Evaluation of Control Rod Drive Mechanism and Reserve Shutdown System Failures, and PCRV Tendon Degradation Issues Prior to Fort St. Vrain Restart

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Table of Contents

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1.0 Background

On June 23, 1984, following a moisture ingress event resulting in a loss of purge flow to the Control Rod Drive Mechanism (CRDM) cavities, 6 of 37 control rod pairs in the Fort St. Vrain (FSV) High Temperature Gas-Cooled reactor failed to insert on a scram signal. Subsequently, all six control rod pairs were successfully driven into the core.

In July, 1984, an assessment team consisting of Nuclear Regulatory Commission (NRC) personnel from Headquarters, Region III and Region IV, and their technical consultant, Los Alamos National Laboratory, conducted an on-site review of the Control Rod Drive Mechanism failures, overall conduct of plant operations, adequacy of technical specifications and a review of the continued moisture ingress problem. An additional plant visit in August, 1984, reviewed CRDM instrumentation anomalies.

1.1 Assessment Report Restart Issues

The results of both assessments were reported in the "Preliminary Report Related to the Restart and Continued Operation of Fort St. Vrain Nuclear Generating Station"[1], in October, 1984. The report concluded that Fort St. Vrain should not be restarted until modifications and/or other corrective actions had been taken, or until all control rod drive mechanisms had been inspected and refurbished to provide reasonable assurance that the control rods would insert automatically on receipt of a scram signal. More specifically, and as included in this technical evaluation, Reference 1 required Public Service Co. of Colorado (PSC) to complete the following, prior to restart:

a. The licensee must identify the CRDM failure mechanism(s) and take corrective actions, or, if the mechansm(s) cannot be positively identified, take other compensatory measures to provide assurance of control rod reliability, which could reasonably include refurbishment of all CRDMs.

b. The licensee must outline and commit to periodic inspection, preventive maintenance and surveillance programs for control rod drive mechanisms and associated position instrumentation. A change in the Technical Specifications shall be proposed to implement a weekly control rod exercise surveillance program for all partially or fully withdrawn control rods. A Limiting Condition for Operation should define control rod operability, and the minimum requirements for rod position indication.

c. The licensee must functionally test one-20 weight % boron and one-40 weight % boron hopper from the Reserve Shutdown System (RSS), to assure the full availability of the RSS, prior to restart. The licensee must outline and commit to periodic inspection, preventive maintenance and surveillance programs for Reserve Shutdown System material. A change in the Technical Specifications shall be proposed to implement the RSS surveillance program. A Limiting Condition for Operation should define and confirm the operability of the Reserve Shutdown System.

d. The licensee should develop a procedure requiring reactor shutdown when high levels of moisture exist in the primary coolant, or when CRDM purge flow is lost.

e. The licensee should implement a procedure for recording representative samples of CRDM temperatures at all operating conditions, until continuous recording capability is available.

f. The licensee should implement procedure to prevent overdriving the control rods past the "Rod-In" limit.

g. The licensee must develop a plan to implement any modifications recommended by the PSC Moisture Ingress Committee that are determined, by PSC, to have a high potential for significantly reducing the severity and frequency of moisture ingress events.

1.2 PCRV Tendon Restart Issues

As a result of previously identified tendon degradation in the Prestressed Concrete Reactor Vessel (PCRV) post-tensioning system, PSC must complete the following, as comfirmed by Reference 2, prior to restart:

a. The licensee should submit documentation evaluating the mechanism(s) causing corrosion on and failure of the PCRV tendon wires, and corrective measures to eliminate further tendon degradation, thereby assuring the continued structural integrity of the PCRV and its post-tensioning system.

b. The licensee should propose and implement a tendon surveillance program that determines the extent of current tendon degradation in the PCRV, and that systematically monitors the rate of tendon corrosion.

1.3 Purpose of the Technical Evaluation

This document provides a technical review of the restart issues identified above, and the corrective measures and/or actions proposed by licensee, based on the licensee's January 31, 1985 submittals (References given as used in this document), and the meeting between the licensee and NRC at the FSV plant site on February 20-22, 1985, as transcribed in References 3, 4 and 5.

2.0 Control Rod Drive and Orifice Assemblies

This section includes a review of CRDM failure mechanisms, Control Rod Drive and Orifice Assemblies (CRDOA) refurbishment, CRDM temperature recording and requalification testing, CRDM preventive/predictive maintenance and surveillance.

2.1 Failure Mechanisms

The failures of control rod pairs to scram, under various operating conditions, has been documented since 1982,[6,7] and are as noted in Table 1 by region, CRDOA number and CRDM purge flow subheader (total of 8 purge flow subheaders).

Table 1. Control Rod Failures

Date	2/22/82		6/23/84					1/14/85			
Region	7	28	6	7	10	14	25	28	28	31	32
CRDOA #	18	44	29	18	14	25	7	44	36	17	15
CRDM Purge Subheader #	1	1	6	1	7	2	5	1	1	2	3

High moisture content in the primary coolant and loss of purge flow were common modes during the 2/22/82 and 6/23/84 events. Substantial descriptions and operating characteristics of the drive motor, friction brake and dynamic braking, the reduction gear mechanism, the cable drum and cable, and the bearing lubricant are provided in Reference 6. The licensee reviewed those CRDM components that could have caused the failures to scram, and postulated various failure mechanisms that could have interacted on each component, as described below.

2.1.1 Motor Brake Malfunctions

During a scram, the motor brake is de-energized and released, thereby freeing the motor rotor shaft and gear train assembly to rotate under the torque applied by the weight of the control rods. In the motor brake assembly, failure of the scram contactor to de-energize dc power to the electromagnet was discounted because the operator had removed the brake fuses following the CRDM failures to insert the control rod pairs.

According to the licensee, electromagnetic remanence and reduced spring constant in the brake spring plungers (due to elevated temperatures) were eliminated as possible failure mechanisms. Some corrosion and rust was identified on the brake disks of CRDOAs 25, 18 and 2[illegible]. However, the disks of a CRDM motor brake assembly with "discoloration and whatever surface variations"[3, p.149], could not be made to stick in an elevated temperature helium environment with high moisture content (test T-228). The licensee concluded that the motor brake was not instrumental in the failures to scram.

Los Alamos agrees with the licensee that the motor brake assembly was probably not related to the CRDM failures.

2.1.2 Reduction Gear Mechanism Malfunctions

The reduction gear train is driven by the motor rotor shaft, and rotates the cable drum with a gear ratio of 1150 between the motor and drum. The condition of the reduction gear mechanism was postulated by the licensee to potentially contribute to a failure to scram through gear tooth or bearing damage, by the presence of large particulate matter preventing gear rotation, and/or the presence of particulate matter in the gears or gear bearings reducing the gear train efficiency--i.e., the torque transmitted from the gear train to the motor rotor shaft might have been insufficient to overcome the friction of the motor bearings.

The licensee stated that no major damage has been identified on several inspected reduction gear mechanisms, even though some wear and debris were observed. The licensee's analyses indicated that particulates with a size of 0.030 inches in diameter or greater, and with a comparable material composition as the reduction gear mechanism (implying comparable hardness), would be required to inhibit gear or gear bearing rotation. Analyses of CRDOA debris[8] showed the presence of rust, molybdenum disulfide and traces of silicon particles, which are relatively soft materials. The average particle of 0.020 inches was uniform in size, and tended to be smaller than that thought to inhibit rotation, even though rust particles on the order of 0.0625 to 0.125 inches were scraped off the ring gear pinion housing of CRDOA 18. However, the presence of debris in the gears and gear bearings tended to support the licensee's case of reduced gear train efficiency when sensitivity studies indicated that the motor bearings were only three times more sensitive to debris than the first pinion gear mesh of the reduction gear assembly, and 500 times more sensitive to debris than the cable drum bearings.

Los Alamos agrees with the licensee that the presence of debris, especially in the first pinion gear mesh and the gear bearings, could reduce the efficiency of the reduction gear train, and thereby contribute to CRDM failures.

2.1.3 Motor and Motor Bearing Malfunctions

During a scram, the motor is de-energized and does not directly contribute to the scram process, even though it operates as an induction generator. However, because 16-20 inch-ounces of resisting torque on the motor rotor shaft can forestall scram,[9] the friction from the motor bearings can be a significant contributor to the failure to scram. Possible contributions to increase the friction include debris in the bearing race, wear on the bearing ball or race, and changes in the lubricant properties during adverse conditions.

The licensee reported that debris was observed in the bearing races of CRDOAs 7, 18 and 44, "roughness in rolling the bearing balls was noted in virtually all of the unrefurbished bearings examined",[6] and minor race wear was identified. Reference 8 verified that the major debris constituents could be attributed to the motor bearing materials (which includes bearing balls, races, and other bearing components), whereas minor constituents were indicative of the motor itself. The analysis provided little evidence to support the theory that debris had been "washed" into the bearing races. The licensee also determined, because of the relatively close bearing tolerances and because rod weight alone might not produce sufficient "crushing force" to deform bearing particulate, that bearing operation could be reduced with the presence of particulate matter. The licensee therefore concluded that internally generated wear byproducts in the CRDM motor bearings contributed significantly to the failures to scram.

Los Alamos agrees with the licensee that increased friction in the motor bearings, caused by the presence of internally generated debris, could have been a likely contributor to the failures to scram. Los Alamos also agrees with the licensee that the "wash in" theory of debris into the motor bearing races is not supported.

Los Alamos contends that the loss of CRDM purge flow allowed primary coolant with high moisture content to enter the CRDM cavity. An independent literature search indicates that the dry film lubricant, molybdenum disulfide, MoS_2 , experiences an increase in its coefficient of friction in the presence of moisture[38]. Therefore, the increased frictional coefficient of the lubricant on the motor bearings, MoS_2, may have also contributed to the CRDM failures by resisting motor rotor shaft rotation.

2.2 Refurbishment Program

The cause of the failures to scram could be attributed to several mechanisms such as reduced reduction gear train efficiency, internally generated debris in the motor bearings causing increased friction on the motor rotor shaft, and possibly an increased frictional coefficient in the dry film lubricant in the presence of moisture. Because the CRDM failure mechanism cannot be specifically delineated, and because of CRDM cable failures, the licensee has undertaken a refurbishment program, involving the CRDM motors and reduction gear mechanisms, on all 37 CRDMs. The licensee reported that the CRDM refurbishment process and a testing program will ensure the ability of the control rods to scram under operating conditions.

In addition, the licensee has elected to replace the control rod cabling and other connecting hardware in light of recently identified stress corrosion problems, to replace the Reserve Shutdown System material due to the discovery of material "bridging" during hopper discharge, and to install seals around certain penetrations into the CRDM cavity to mitigate the effects of primary coolant ingress by natural circulation.

2.2.1 CRDOA Refurbishment

The licensee has proposed complete refurbishment of all Control Rod Drive and Orificing Assemblies to ensure that the CRDOAs will perform their intended safety functions, and to avoid potential operability problems that could limit plant availability. As specified in Reference 10, the following major components are to be inspected, tested, refurbished or replaced, as necessary:

1. Control Rod Drive (200) Assembly--shim motor and brake assembly, bearings, reduction gears, limit switches/potentiometers.
2. Orifice Control Mechanism--orifice control motor, bearings, potentiometer, gears, drive shaft and nut, drive shaft housing.
3. Control rod clevis bolts.
4. Reserve Shutdown System--boron balls, rupture disks, DP switch.

Design modifications include the replacement of control rod cables, cable end fittings, and cable clevis bolts, the installation of new purge seals into the CRDM cavity, and the installation of RTDs (Resistance Temperature Detectors) in all CRDOAs--the impact of these design changes will be evaluated later in this report.

Each CRDOA will undergo the following series of scram tests in the refurbishment process[6]: a pre-refurbishment, in-core full scram test; a pre-refurbishment full scram test in the Hot Service Facility (HSF); a scram test with refurbished reduction gear mechanism and unrefurbished shim motor, using dummy weights; a full scram test using a "standardized" motor, using dummy weights; a scram test with completely refurbished 200 assembly, using dummy weights; a post-refurbishment, full scram test in the HSF; and finally, a post-refurbishment, full in-core scram test.

As designated by the licensee in Reference 6, back-EMF voltage measurements from the shim motor will be taken for the series of scram tests conducted before, during and after refurbishment, and should define the CRDM operating characteristics. From the back-EMF voltage measurements, the licensee states that they can generate the following information--voltage versus time, frequency versus time, voltage versus frequency, acceleration versus time, torque versus time, peak angular velocity, time to peak back-EMF and angular velocity, average torque on motor rotor during acceleration to peak velocity, maximum torque on motor rotor each 10 second interval, maximum deviation of torque values each 10 second interval, and gear train efficiency.

The licensee has proposed a CRDOA refurbishment acceptance criterion, taking into account the results of the back-EMF voltage measurements and the resulting calculations of acceleration and torque such that[6]:

1. The minimum calculated average torque during acceleration to peak velocity will be 17.0 inch-ounces; this value corresponds to an average acceleration to peak velocity of 98.83 radians/second^2.
2. The maximum torque calculated during "steady-state" will be 7.0 inch-ounces.

According to the licensee, final acceptance of a refurbished CRDOA will be based upon the results of its in-core full scram test.

Los Alamos agrees with the mechanical refurbishment of all CRDOAs, as the program is currently being implemented by the licensee. In particular, the replacement of shim motor bearings[3, pp. 174-75] is considered essential to the refurbishment process. However, the current program of mechanical refurbishment alone cannot ensure CRDOA operability.

From the documentation presented by the licensee and reviewed earlier in this section, Los Alamos believes that the proposed back-EMF testing and acceptance criteria have potential in providing a data base from which control rod operability might be determined. But, an element of uncertainty, as to CRDOA operability based on back-EMF testing, is introduced because the test method and interpretation of its results are still in the developmental stages, and because in-core full scram testing of refurbished CRDOAs has not yet taken place.

Los Alamos recommends that the back-EMF testing method continue to be developed, that the further collection of back-EMF information be used in preparing a statistical data base for possibly defining CRDOA operability, and that more attention be paid to the initial, start-up scram characteristics of the CRDOA, in developing a better understanding of break-away torque effects. In line with Region IV's increased inspection of the refurbishment process, we suggest a review, by Region IV, of all testing results pertaining to CRDOA refurbishment acceptability, after in-core testing is complete, but prior to startup. As an additional method to ensure CRDOA operability during scram, a procedure requiring control rod run-in is recommended.

As a post-startup item, Los Alamos recommends that a final determination be made as to the suitability and acceptability of back-EMF testing in defining CRDOA operability.

2.2.2 Control Rod Cable Replacement

In September, 1984, the control rod cable on CRDOA 25 was severed in several places during an investigation of a slack cable indication.[11] A subsequent metallurgical examination[12] of the austenitic 347 stainless steel cable indicated that the cable surface was pitted and cracked, that the delta-like material cracks were typical of stress corrosion cracks, and that the fracture surfaces were brittle in nature. Further investigation revealed that the 347 SS cable material was susceptible to stress corrosion when under the existing stressed conditions, and in the presence of chlorides and moisture.

The potential sources of the chlorides in the primary coolant contributing to the chloride stress corrosion are reviewed in Reference 13. The licensee states that the chlorine occurs as two different species--HCl gas and a salt; the sources of the gas species include the fuel rods, H-327/H-451 graphite, PGX/HLM graphite and the Ti sponge, whereas the sources of the salt species include the ceramic insulation, concrete and water, all to varying degrees.

As part of the overall CRDOA refurbishment program, the licensee elected to replace the control rod cable with Inconel 625, which is considered resistant to chloride stress corrosion, and has increased strength and fatigue properties over the former 347 SS. Cable components and connecting hardware that were made from materials susceptible to stress corrosion, and are being replaced with materials more resistant to stress corrosion include:

	Component	Material
1.	Cable and rod portion of the ball end	Inconel 625--high strength and resistance to oxidation
2.	Anchor, set screw	Martensitic steel-high strength, ability to be nitrided, resistance to oxidation
3.	Spring, connecting bolt	Inconel X-750--high yield strength, resistance to oxidation.

Drawing numbers and material information are available in Reference 12. A safety analysis of the material changes in the reactor control rod drive and orificing assembly, which are classified as Class I, Safety Related and Safe Shutdown components, is included in Reference 14.

Los Alamos metallurgical analyses on a sample of the corroded control rod cable[15] also indicate pitting on the cable surface, ductile and brittle fracture surfaces, and to a lesser degree than the licensee, cracking indicative of stress corrosion cracking. Qualitative measurements confirm the presence of chlorine on fracture surfaces. Therefore, Los Alamos agrees that chloride stress corrosion contributed to the degraded condition of the control rod cable. The Los Alamos analysis also observed that a certain particle removed from between the individual cable strands of the Los Alamos sample had a "shaved" appearance, and was identified as a 7000 series aluminum alloy--the licensee noted that the control rod cable drum is constructed of 7075 aluminum alloy[4, p.20], and that no excessive drum wear had been noted.

Los Alamos agrees that the licensee's recommended material changes tend to improve the overall resistance of the CRDOA cable components and connecting hardware to chloride stress corrosion. However, Los Alamos also recommends a continued analysis into the sources of the chlorine and its effects on other reactor components, especially components potentially subjected to high chlorine concentrations such as the bottom plenum or other areas where water could accumulate.

2.2.3 Reserve Shutdown System Material-Related Failure

In November, 1984, during the required testing of a 20 weight % boron and a 40 weight % boron hopper in the Reserve Shutdown System, only half of the RSS material in CRDOA 21 (40 weight % boron) was discharged. The licensee's examination of the undischarged material revealed that the B_4C boronated graphite balls had "bridged" together through a crystalline structure on the ball surfaces. Analyses on the crystalline material indicated that it was boric acid.[16] The formation of the boric acid crystals was caused by moisture reacting with residual boric oxide in the RSS material. It was concluded that the moisture had entered the RSS hopper through the CRDOA vent/purge line by "breathing", and/or by water contamination in the helium purge line.

In Reference 16, the licensee proposed a threefold corrective action to the RSS material problems. First, new RSS material, manufactured by Advanced Refractory Technologies (ART) in late 1984 and early 1985, has an order of magnitude less residual boric oxide in the B_4C material, and will be installed in all RSS hoppers as part of the overall CRDOA refurbishment program. No effort will be made to use ART blended RSS material currently in stores[4, p.32] unless NRC is notified. Second, an expanded RSS material surveillance program, which will be incorporated into the Technical Specification, will test one 20 weight % boron hopper and one 40 weight % boron hopper during each refueling outage, and will include visual examinations for boric acid crystal formations, chemical analyses of RSS material for boron carbide and leachable boron oxide content. Third, efforts will be made to mitigate or eliminate the ingress of moisture into the RSS hoppers by installing a knock-out pot, moisture elements, and a back-up helium source for the main CRDOA purge and Reserve Shutdown System purge lines.[17] Each knock-out pot will be equipped with a sight glass and a high level alarm in the Control Room.

Los Alamos concurs that the crystalline structures on the surface of the B_4C RSS balls is meta-boric acid,[18] most probably formed by moisture reacting with leachable boric oxide in the B_4C material. In light of the new RSS material to be used, the increased surveillance efforts, and measures to mitigate the ingress of moisture in the RSS hoppers, Los Alamos agrees that the refurbished RSS should be able to reliably perform its function.

2.2.4 Purge Flow and Seal Replacement

Just prior to the June 23, 1984 event when 6 of 37 control rod pairs failed to insert on a scram signal, a high moisture content in the primary coolant resulted in the loss of purge flow into the CRDM cavities. The loss of purge flow may have allowed the additional ingress of moist primary coolant into the CRDM cavities, resulting in mechanisms that may have contributed to the CRDM failures. Because the exact CRDM failure mechanism has not been determined, and to alleviate the possibility of purge flow loss and/or high moisture content in the primary coolant contributing to future CRDM failures, the licensee has proposed several corrective measures[19] as part of the overall CRDOA refurbishment program.

To provide an accurate measure of the purge flow into the CRDM cavities, the licensee has proposed that new flow indicators with a range of 0-20 scfm be installed on each helium purge line, providing local indication, remote indication in the Control Room, and an alarm in the Control Room to indicate low flow conditions.[20] A minimum of 8 bypass lines (one line serviced by each of the 8 purge flow subheaders) will be installed prior to restart. The licensee intends to install the flow instrumentation[4, pg 3-4] on these subheaders when the devices are available.

As mentioned in section 2.2.3, to reduce the possibility of moisture ingress into the CRDM cavities via the helium purge lines, the licensee will install a knock-out pot, moisture elements and a back-up helium source for the main CRDOA purge and RSS purge lines, prior to criticality following the fourth refueling outage[4, pg 5]. The knock-out pots will be equipped with a sight glass and a high level alarm in the Control Room. The helium trailer, which will act as the back-up source of dry helium for purge, can provide helium at a rate of 7.4 acfm (4.5 lbms/hr per penetration at 700 psig) for approximately 2 hours.[17]

To mitigate the ingress of primary coolant, which could contain moisture, into the CRDM cavity, seals will be installed on four large flow passages into the CRDM cavity--the two passages in the reserve shutdown tube holes, and the two passages over the eye bolts that penetrate the floor of the CRDM cavity.[21] Cover plates with integral gaskets will also be installed on the four access openings on the lower CRDM housing. Thermal and mechanical analyses[22] have determined that the seal additions will not interfere with the RSS performance under the influence of mechanical, thermal or seismic loadings. The flow calculations in Reference 22 conclude that addition of the mechanical seals to the RSS pressure tubes and the lifting eyebolts will reduce naturally convective ingress of primary coolant into the CRDM cavity from a flow rate of 0.68 acfm to less than 0.006 acfm. Additional calculations have confirmed that the seals are able to withstand both a design basis slow depressurization transient and a design basis rapid depressurization transient.

The licensee has proposed a procedure in Reference 23 that basically requires reactor shutdown in the event CRDM purge flow is lost, or if high moisture content is present in the primary coolant.

Los Alamos agrees with the efforts of the licensee in monitoring the flow and moisture content of the helium purge into the CRDM cavities, in restricting the ingress of moisture into the CRD cavities via the purge lines, and in providing a back-up source of helium in case of purge flow loss. From the review of the provided documentation, Los Alamos agrees that the addition of seals and coverplates with integral gaskets will indeed mitigate the ingress of primary coolant and moisture into the CRD cavities through penetrations.

In addition, Los Alamos believes that the procedure requiring reactor shutdown with loss of purge flow or high moisture levels in the primary coolant fulfills the requirements of the assessment report[1]. The licensee defines "high moisture levels" in Reference 23.

2.3 CRDM Temperature Recording and CRDM Requalification

The lack of direct measurements of CRDM temperatures during the June 23 event, and during steady state and other transient operating conditions, has prompted the installation of RTDs to monitor the CRDM cavity closure plate (ambient), orifice valve motor plate and control rod drive motor temperatures. Strip chart recorders will continuously record the three temperatures for each CRDM,[24] and will provide a CRDM operating temperature data base. The old data collection surveillance procedure[25] will be modified to collect data on a continuous basis.[4, p.60] The licensee intends to install the permanent recorders prior to restart.[4, p.57]

The licensee postulates in Reference 26 that "the maximum temperature rating of the drive mechanism which might inhibit the scram function is 272°F", and in monitoring CRDM temperatures "the maximum temperature rating of 272°F should not be exceeded during power operation".

The licensee has also proposed a CRDOA requalification testing program that is designed to establish a temperature at which the CRDOA is qualified for operation.[27] The helium test environment will be operated at 250°F, 260°F, 270°F, 280°F, 290°F and 300°F with a goal of qualifying all CRDOA components for 300°F operation. Results of the requalification testing are anticipated by the end of 1985.

Los Alamos agrees that the placement of CRDOA thermocouples, and the continuous data monitoring at all operating conditions is sufficient to provide a CRDOA temperature data base during steady state and transient operating conditions.

In addition, Los Alamos believes that the CRDOA is currently only qualified to operate up to 215°F based on the original mechanical CRDOA qualification tests, an NRC recommendation,[28] and previous Los Alamos calculations.[29] The licensee's argument that the CRDOA is qualified for 272°F operation based on analytical calculations[4, p.49] is not substantiated. Therefore, Los Alamos recommends that CRDOA operation be limited to 215°F until mechanical requalification supports a higher operating temperature.

2.4 CRDM Surveillance and Preventive/Predictive Maintenance

The licensee has proposed a set of preventive/predictive maintenance tests and surveillance inspection procedures that are intended to monitor the performance of the CRDOAs and to determine the overall operability of the CRDOAs during reactor operation. Initial development of these operating tests are considered part of the CRDOA refurbishment program, and will utilize the data base and resultant trends formulated during refurbishment.

2.4.1 CRDM Preventive/Predictive Maintenance

The licensee's CRDOA preventive/predictive maintenance program is proposed in Reference 30. According to the licensee, the normal preventive maintenance (PM) program will be implemented on a refueling basis rotational cycle for CRDOAs that would normally be removed for refueling, unless the predictive maintenance (PDM) program indicates the need for more frequent maintenance. The PM program would emphasize the mechanical examination and refurbishment of the shim motor/brake assembly, the drive train, control rod cable, reserve shutdown system, position potentiometers, limit switches, orifice drive motor assembly, orifice drive lead screw, assorted seals, valves, electrical components, bolts and the absorber string.

On the other hand, the predictive maintenance techniques would be used to monitor the most important aspect of CRDOA performance--the "scram capability"--by determining the shim motor/brake and gear train performance. The tests proposed in the PDM program include wattage requirements, back-EMF voltages, delivered torque at the motors, scram times, rod drop rates and torques to rotate motor/brake assemblies. Certain aspects of the PDM program would be implemented on a weekly basis to determine scram capability and temperature performance during power operation. The licensee has also proposed that testing information be acquired during reactor shutdown for trending purposes.

Los Alamos concurs with the proposed preventive maintenance program as outlined by the licensee, on the assumption that data acquired during reactor operation will show that predictive maintenance techniques can be used to detect a reduction in CRDOA performance. The PDM testing techniques are closely linked to the techniques that are being used for the acceptance criteria in the refurbishment program, and will therefore be dependent on the suitability and acceptability of back-EMF testing for determining CRDOA operability, as discussed in section 2.2.1.

2.4.2 CRDM Interim Operational Surveillance

The licensee's CRDOA interim surveillance program is proposed in Reference 31. The surveillance tests are scheduled on a weekly basis, using a 10" rod drop method on all withdrawn and partially inserted control rods, except the regulating rod.[5, pg 82] The surveillance tests will obtain data for analysis and long term trending, exercise the rod, test selected circuitry, verify FSAR (Final Safety Analysis Report)[9] assumed scram times, and confirm control rod operability. In addition, CRDOA temperature and purge flow information will be collected.

For a fully withdrawn rod, analog and digital position information will be obtained, "Rod-Out" lights will be verified on, "Rod-In" and "Slack Cable" lights will be verified off, and the rod will be dropped approximately 10" by de-energizing the brake, while back-EMF data are obtained for future trending. The "Rod-Out" light indication will be verified off, and analog and digital information will be compared, with an acceptable deviation of 10 inches between position indications. The rod will then be withdrawn to the full out position, so that analog and digital positions can again be obtained. Control rods that are partially or fully inserted will undergo variations of this method.

Quarterly surveillance tests are intended to supplement weekly surveillance information, and to verify redundancy of selected control rod position limit switches. Refueling shutdown surveillance will acquire the same information as the weekly and quarterly tests, except full stroke insertion tests will be performed.

The operability acceptance criteria, according to the licensee, will be based on distance and time rod drop data used to calculate a conservative <u>average</u> full length scram time. A CRDOA will be considered inoperable if it does not meet the maximum scram time of 160 seconds as defined in the FSAR[9]. Such an indication would warrant back-EMF testing in confirming scram operability.

Los Alamos agrees that the basic surveillance methodology is sufficient to exercise the control rod, verify FSAR scram times, and to test selected circuitry. However, references to 272°F as the maximum CRDOA operating temperature are still considered inappropriate as discussed in section 2.3, and a 10 inch deviation is not considered acceptable between digital and analog position indications--such a deviation could inadvertently lead to control rod overdrive through a misinterpretation of rod position. Also, the back-EMF testing methods and interpretation of the results are still in the developmental stages, and an engineering determination of the suitability and acceptability of this testing method in determining continued CRDOA operability will need to be made before the licensee can finalize this portion of the surveillance program.

3.0 Moisture Ingress Issues

The licensee has submitted[32] a listing of the issues considered, and actions taken, by the FSV Improvement Committee (formerly the FSV Moisture Ingress Committee) in significantly reducing the frequency and severity of moisture ingress events. The issues were divided into four categories:

1. Issues currently under consideration by the Fort St. Vrain Improvement Committee.
2. Circulator Auxiliary System modifications yet to be completed prior to startup.
3. Circulator Auxiliary System modifications to be completed prior to startup, provided material availability and schedule permits.
4. Items identified by the Moisture Ingress Committee which are installed and operational.

Los Alamos believes that a listing of intended and installed modifications does not provide any indication as to what any given modification really is, why they contribute to the reduction in potential for moisture ingress events, nor which improvements will substantially reduce the severity and frequency of moisture ingress events. The licensee has committed to submit a more explanatory version of the actions to mitigate moisture ingress, prior to restart[4, pg 86].

4.0 PCRV Post-Tensioning Tendon System

In the spring of 1984, during scheduled PCRV tendon surveillance, tendons with corroded and broken wires were found. Since that time, the licensee has evaluated the corrosion mechanism, has performed lift-off tests on selected tendons to determine their load-carrying capability, and proposed corrective actions and an increased surveillance procedures.

4.1 Tendon Accessibility, Extent of Known Degradation and Failure Mechanism

The licensee, in determining the extent of tendon corrosion in the PCRV, determined what fraction of the tendons were available for visual examination and lift-off tests. The tendon system is subdivided into four major groups: the 90 longitudinal (vertical) tendons have 169 wires per tendon; the 210 circumferential tendons in the PCRV sidewall have 152 wires per tendon, and the 50 circumferential tendons in both the top and bottom heads have 169 wires per tendon; the 24 bottom cross-head tendons, and 24 top cross-head tendons have 169 wires per tendon. Of the four groups, the licensee states the following accessibility[33]:

Tendon Group	Both Ends Acces.	One End Acces.	Neither End Acces.
Longitudinal			
Visual	20	69	1
Lift-off	0	74	16
Circumferential			
Visual	281	27	2
Lift-off	236	62	12
Bottom cross-head			
Visual	20	4	0
Lift-off	16	4	4
Top cross-head			
Visual	17	7	0
Lift-off	16	6	2

The number of tendons with known broken wires as identified in the licensee's 1984 surveillance,[34] included 10 longitudinal tendons with 1 to 22 broken wires, 2 circumferential tendons with 2 and 15 broken wires, 8 bottom cross-head tendons with 1 to 19 broken wires, and no top cross-head tendons with broken wires. In some cases, the total number of corroded, broken wires include wires broken during lift-off tests, or during retensioning.

The results of 74 longitudinal lift-off tests[35] indicated that tendons with identified broken wires generally had a slightly smaller lift-off value than intact tendons. Thirty lift-off tests on circumferential tendons showed little change in lift-off value. Some of the fifteen bottom cross-head tendon lift-off tests showed a definite reduction in lift-off value for tendons with multiple wire breaks. The value of the lift-off test on one top cross-head tendon was nominal. All lift-off test values exceeded the minimum limits.

The licensee conducted metallurgical investigations into the cause of the corrosion, and determined that microbiological attack on the tendon NO-OX-ID CM organic grease caused the formation of formic and acetic acids.[34,36] The acids, in conjunction with moisture in the tendon tube, vaporized and recondensed on the cooler portions of the tendons--in this case, usually toward the tendon ends. The acidic attack resulted in reduced cross-sectional wire area, stress corrosion cracking, localized tensile overload and wire breakage.

Los Alamos believes, based on the documentation presented by the licensee, that microbiological attack of the tendon grease and the resultant formation of acetic and formic acids, in the presence of moisture, is a probable cause for the currently observed tendon corrosion, and has led to the subsequent wire breakage through tensile overload. However, Los Alamos believes that the extent of known tendon corrosion, breakage and previous surveillance have not been clearly defined by the licensee. Los Alamos therefore recommends that a complete map be made that lists each tendon, its visual examinations and lift-off values, and the number and location of corroded and broken wires. An indication of the degree of wire corrosion would also be desirable.

4.2 Tendon Corrosion Corrective Measures

The licensee evaluated several methods for arresting the corrosion process,[34,36] including the use of ozone as a biocide to kill the microorganisms, the use of an alkaline grease which should not be conducive to microbiological growth, and the use of an inert blanket consisting of nitrogen gas. The licensee's consultants found that the nitrogen atmosphere arrested the growth of the microbes in the NO-OX-ID CM organic grease[34,35], and eliminated the oxygen which is necessary for the corrosion process to continue. Based on these results, and as a short term action, the licensee has proposed that nitrogen blankets be established on the longitudinal and bottom cross-head tendons. Long term actions would include further investigations into the corrosion process and arresting techniques, and the possible installation of additional load cells in monitoring the PCRV behavior.

Los Alamos believes that the use of a nitrogen blanket to halt the corrosion process may be suitable, but difficult to implement as proposed. The tendon tubes are not likely to be leaktight, and maintaining an inert gas atmosphere at a set over-pressure may prove difficult. Consideration might be given to maintaining an intermittent or continuous purge flow through the tendon tubes, as needed, rather than to maintaining a specified overpressure. However, Los Alamos recommends that initially the nitrogen be purged through the individual tendon tubes to remove as much moisture as possible, and that gas samples be used to monitor moisture and oxygen reduction. Further investigation into the long term effects of a nitrogen blanket on tendons, the corrosion process and currently available corrosion acids are also recommended.

4.3 PCRV Tendon Interim Surveillance

Because the total extent of tendon corrosion in the PCRV is unknown, because the rate of existing corrosion is unknown, and because the use of a nitrogen blanket as an arrest to the corrosion process is an unknown, the licensee has proposed an interim surveillance program designed to address each of these issues.[5, pp.164-7.] The interim tendon surveillance program would include increased visual and lift-off surveillance for three years, or until effective corrosion control has been established. Two populations of tendons would be inspected--a population of tendons that have not been previously identified as being corroded, and a control population with known corrosion. On a six-month frequency, visual surveillance of both tendon ends, when accessible, would include:

Tendon Group	No. of New Tendons	No. of Control Tendons
Longitudinal	24	6
Circumferential	13	3
Bottom cross-head	6	2
Top cross-head	1	1

Lift-off tests would be performed on two frequencies--an 18 month frequency for the population of new tendons, and a 6 month frequency for the control population. The number of tendons for lift-off will include:

Tendon Group	No. of New Tendons	No. of Control Tendons
Longitudinal	12	3
Circumferential	13	3
Bottom cross-head	3	1
Top cross-head	1	1

As an acceptance criteria, the licensee proposed that, based on visual examinations, a mandatory engineering evaluation be conducted on any tendon that has 20% of its wires broken. For any tendon that has only one accessible end, the mandatory engineering evaluation will be conducted when any tendon has 10% of its wires broken. The control tendon population will include those tendons with the worst known corrosion with ready accessibility.

Los Alamos agrees that the increased tendon surveillance program of the nature proposed by the licensee will provide more information on the extent of corrosion in the PCRV by inspecting new tendons each surveillance, and at the same time, monitor the rate of corrosion with the control tendon population. The increased surveillance should also determine the effectiveness of the nitrogen blanket in arresting corrosion, or any other corrective measure the licensee may propose. Los Alamos recommends that the licensee submit an outline of the intended mandatory engineering evaluation, which should include all lift-off, load cell and relaxation data incorporated into a safety evaluation. The licensee should define the extent of the visual and lift-off testing procedures, and could use US/NRC Regulatory Guide 1.35[37] for guidance.

4.4 PCRV Structural Calculations by Los Alamos National Laboratory

The PCRV tendons are intended to apply sufficient compression in the concrete to balance or exceed the circumferential and vertical tension in the concrete that results from the internal pressure. A combined analytical and numerical study[39] was undertaken by Los Alamos National Laboratory to evaluate the evolution of these stresses, both to the initial prestressing and to subsequent partial and total rupture of these tendons. At the stress levels anticipated in the concrete, and for the anticipated operating life span of the PCRV, the concrete behavior was modeled as a linear viscoelastic solid with the creep strain varying proportionally with the logarithm of time at constant stress throughout the projected reactor lifetime.

A one-dimensional model of a long concrete column of rectangular cross-section, with an embedded prestressing tendon along the length, was used to evaluate the concrete and steel stresses as well as the hold-down and lift-off forces. These were evaluated for the intact tendons and the degraded tendons. The degree of tendon degradation is described through the ratio of the number of unbroken strands to the original number of strands. Initial time of rupture was varied from the time of initial prestressing to 400 days after emplacement. The formulation led to an integral equation, which was solved numerically. The hold-down forces decayed approximately with the logarithm of time and for both the extreme observed degradation (21 broken strands) and for a more extreme case (40 broken strands), the hold-down force still exceeded the minimum safety design requirements.

In addition, several finite element calculations, using the finite element code NONSAP-C, were made to evaluate complete tendon failure in a 60° sector of the Fort St. Vrain PCRV. This code has an extensive material library of constitutive relations to model the various properties of concrete, together with a specialized element model to simulate prestressing tendons. Two rows of vertical and an arc row of circumferential tendons were incorporated in the model as a baseline calculation. The tendons were prestressed to 70% of the ultimate and an internal pressure of 775 psi was applied (this pressure is the internal pressure of the helium coolant in the HTGR) and the creep of the concrete and slow decay of the tendon stresses were evaluated out to 30,000 days. Then, three cases wherein one tendon was removed at one day were evaluated. First the middle vertical tendon in the outer row and in line with the outer buttress was removed. Second, an inner vertical tendon opposite the thinnest portion of the PCRV wall was removed. Finally, an inner layer circumferential tendon at midheight was removed. Stress redistributions at 300 days after ruptures were calculated and shifts of the remaining tendon loads to accommodate the broken tendon were calculated. Regions of local tensile and shear stress in the concrete portion of the PCRV were identified and related to overall structural integrity.

With all tendons present, the mean vertical stress was about -760 psi, the radial stress decreased from the applied internal pressure of -705 to about -1200 psi at the ring of circumferential tendons and the tangential stress ranged from -2400 psi at the inner wall to about -2200 psi at the same place. Removal of a vertical tendon reduced the mean axial stress by about +40 psi, the local tangential stress by -10 psi and did not materially affect the radial stress. Removal of a circumferential tendon reduced the mean tangential stress by +30 psi and the local axial stress by -80 psi. The vertical hold-down force from zero days through 30,000 days decreased linearly and remained above the prescribed safety limit, as did the circumferential hold-down force.

Comparison of the analytical solution and a small finite element problem simulating the analytical problem was made to verify the visco-elastic creep models and the tendon element in the NONSAP-C code. Excellent agreement for stresses, strains and hold-down forces was obtained.

5.0 Conclusions

Los Alamos concludes that the licensee, Public Service Co. of Colorado, has made a conscientious effort to address all of the restart issues listed in the assessment report.[1] The refurbishment program on all CRDOAs provides confidence in CRDOA operability during reactor operation and the ability to scram, even if the exact "failure to scram" mechanism has not been defined. Questions concerning the reliability of the back-EMF testing procedure on the shim motor/brake assembly in determining control rod operational acceptability still exist, but further method development, more experience with result interpretation, and in-core testing may alleviate the questions. Until CRDOA operability can definitely be ascertained with these methods, we recommend that the licensee have backup measures such as rod run-in following scram.

Control rod cable and connecting hardware material replacement, along with replacement of the Reserve Shutdown System material, serve to rectify the material problems brought on by corrosive mechanisms.

In light of chloride stress corrosion problems, Los Alamos also recommends that <u>all</u> reactor components exposed to the primary coolant be reviewed for susceptibility to chloride attack, especially the PCRV liner. Review should continue into the source of chlorine and methods to eliminate its generation and presence.

The effects of purge flow loss have not been determined to be instrumental in CRDOA failures to scram, yet the licensee has committed to maintaining purge flow by external means, and to reducing the effects of primary coolant naturally convecting into the CRDOA cavity with extra seal installation.

Even though current qualified CRDOA operating temperatures are very much in question, the licensee is in the process of requalifing the mechanism for temperatures more in line with those anticipated during reactor operation.

From a mechanical standpoint, CRDOA preventive/predictive maintenance procedures are certainly reasonable, but like the proposed surveillance program, they are dependent on back-EMF testing methods which are still in the developmental stages.

Evaluation of moisture ingress corrective measures was difficult due to the lack of information with which to understand the measures taken. The licensee has committed to submit a more explanatory version of the actions to mitigate moisture ingress prior to restart.

The extent of PCRV tendon degradation is not well known, even if the licensee may have determined the cause of the corrosion. Further investigation into arresting measures is definitely required, especially because the nitrogen blanket technique may be so difficult to employ. However, the interim surveillance program should provide information on the degree and rate of corrosion, in addition to establishing a tendon wire loss acceptance criteria. The tendon acceptance criteria should ensure PCRV margins to safety.

6.0 References

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