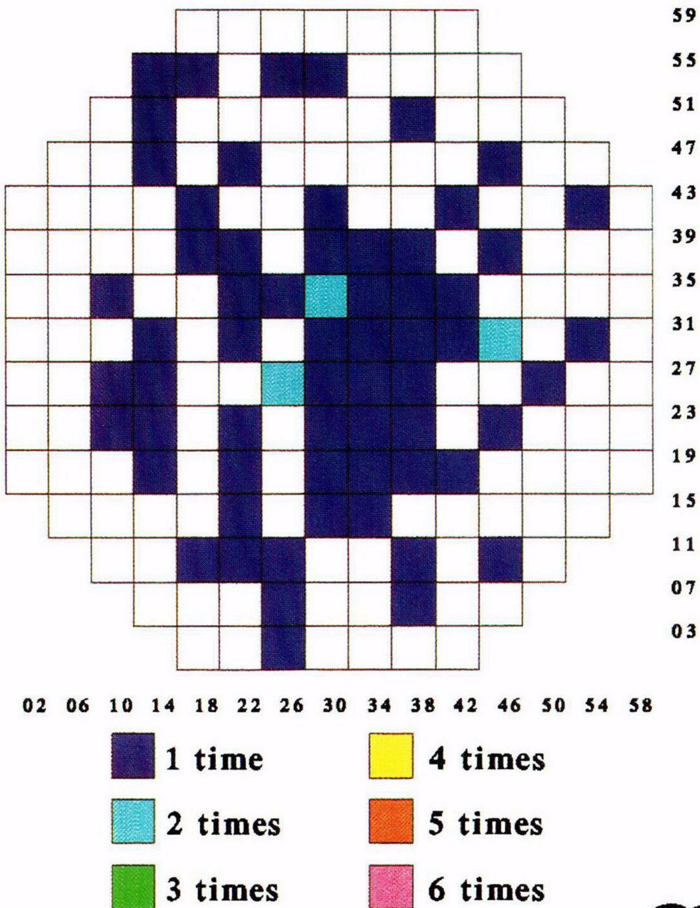
Unit M

CRD Changeout History



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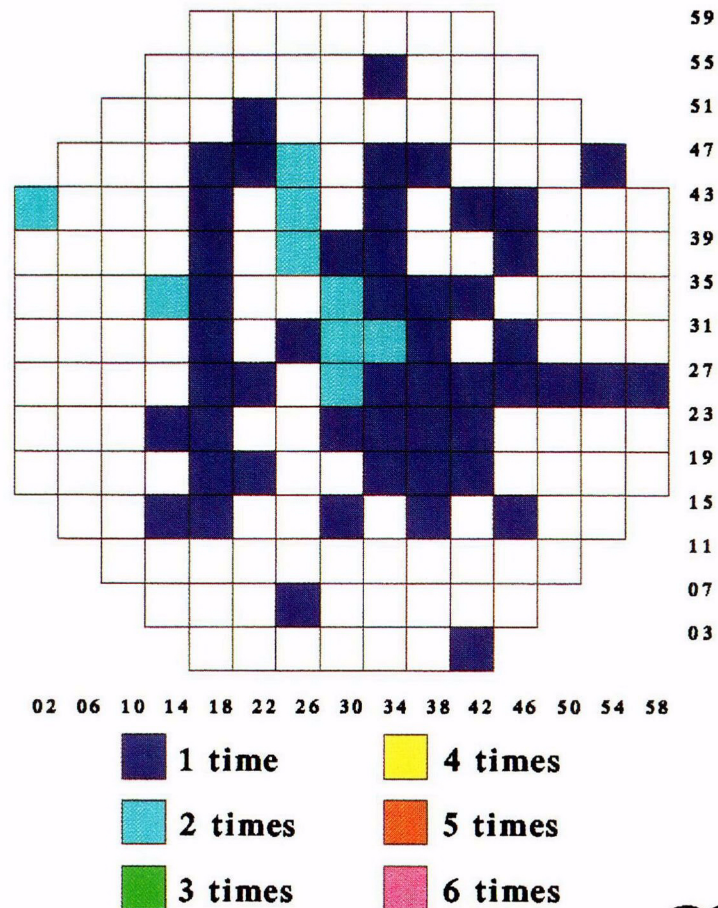
Unit N

CRD Changeout History



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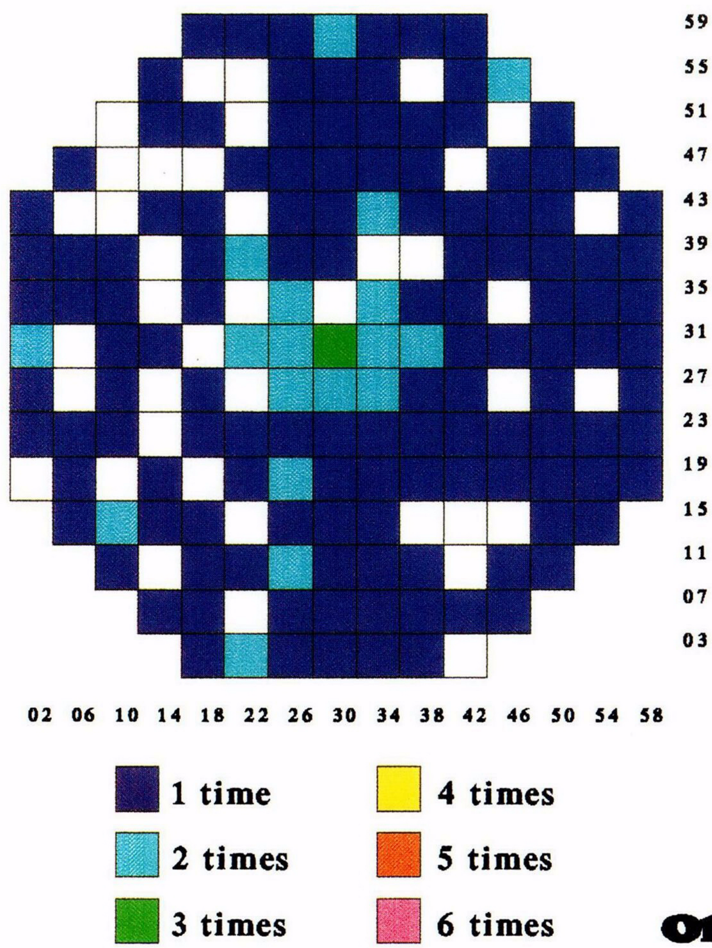
Unit O

CRD Changeout History



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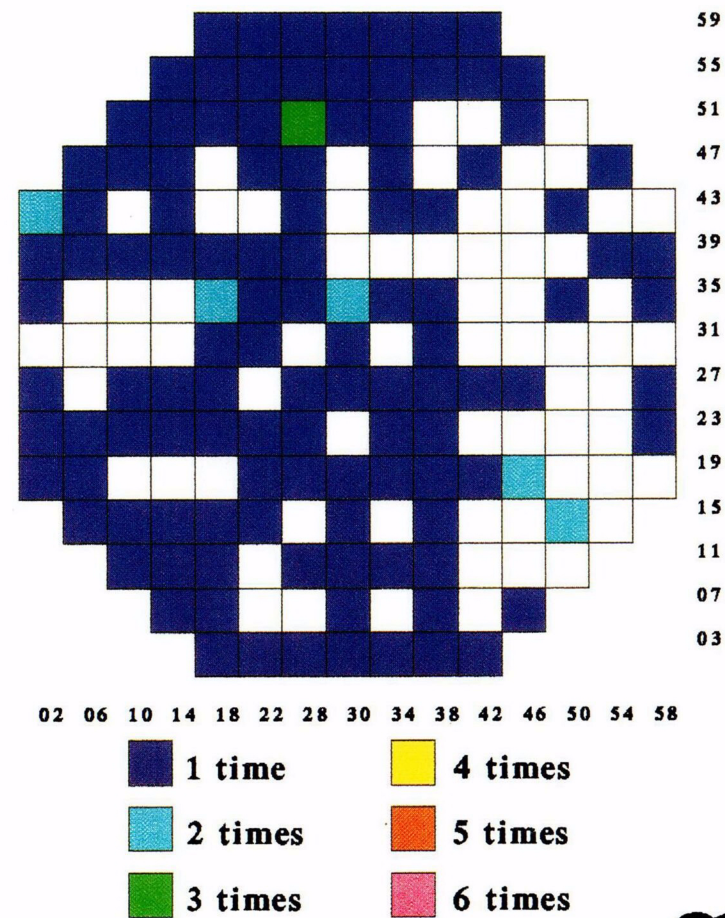
Unit P

CRD Changeout History



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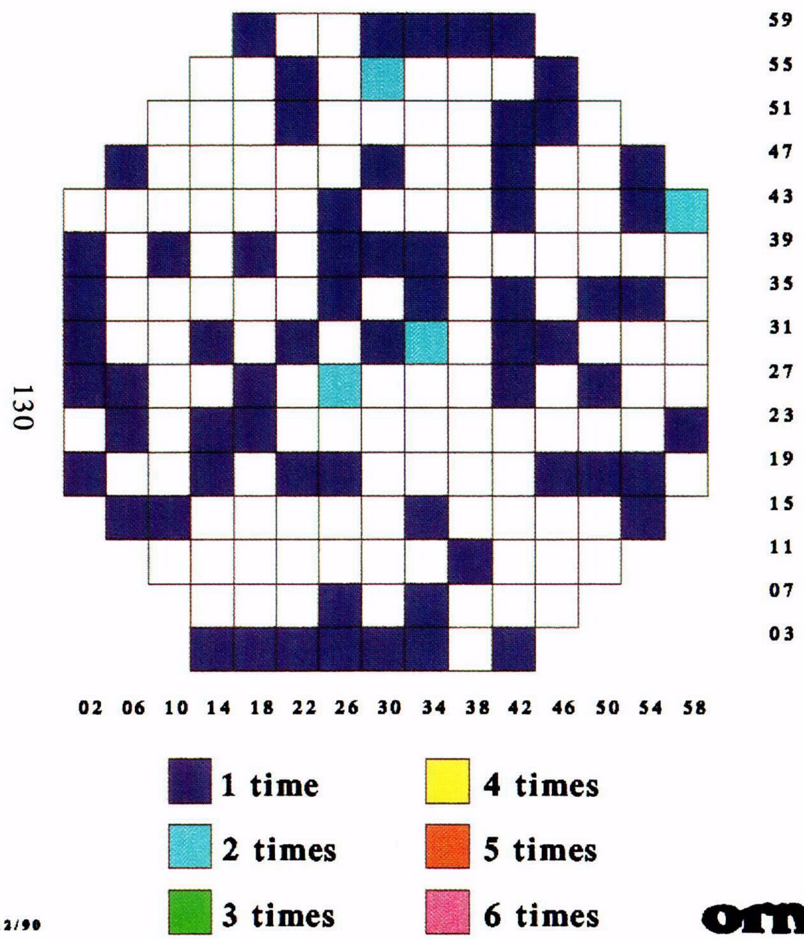
Unit Q

CRD Changeout History



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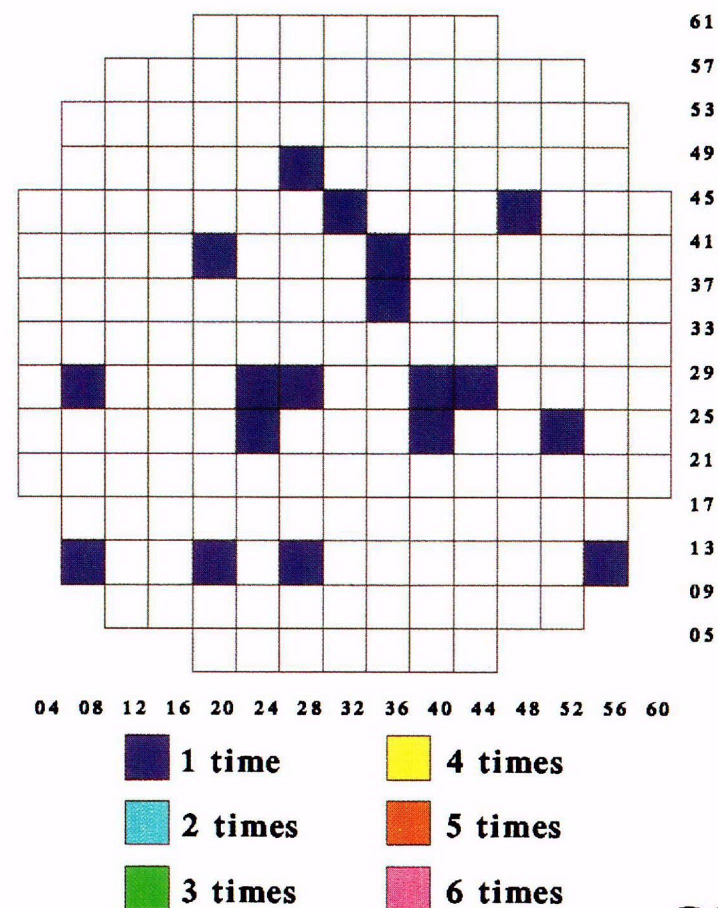
Unit R

CRD Changeout History



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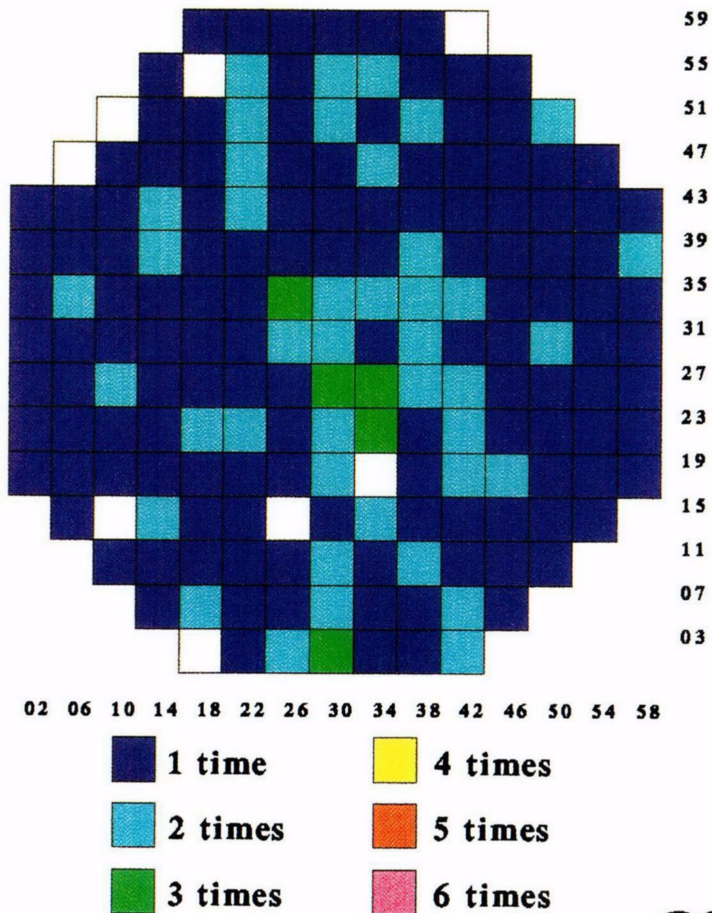
Unit S

CRD Changeout History



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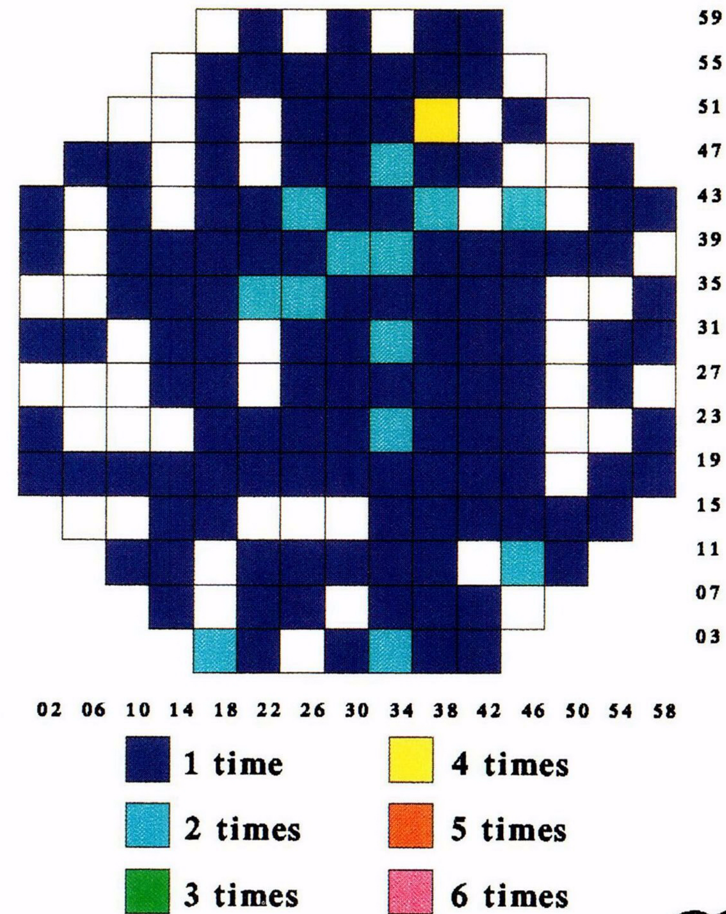
Unit T

CRD Changeout History



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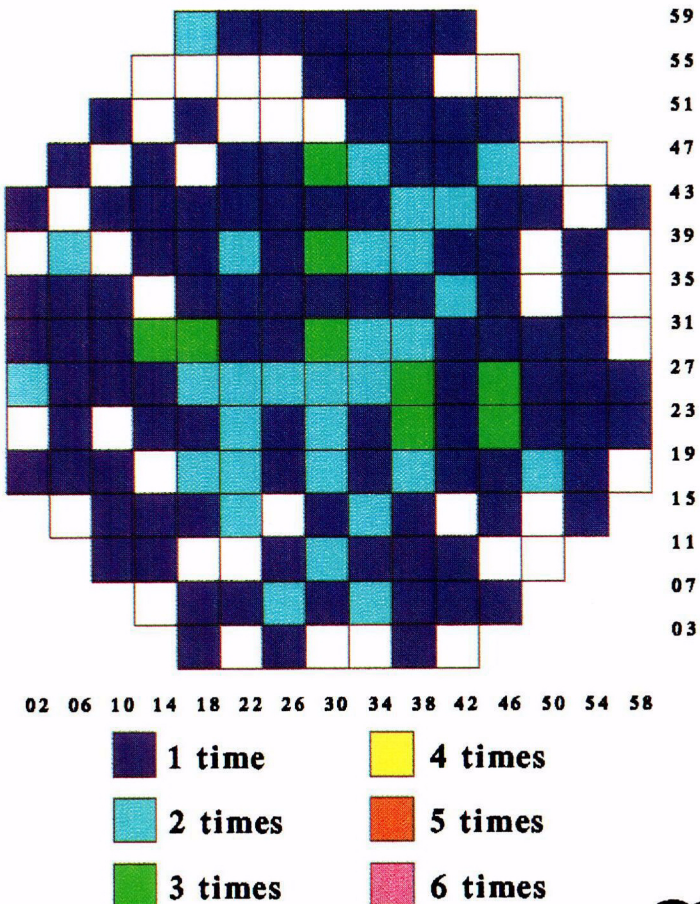
Unit U

CRD Changeout History



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10. SUPPLEMENTARY NOTES

11. ABSTRACT *(200 words or less)*

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.

Nearly 23% of the NPRDS CRD system component failure reports were attributed to the CRDM. The CRDM components most often requiring replacement due to normal wear and aging are the Graphitar seals. The predominant causes of aging for these seals are mechanical wear and thermally induced 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.

12. KEY WORDS/DESCRIPTORS *(List words or phrases that will assist researchers in locating the report.)*

aging	control rod drive
BWR	HCUs
failures	hydraulic control unit
reliability	nuclear power plants
maintenance	NPAR
ALARA	operating experience
CRDs	NPRDS
CRDMs	Graphitar

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