

# LEAK IN CONTROL ROD DRIVE MECHANISM HOUSING, PALISADES NUCLEAR PLANT

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## Abstract

This paper is the first of a series of 3 papers which address a leak in a control rod drive mechanism housing which occurred at Palisades Nuclear Power Plant in the August 2012. This paper will: provide some background concerning control rod drive mechanisms; describe the event and associated inspections; provide some background regarding other, related events; describe plans for future activities; and provide some regulatory context. This paper will also begin a discussion of the failure mechanism and the laboratory analysis performed in response to this failure. These last two topics are the subjects of the companion papers.

Keywords: stress corrosion cracking, control rods, leakage, nondestructive examination, stainless steel, crack growth

## Introduction

In the United States, commercial nuclear power plants fall into one of two general categories: boiling water reactors or pressurized water reactors. This paper will consider only pressurized water reactors. During routine operation of pressurized water reactors, the nuclear chain reaction is generally controlled through adjustment of the concentration of boric acid in the primary coolant. Major changes in the rate of the nuclear chain reaction or shutdown of the reactor are achieved by insertion of neutron absorbing material into the core. This neutron absorbing material is contained in control rods. The number and location of control rods is specific to the design of each plant.

Due to the length of the reactor core, generally in excess of 10 feet, and the need to have control rods fully inserted into the core and fully removed from the core, it is necessary that the control rods move vertically through at least that distance. It is also necessary that control rods be fail safe, i.e., in the event of loss of power or control signals to the control rods, the rods will fully insert into the core.

To meet these requirements, the upper heads of pressurized water reactors are fitted with tubes which serve as part of the reactor coolant pressure boundary and contain the control rods and their drive mechanisms. These tubes are called control rod drive mechanism (CRDM) housings. At Palisades Nuclear Plant<sup>1</sup> (Palisades), movement of the control rod within the housing is accomplished through the use of a rack and pinion drive system. A generic cross section view of a rack and pinion system is shown in Figure 1 [1].

CRDM housings are primarily constructed from 300 series austenitic stainless steel and may or may not contain components constructed from nickel alloy or martensitic stainless steel. As shown in Figure 2 [2], 300 series stainless steel is subject to stress corrosion cracking in water containing chlorides and

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oxygen. This phenomenon generally occurs at temperatures above 60°C (140°F) although some instances of cracking have been observed at lower temperatures. As shown in Figure 3, chloride stress corrosion cracking is generally transgranular and highly branched. Transgranular chloride stress corrosion cracking may occur in weld metal, weld heat affected zones and base metal [3]. Sensitization is not required for transgranular chloride stress corrosion cracking, however, in some instances especially where sensitization is present, chloride stress corrosion cracking may be intergranular in nature [2]. Although chloride stress corrosion cracking normally occurs in the presence of chlorides, identical cracking may occur in the presence of other halogens such as fluorides. This may be significant near welds as fluxes for some stainless steel welds contain fluorides [4].

In the remainder of this paper several past events associated with chloride stress corrosion cracking of CRDM housings will be described. These descriptions will be followed by a description of the current event and future actions which have been proposed by Palisades.

### **Canopy Seal Welds**

Reactor vessel head penetrations in pressurized water reactors designed by Westinghouse<sup>2</sup> consist of nickel alloy tubes which are inserted into openings in the head and secured by J-Groove welds. The upper ends of these tubes are welded to 300 series stainless steel flanges equipped with ACME threads. CRDM housings are screwed onto these threads. Due to the fact that the American Society of Mechanical Engineers<sup>3</sup> Boiler and Pressure Vessel Code (ASME Code) does not generally permit the use of a threaded joint as the sole means for retaining pressure and leakage in these components, the threaded joint, which is designed to provide structural integrity (forms the pressure boundary), is supplemented by a seal weld, which is intended to retain leakage past the threads. A typical joint configuration is shown in Figure 4 [5].

As previously stated, the components and weld metal which comprise the canopy seal weld are 300 series stainless steel. Pezze and Wilson [5] describe failure analyses of canopy seal weld leaks from five different power plants. While these leaks do not constitute a significant risk of a loss of coolant accident because the threaded joint maintains the connection's structural integrity, leakage through the seal weld and surrounding base metal poses some risk of boric acid corrosion to adjacent components.

In their analysis Pezze and Wilson identified that all the observed cracking:

- a. originated on the component inner diameter and progressed outward;
- b. occurred in both base metal and weld metal;
- c. was transgranular in nature;
- d. and was associated with the presence of chlorides at concentrations greater than that found in bulk pressurized water reactor coolant.

Pezze and Wilson also postulated the presence of oxygen at the location of cracking due to the fact the cavity associated with the seal weld is a dead leg. Pezze and Wilson further postulated that chlorides were present in the cavity at higher levels prior to the initiation of leakage than at the time of measurement due to the fact that the presence of a leak created a flow path through the cavity. Pezze and Wilson noted that the components and welds examined were not sensitized and that sensitization is not

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required for transgranular stress corrosion to occur. As will be discussed in greater detail below, no beach marks were observed in the investigation of canopy seal weld failures [5].

It should be noted, however, that, as describe in Nuclear Regulatory Commission<sup>4</sup> (NRC) Information Notice 2006-27 [6], intergranular stress corrosion cracking has occurred in dead leg components constructed from sensitized stainless steel. As shown in Figure 2, intergranular cracking of sensitized stainless steels may occur at contaminant levels which are significantly lower than are required to produce transgranular stress corrosion cracking in non-sensitized material.

### **CRDM Seal Housings, Palisades**

Beginning in 1986 Palisades began to experience reactor coolant system leakage from the J-Groove weld in the CRDM seal housing (which is located above the CRDM Housing). These seal housings were constructed from type 304 stainless steel. A cross section of the seal housing portion of the CRDM housing is shown in Figure 5. Additional events occurred in 1988, 1991-1993, 1999 and 2001.

In each case, failure analyses determined that the observed leakage was caused by transgranular stress corrosion cracking. Failure analyses postulated the presence of chlorides and oxygen at levels greater than typically found in PWR primary water. Destructive analyses also identified a shallow layer of cold worked material which was present on the inside surface of the pipe at the location where the observed cracks initiated.

Cracking became sufficiently prevalent that, between 1991 and 1993, all the seal housings were replaced with seal housings which were constructed from type 347 stainless steel and redesigned to reduce residual and operating stresses. It appears that this material change was made based on the inherent resistance of type 347 stainless steel to sensitization and the mistaken belief that the absence of sensitization would reduce the potential for transgranular chloride stress corrosion cracking.

At this time Palisades concluded that temperature may be a significant issue related to the observed cracking. This concept was based on the occurrence of cracking at Palisades and the absence of cracking at Fort Calhoun Station<sup>5</sup> (Fort Calhoun). The predominant difference in the seal housings at the two plants was that the seal discharge temperature at Fort Calhoun was 30°F cooler than that at Palisades. Efforts were made to reduce the temperatures of the seal housings at Palisades.

The changes in design, material, and operating conditions did not prove to be fully effective; cracking continued to occur in the seal housings. In 2001 Palisades replaced all the seal housings with housings constructed from Alloy 600 and redesigned using a one piece forging to minimize residual and operating stresses. Alloy 600 is considered to be more resistant than austenitic stainless steels to stress corrosion cracking under the environmental conditions which exist in the seal housings.

In the available failure analyses, no mention is made regarding the presence or absence of beach marks on any the seal housing fracture surfaces examined.

### **CRDM Housing, Weld 5, Fort Calhoun Station, 1990 [7]**

In 1990, following 17 years of operation, Fort Calhoun detected leakage from one of two spare CRDM housings. Spare housings are installed on the reactor head in a manner identical to active housings but do not contain a control rod drive mechanism. As shown in Figure 6 [7], the leak was associated with weld

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number 5. Weld 5 is a non-pressure boundary weld overlay provided to ensure accurate alignment of the CRDM as it is inserted into the housing. Both weld 5 and the CRDM housing tube were constructed from type 348 stainless steel.

The failure analysis performed in response to this event identified the source of the leak as a transgranular chloride stress corrosion crack. The failure analysis also identified a second, non-through-wall crack at weld 5 in this housing. Extent of condition inspections revealed additional, non-through-wall cracks at weld 5 in the other spare CRDM housing. Based on measurements made during the failure analysis, circumferential tensile stresses (which support axial cracking) of approximately 70% of the yield strength of the material existed at the inside diameter of weld 5.

The fact that the observed cracking occurred in the two spare CRDM housings and not in active CRDM housings was, at the time, considered to be of great importance. As discussed above, it has been shown above that all CRDM housings contained tensile stresses sufficient to cause cracking and all CRDM housings contained susceptible material. It was believed, however, that only the spare housings contained an environment which would cause cracking.

This belief was based on the fact that active housings were vented and had leakage through the seals. As such, these housings were not dead legs. Alternatively, the spare housings are not vented and are dead legs. Dead legs are thought to retain higher oxygen and chloride levels from refueling outages than areas of the reactor coolant system which are exposed to active flow.

Analyses performed as part of the failure analysis indicated that the oxygen content in the spare housings (204°C) was between 300 and 1300 ppm. Additional analyses indicated that this level of oxygen would not change substantially during an 18 month refueling cycle but would begin to drop slowly after that time due to natural circulation and diffusion. Conversely, the oxygen level in active CRDM housings should drop to levels consistent with bulk primary water, i.e., 5 ppb in a relatively short time following a refueling outage.

An interesting aspect of this failure analysis, as shown in Figure 7 [1], is the presence of beach marks on the crack fracture surfaces examined. While beach marks are normally associated with fatigue fractures, Lisowj reported ample evidence of transgranular stress corrosion cracking and no evidence to support a fatigue failure. Based on the apparent cyclical nature of the crack growth Lisowj proposed that each beach mark was related to a refueling cycle as this was the only common plant operational cycle which would affect the CRDM housings [7].

The rate of crack growth for this failure was estimated based on the number of beach marks present and crack growth rates contained in the literature. While the beach marks were correlated with refueling outages, the lack of variability in oxygen content over time indicates that temperature/pressure cycles rather than oxygen variability may be responsible for the cyclic nature of crack growth.

### **CRDM Housing, Weld 3, Palisades, 2001**

In 2001 Palisades detected leakage from CRDM housing number 21. The location of this CRDM housing in relation to other CRDM housings is shown in Figure 8. CRDM housing 21 is an active housing as opposed to a spare as had previously occurred at Fort Calhoun. As shown in Figure 6, the failure analysis performed in response to this event identified both axial and circumferential cracks associated with weld number 3. Extent of condition inspections revealed additional, non-through wall cracks associated with weld 3 in 41 of the 44 remaining housings for a total of 42 of 45 housings containing cracks.

As was the case in the Fort Calhoun event, a failure analysis of the component revealed that the cause of the leak was transgranular stress corrosion cracking and that the fracture surface contained beach marks (no publicly available photograph). Cracking was attributed to elevated levels of chlorides and oxygen as well as higher than normal weld residual stresses and cold work resulting from extensive grinding performed on the ID of the weld.

The rate of crack growth for this failure was estimated based on the number of beach marks present. The time intervals proposed between beach marks were much shorter than refueling intervals and are consistent with plant outages involving pressure/temperature cycles which may or may not include oxygen ingress.

In response to the observed cracking, Palisades replaced all 45 CRDM housings with housings thought to be more resistant to cracking. Principal changes included:

- a. Elimination of weld number 2 (see Figure 6)
- b. Relocation of weld number 3 to a higher location thereby minimizing the deposition of crud in the gap between the weld and the bottom plate of the rack and pinion assembly
- c. Reduction in residual stresses and cold work on welds by requiring better surface finishes
- d. Use of heat sink welding to reduce ID residual tensile stresses

In addition to the design changes listed above which were implemented to reduce stress corrosion cracking, the tube of the CRDM housings were changed from type 347 stainless steel to type 316 stainless steel, due to materials availability issues.

### **CRDM Housing, Weld 5, Palisades, 2012**

#### Event Chronology

Beginning on approximately July 14, Palisades began to observe a generally increasing trend in unidentified leakage. While within technical specification limits, this increasing leakage trend prompted Palisades to make an entry into containment to attempt to identify this leakage. This tour of containment did not include an inspection of the CRDM housings as this area of containment is not accessible when the plant is at full power. The containment tour was unsuccessful in identifying the source of leakage.

On August 12, the unidentified leakage rate remained well within allowable technical specification limits but exceeded a plant administrative limit. At this point the plant reduced power to permit inspection of the reactor head and CRDM housings. In this inspection tour, a steam leak was identified in CRDM housing 24 pointing toward CRDM housing 44 (see Figure 8). The leak was located approximately 1 foot above the CRDM housing to reactor head flange.

Once the source of the leakage was identified, the plant appropriately reclassified the leak as a pressure boundary leak. Since plant technical specifications do not permit any pressure boundary leakage, the plant proceeded to a cold shutdown condition to make repairs.

#### Non Destructive Evaluation

Once the plant reached a cold shutdown condition, plant personnel performed a dye penetrant exam in the area of the steam leak. As shown in Figures 9 and 10, the leak was a 1/8<sup>th</sup> inch by 1/16<sup>th</sup> inch L shaped crack located at the upper end of the witness mark. The witness mark is a groove machined in the OD of the CRDM housing during manufacturing which is used as a reference point for determining critical dimensions.

Following the dye penetrant examination, Palisades NDE contractor performed an ultrasonic examination (UT) consisting of 3 passes, one at the elevation of the observed leak, one 1/2 inch below the leak, and one 1/2 inch above the leak. While a track was used to control the path of the UT transducer, the transducer was manually controlled. The examination utilized a conventional (as opposed to phased array) transducer but was encoded so as to permit later review of the data. This examination identified 7 cracks.

To determine whether cracking was limited to CRDM housing 24, UT examinations identical to those described above were performed on 8 additional CRDM housings which were located on the periphery of the head. As shown in Figure 11, which is a photo of the Palisades reactor head and CRDM housings, CRDM housings not on the periphery of the head could not be examined with the available equipment due to access considerations. The NDE vendor stated that no reportable indications were observed.

Following the UT examination, CRDM housing 24 was removed from the reactor head and replaced. The original housing was sent out for metallurgical failure analysis. An initial dye penetrant examination of the failed housing revealed the presence of 9 cracks rather than the 7 cracks originally identified by UT. The cracks which had not been detected were outside the area originally examined (crack + and - 1/2 inch). As a result, the additional 8 CRDM housings were reexamined. The area covered in the re-exam was crack + 1 inch and crack - 1 1/2 inch. The NDE vendor again stated that no reportable indications were observed.

### Destructive Examination

A full description of the destructive analysis of the failed component is available in a companion paper [8]. This paper will address 3 key components of the destructive analysis.

Upon receipt, by the Babcock and Wilcox<sup>6</sup> (B&W) laboratory the CRDM was sectioned circumferentially and subjected to dye penetrant examination. As shown in Figure 12 [8], the dye penetrant examination revealed 9 axial cracks and 1 rub mark. The rub mark is believed to indicate impingement of the CRDM on the housing during operation. The 9 cracks were located in two groups. Each crack group and the rub mark were located approximately 120° from each other. The spacing of the crack groups and rub mark is believed to be significant in that it indicates non-uniformity in the circumferential stresses in the CRDM housing with circumferential position around the housing. No cracks were found in any other CRDM housing sections.

The witness mark, as shown in Figure 10, is machined into the outside diameter of the housing during the manufacturing process as an aid to locate and size critical dimensions such as weld 5. The witness mark and weld 5 should be concentric to both the ID and OD of the CRDM housing. On CRDM housing 24, neither the witness mark nor the ID surface of weld 5 were concentric to either the ID or the OD of the housing or each other. Additional investigation revealed that two of the bolt holes in the lower CRDM housing flange were enlarged in the field to permit installation onto the head penetration. These observations, in conjunction with the rub mark support the possibility that the CRDM internals were misaligned in the CRDM housing and created non-uniform circumferential stressing in the CRDM housing which contributed to the observed cracking.

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As shown in Figure 13 [8], examination of the fracture surfaces revealed beach marks as seen in previous failures. The crack which resulted in the through wall leak had 6 beach marks. Other cracks had between 4 and 6 beach marks. As in previous failures, the fracture surface supported transgranular stress corrosion cracking as the cracking morphology. No evidence of fatigue was observed. Although chlorides were not identified, the presence of chlorides and elevated levels of oxygen were inferred based on past findings of elevated levels of chlorides and oxygen in CRDM housings. Cracking was, therefore, attributed to transgranular chloride stress corrosion cracking.

Based on the analysis of the fracture surface, one of the conclusions reached by B&W and Palisades was:

Oxygen ingress occurs during reactor outages. The surface oxide color differences noted in each of the beach marks clearly shows the initiation region to be older than the subsequent beach marks; however, it could not be conclusively determined if the beach marks corresponded to refueling outages (i.e., 18 month cycle) or shorter periods as occurred during outages over the past 24 months

### Future Activities

Due to the potential generic implications of the events described above, the NRC must consider the potential need for future actions on three levels, i.e.:

- a. actions required at Palisades due to the most recent event
- b. actions required at both Palisades and Fort Calhoun based on the similarity of installed equipment
- c. actions required at all pressurized water reactor plants due to potential similarities of materials, stress levels and environments.

Items b and c may be addressed through proposed changes in the ASME Code but remain under consideration and will not be addressed further here.

Palisades has currently proposed to inspect weld 5 of approximately ¼ of the CRDM housings using an eddy current inspection technique in each of the next four refueling outages, the first of which occurs in October of 2013. Palisades continues to evaluate the need for inspections beyond four refueling outages and the type and frequency of inspections required for welds 3 and 4.

The adequacy of the frequency of the proposed exams depends, to a large extent, on the crack growth rates experienced in the 2012 event as well as the previous events described. A brief description of crack growth rate information is provided here. Additional details are provided in a companion paper [9].

In evaluating the adequacy of Palisades proposed inspection plan 5 crack growth rate scenarios were considered:

- a. Based on literature data, Contractor A estimated that a 10% through wall flaw with an aspect ratio of 6:1 would require 4 years to reach 50% through wall.
- b. Based on literature data, Contractor B estimated the crack growth rate to be  $2.1 \times 10^{-5}$  in/hr or 0.18 in/yr. This is approximately three times faster than the crack growth rate proposed by Contractor A.

- c. Based on the concept of oxygen ingress at refueling outages 6 cycles of 18 months duration would require 9 years for the crack to grow through wall
- d. Based on the concept of temperature/pressure cycles, the plant experienced 6 cold shutdowns in approximately 2 years preceding the crack. This equates to 2 years for the crack to grow through wall.
- e. Based on the concept that oxygen may be required for crack growth and that oxygen is rapidly purged from the CRDM housings due to leakage past the seals, crack growth occurs only during the first few weeks of operation following a refueling outage, followed by no growth for the remaining period of operation when oxygen concentrations are low. This equates to 6 oxygen ingress events (irrespective of time between events) for the crack to grow through wall.

Based on the inability to conclusively identify the source of the beach marks and the past correlation of the beach marks with pressure/temperature cycles, the NRC found scenario (d) to be both conservative and technically feasible. The NRC also found insufficient technical support for the remaining scenarios to justify their use for regulatory purposes. Based on the fact that the inspection interval proposed by Palisades is shorter than the minimum length of time to produce a through wall crack as proposed in scenario (d), above, and that a substantial sample of the population of CRDM housings is being inspected during each inspection interval, the NRC finds the inspection interval proposed by Palisades to be acceptable.

### **Conclusions**

1. Transgranular stress corrosion cracking has occurred in canopy seals in several nuclear power plants. Transgranular stress corrosion cracking has occurred in CRDM seal housings at Palisades. Transgranular stress corrosion cracking has occurred in CRDM housings at Palisades and Fort Calhoun.
2. Cracking is attributed to the use of materials subject to chloride stress corrosion cracking, the presence of residual stresses at the welds, and the presence of chlorides and oxygen due to dead leg or restricted flow conditions. Fluorides in weld flux may also contribute to cracking.
3. The leaking CRDM housing at Palisades in 2012 contained manufacturing anomalies which affected the witness mark, weld 5, and two flange bolt holes. These anomalies will contribute to misalignment of the CRDM inside the housing. Misalignment is probably responsible for the rub mark and may contribute to the formation and position of the observed cracks in this housing.
4. The fracture surfaces of cracks which have occurred in welds 3 and 5 of rack and pinion CRDM housings have not illustrated any evidence of fatigue but have contained beach marks.
5. The beach marks correlate to certain operational cycles of the plants, however, it cannot be conclusively demonstrated whether they are related to oxygen ingress or pressure/temperature cycles.
6. The licensee's inspection program includes inspection of all of the CRDM housings over the next 4 refueling outages. Approximately 25% of the housings will be inspected during each outage. The inspection of 25% of the CRDM housings each interval is sufficient to indicate that, in the event no indications are found during a given inspection, the probability that flaws exist in other

housings is very low. As such, it may be considered that the inspection of approximately 25% of the CRDM housings every refueling outage bounds all the crack growth rate mechanisms considered.

8. Generic implications to the 2012 event may be addressed by proposing changes to the ASME Code. The need for such action remains under consideration.

### **Observation**

Although not a scientific or engineering conclusion based on this work, it should be noted that a number of failures of austenitic stainless steel components have occurred in CRDM housings. In each event some specific condition (stress, material, environment) about the event in question was identified to justify why cracking would not occur in the future at other locations. These distinctions and their associated predictions have not fared well in the light of history. Caution may be advisable in future attempts to categorize cracking of austenitic stainless steels in CRDM housing environments as unique events.

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## Figures

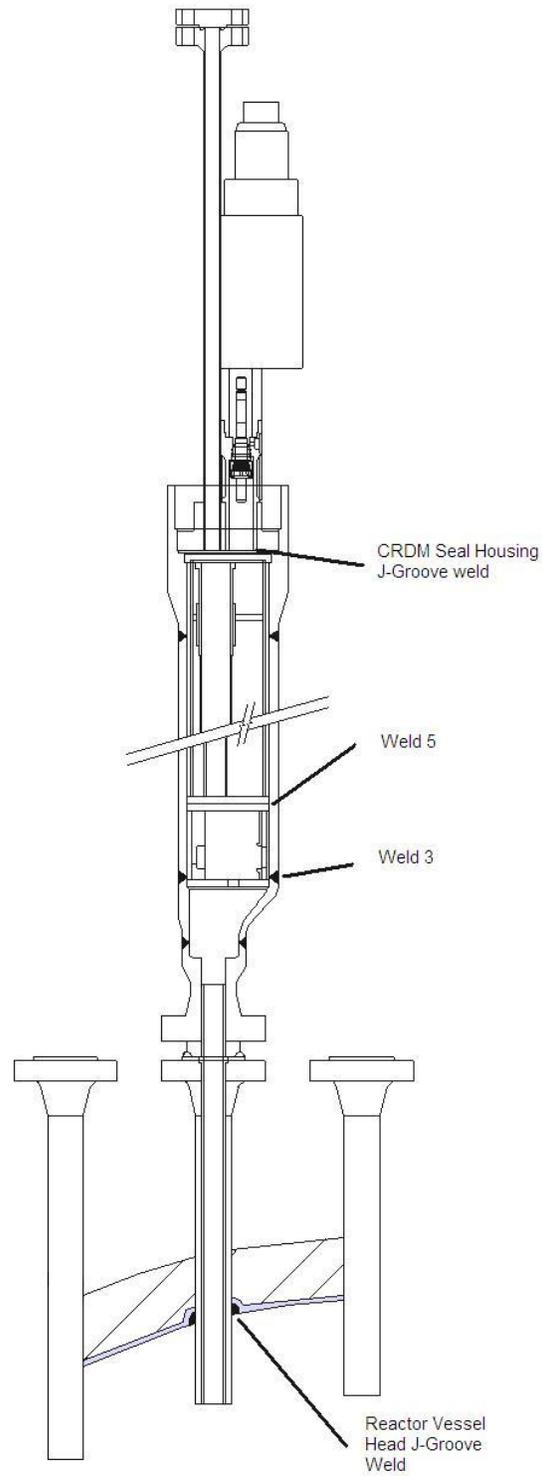


Figure 1: Generic cross section view of a CRDM rack and pinion system [1]

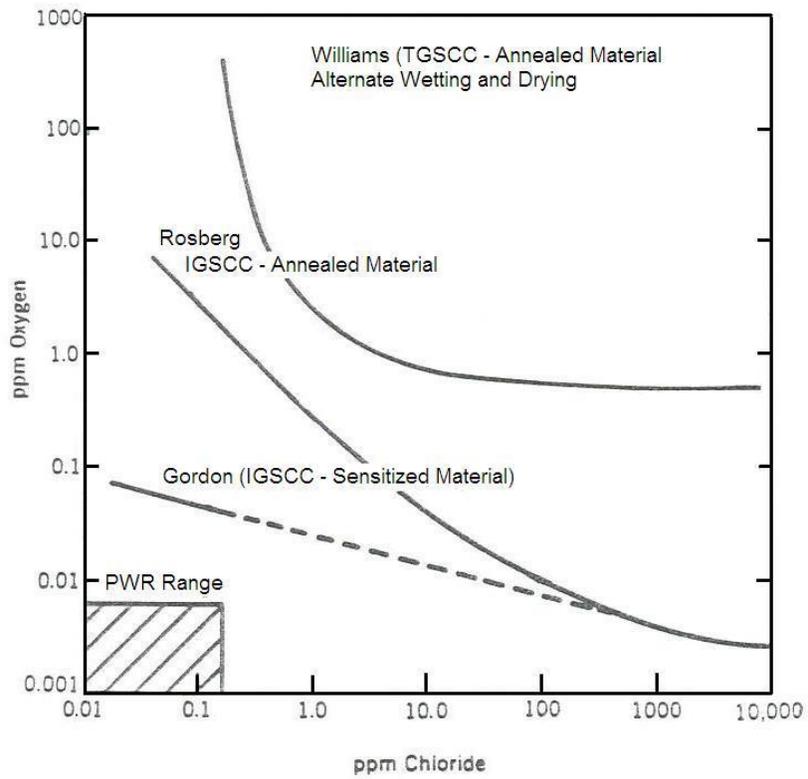


Figure 2: Concentrations of oxygen and chlorides leading to stress corrosion cracking after [2]

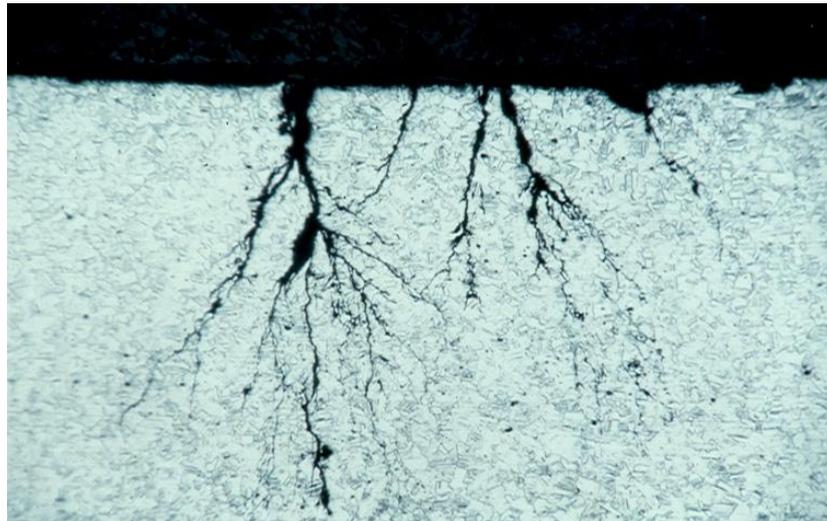


Figure 3: Typical chloride stress corrosion crack in 300 series stainless steel (micrograph courtesy of Mark Mucek, UOP LLC)

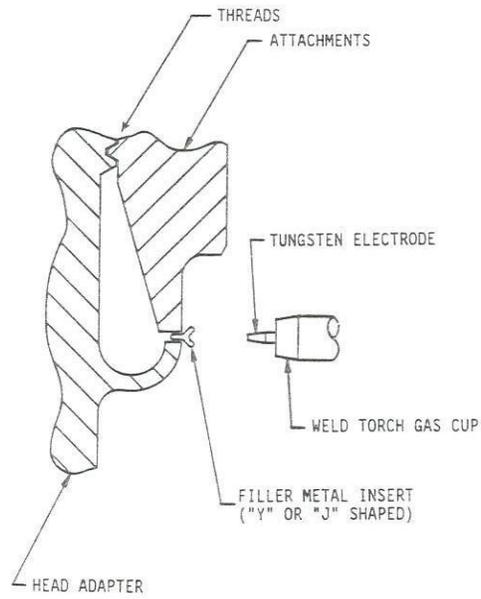


Figure 4: Cross section of mechanical CRDM housing joint showing location of canopy seal weld [5]

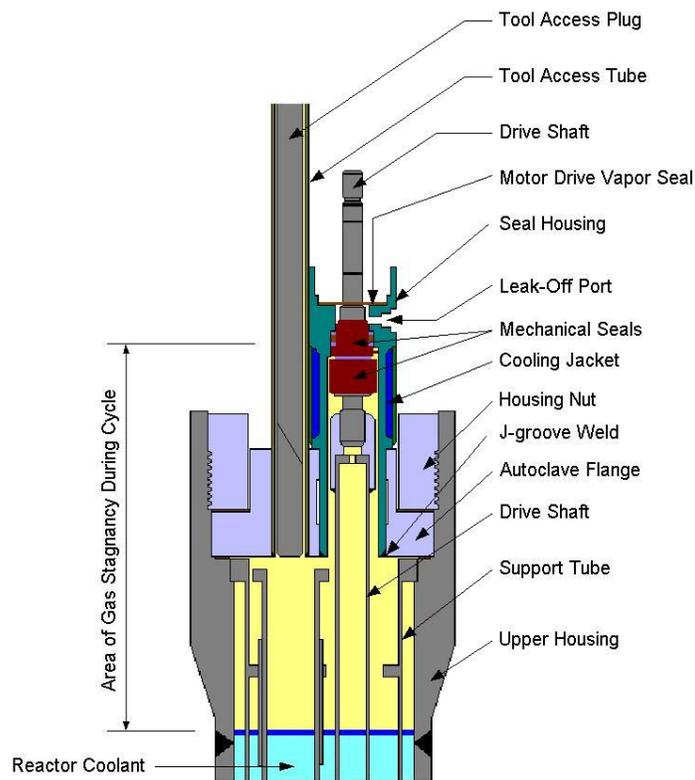


Figure 5: Cross section of the seal housing area of the CRDM housing. [1]

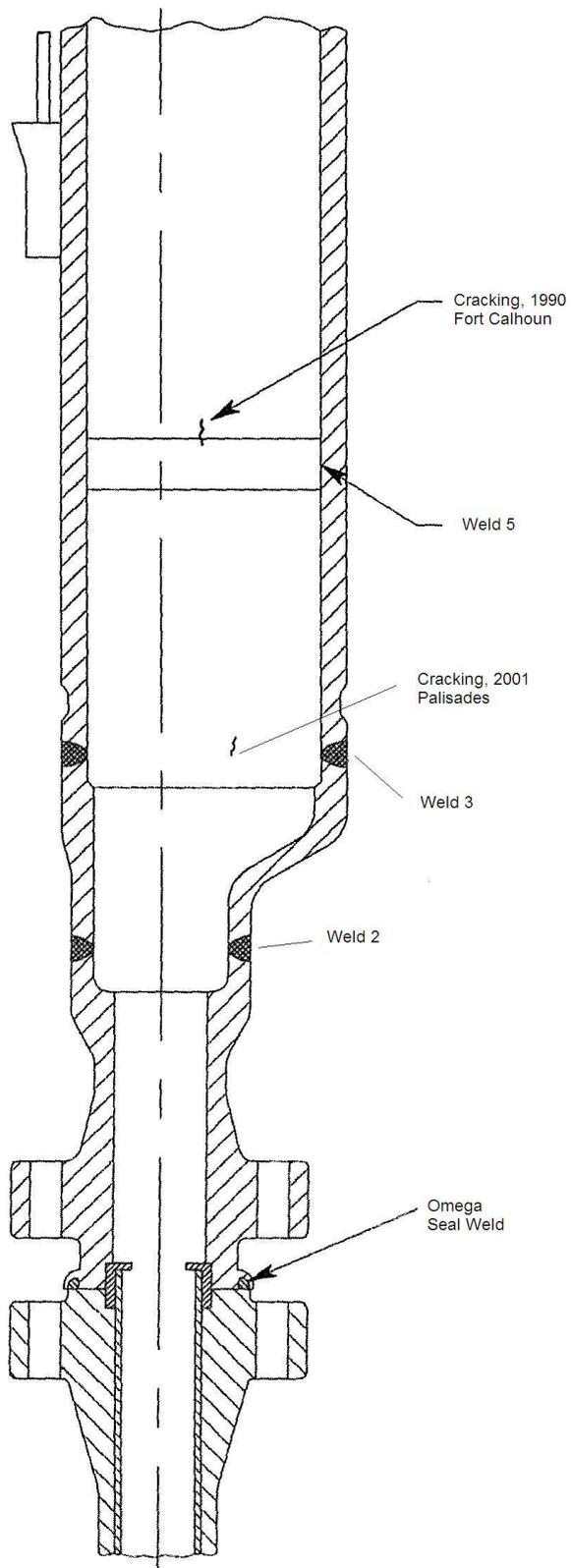


Figure 6: Detail showing location of significant welds and two leakage events. [7]



Figure 7: Fractograph showing transgranular SCC and accompanying beach marks [1]

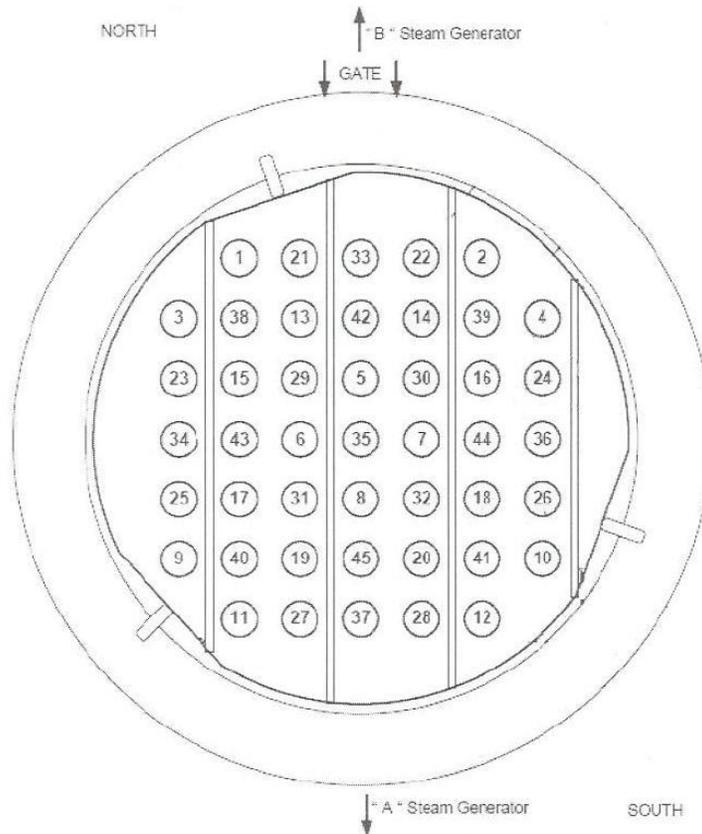


Figure 8: Diagram showing arrangement of CRDM housings (After [9])

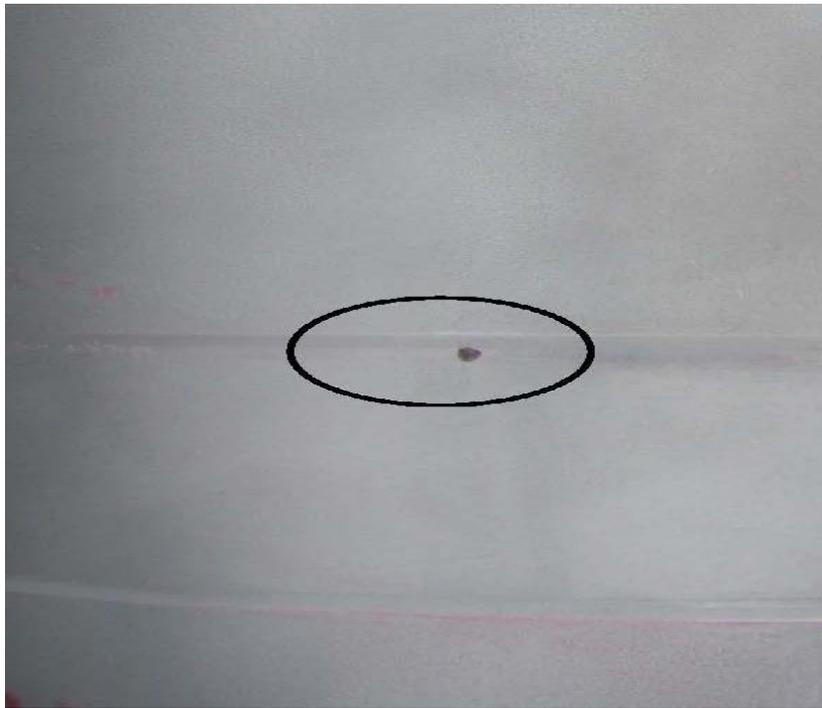


Figure 9: Dye Penetrant Exam Results, through wall leak in CRDM housing 24, Palisades 2012 (After [9])

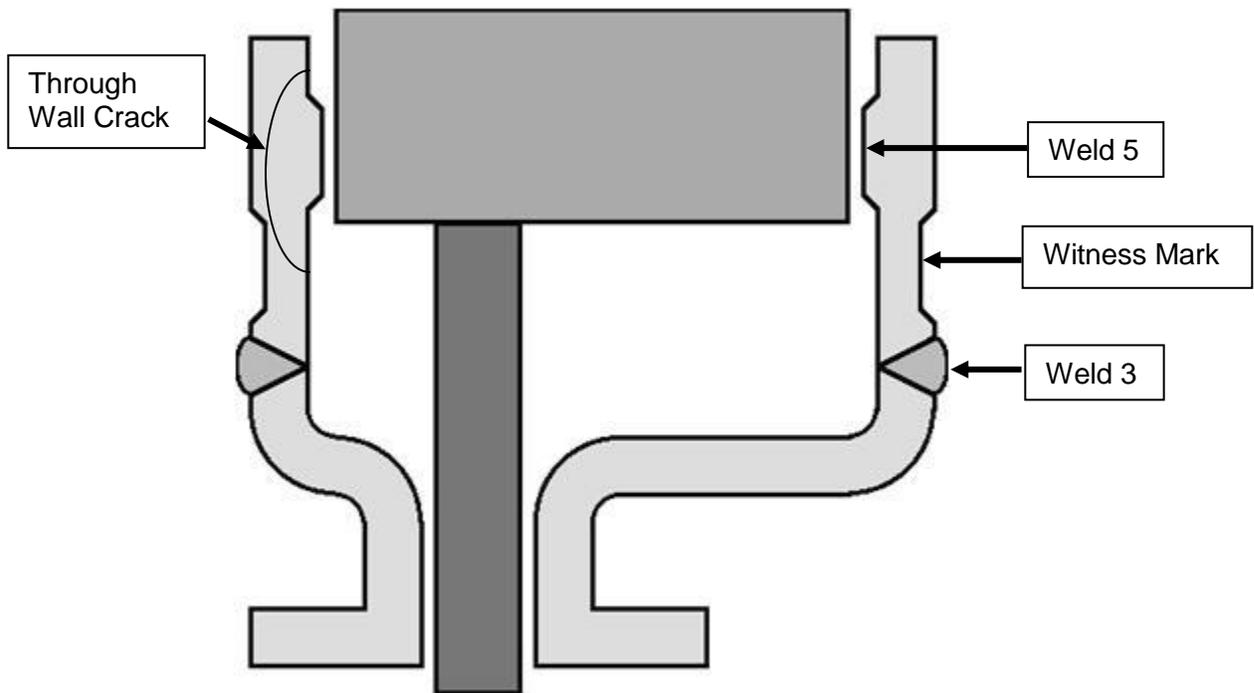


Figure 10: Simplified cross section of CRDM housing showing welds 3, 5, witness mark, and OD location of steam leak

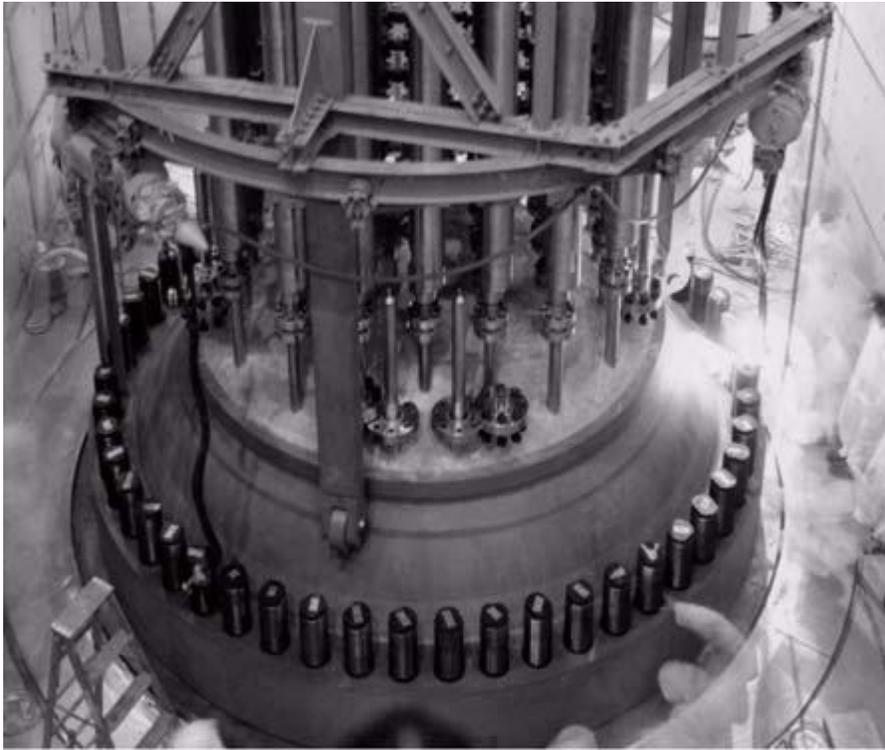


Figure 11: Photo of reactor vessel head and CRDM housings. Note limited access for inspection of interior housings [9]

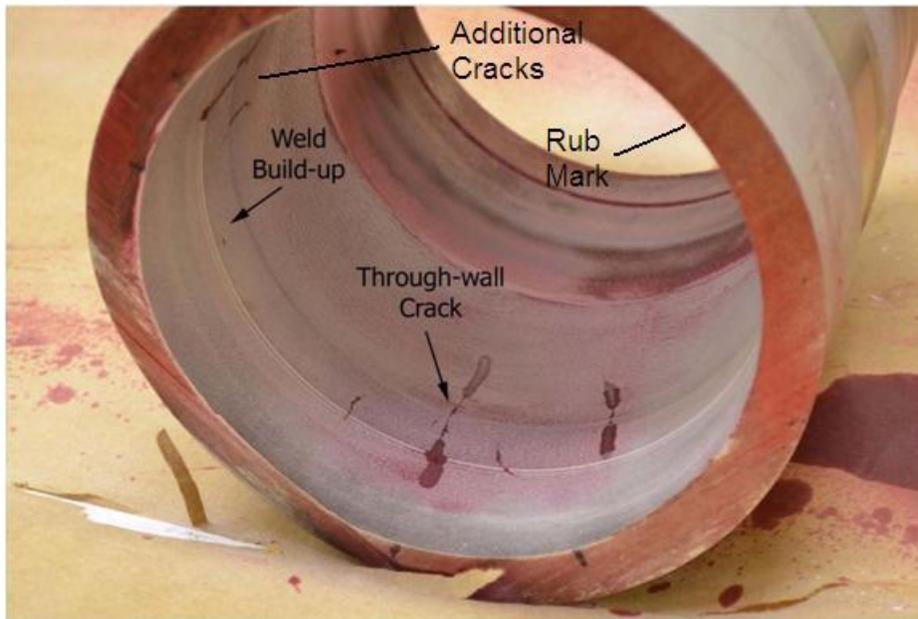


Figure 12: Dye penetrant exam of outside diameter of CRDM housing 24 showing leak two areas of cracking and location of rub mark [8]

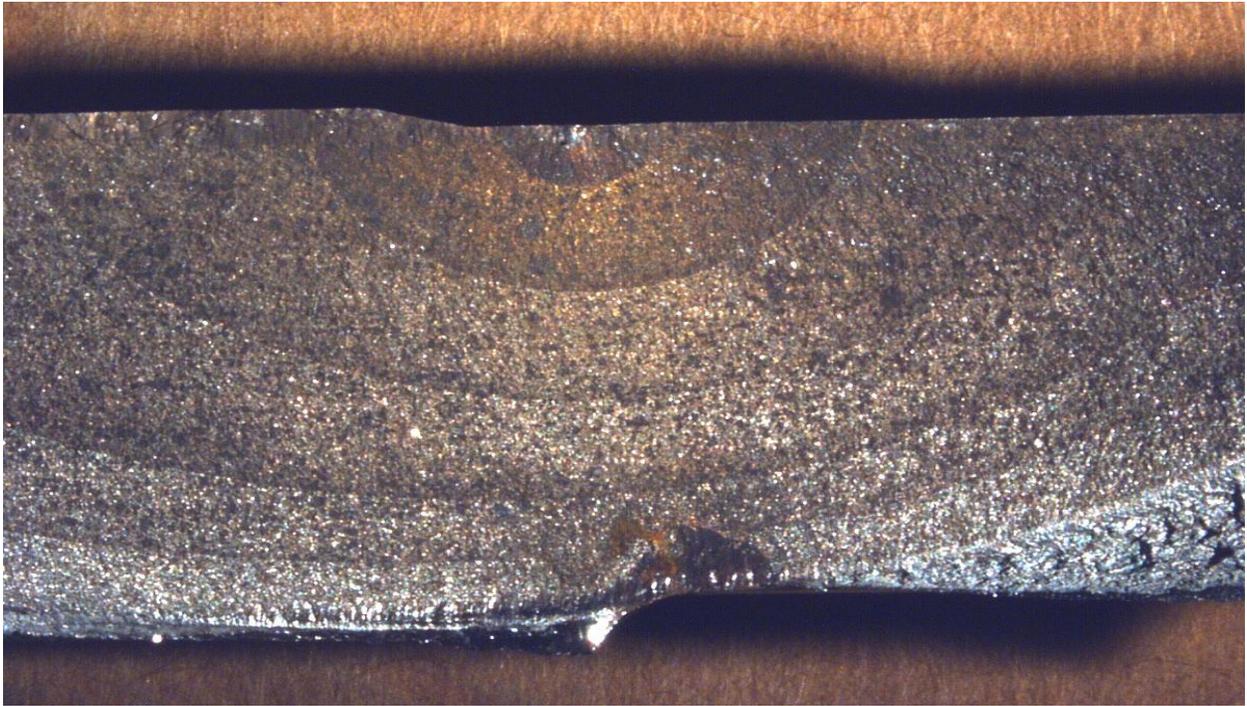


Figure 13: Macrograph showing beach marks, Palisades 2012 [8]