FORT ST. VRAIN CIRCULATOR OPERATING EXPERIENCE

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Abstract

Fort St. Vrain, on the system of Public Service Company of Colorado, is the only high-temperature gas-cooled power reactor in the United States. Four helium circulators are utilized in this plant to transfer heat from the reactor to the steam generators. These unique machines have a single stage axial flow helium compressor driven by a single stage steam turbine. A single stage water driven (pelton wheel) turbine is the back-up drive utilizing either feed water, condensate, or fire water as the driving fluid.

Developmental testing of the circulators was accomplished prior to installation into Fort St. Vrain. A combined machine operating history of approximately 250,000 hours has shown these machines to be of conservative design and proven mechanical integrity. However, many problems have been encountered in operating the complex auxiliaries which are necessary for successful circulator and plant operation.

It has been 15 years since initial installation of the circulators occurred at Fort St. Vrain. During this time, a number of significant issues had to be resolved dealing specifically with machine performance. These events include cavitation damage of the pelton wheels during the initial plant hot functional testing, cracks in the water turbine buckets and cervic coupling, static shutdown seal bellows failure, and, most recently, degradation of components within the steam drive assembly.

Unreliable operation particularly with the circulator auxiliaries has been a focus of attention by Public Service Company of Colorado. Actions to replace or significantly modify the existing circulators and their auxiliaries are currently awaiting decisions concerning the long-term future of the Fort St. Vrain plant.

INTRODUCTION

Fort St. Vrain is a 330 megawatt electric generating station owned and operated by Public Service Company of Colorado and situated approximately 40 miles north of Denver. The plant was designed by General Atomic Company and utilizes helium as the primary coolant. A pre-stressed concrete reactor vessel (PCRV) contains the total primary coolant system including the reactor, steam generators, and helium circulators (Figure 1). Primary coolant helium at approximately 700 psia is directed downward through the graphite moderated and reflected core where it is divided into two identical loops, each consisting of steam generator modules and two helium circulators. The cold helium then flows up the core barrel at the periphery of the reflector to an upper plenum, completing the primary coolant loop.

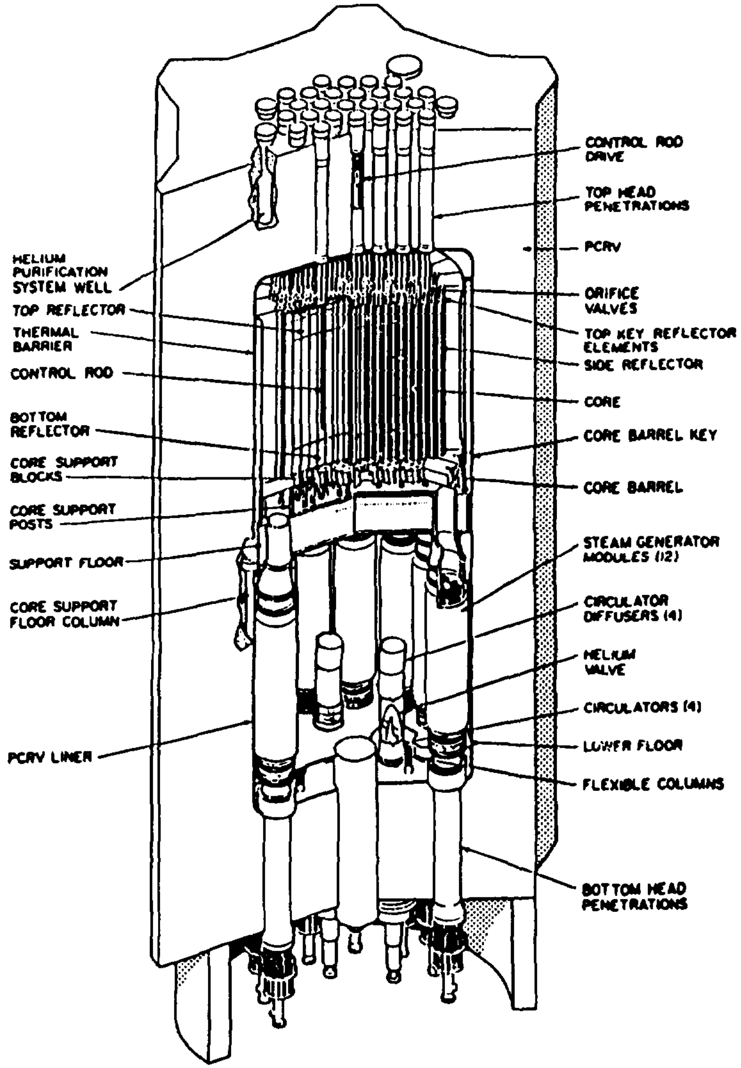

FIGURE 1 Fort St. Vrain Reactor Arrangement

THE HELIUM CIRCULATORS

The helium circulators (Figure 2) have a single-stage axial flow helium compressor with a steam driven single-stage turbine using exhaust steam from the high pressure generating turbine. A single-stage water driven (Pelton wheel) turbine is the backup drive. This water turbine can use feedwater, condensate, or fire water as the driving fluid.

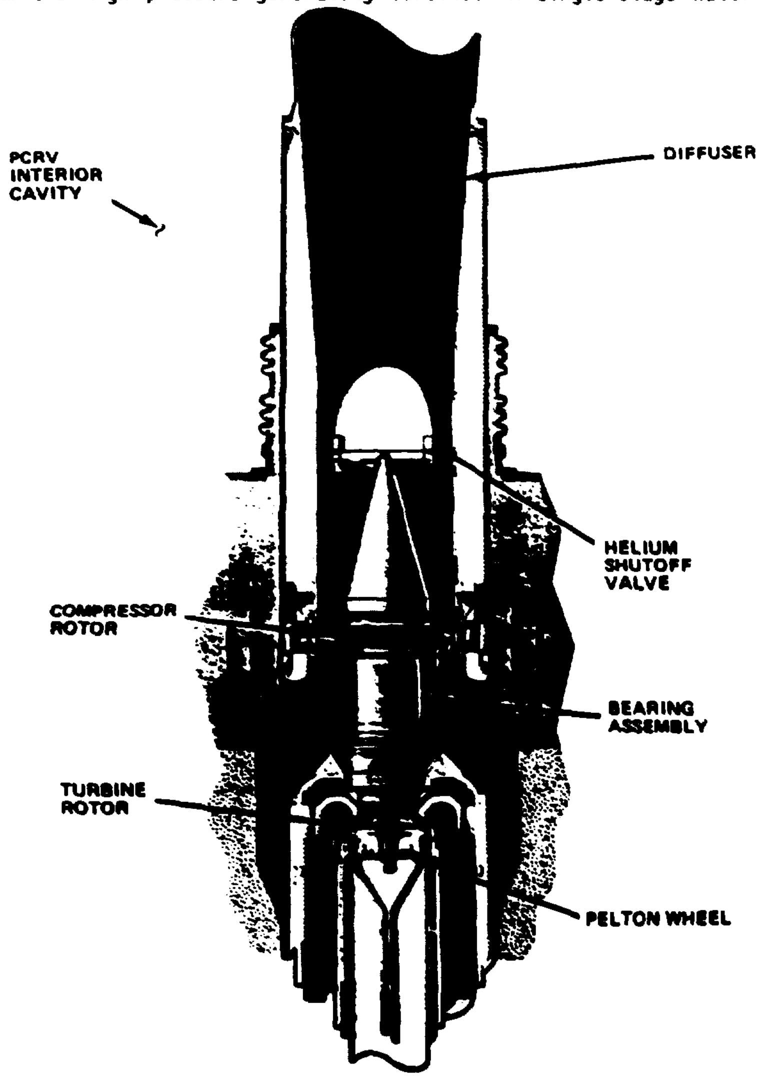

FIGURE 2 Fort St. Vrain Helium Circulators

The circulator shaft weighs approximately 500 lbs. and is 37 inches in length. The helium compressor, steam turbine, and water turbine have diameters of 32, 17, and 6 3/4 inches, respectively. Circulator operating characteristics are shown in Table 1 [1].

Table 1

Individual Circulator Operating Characteristics

Full load steam turbine power	5 504 hp
Water turbine design power	579 hp
Rated speed	9 550 rpm
Maximum continuous operating speed	10 800 rpm
Design overspeed	13 500 rpm
Helium conditions	
Mass flow rate	242 lb/s
Inlet pressure	686 psia
Inlet temperature	742° F
Design static pressure rise	14 psi
Steam conditions	
Mass flow rate	155.3 lb/s
Inlet pressure	848 psia
Inlet enthalpy	1 357.8 Btu/lb
Enthalpy drop	25.5 Btu/lb

An elaborate system of auxiliaries is required to maintain proper circulator operation. Figure 3 is a schematic representation of most of the auxiliaries required for the operation of two circulators in a single coolant loop. Basically, the circulators are equipped with a purified buffer helium supply which prevents the primary coolant from flowing down the shaft, and bearing water from flowing up the shaft.

Part of this buffer helium is mixed with bearing water and is eventually removed in the high pressure separator. The helium is then compressed through the buffer helium recirculators, passes through a dessicant type dryer, and then flows back to the initial buffer supply line. A shutdown seal is utilized to seal the shaft from contaminated primary coolant when the circulator is shut down. This is a mechanical seal actuated by pressurizing the bellows which causes metal-to-metal contact between a seal ring and a machine surface lip on the circulator shaft.

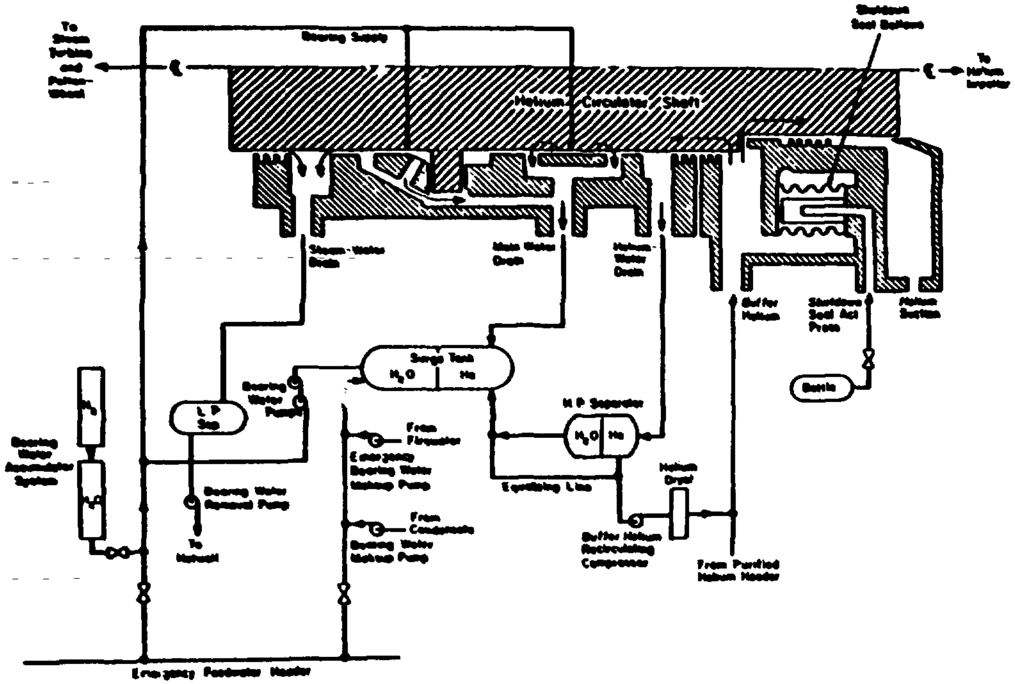

FIGURE 3 The FSV Helium Circulator Auxiliaries

All circulator bearings are water lubricated. Normal bearing water is supplied by two of three multi-stage pumps running in series. Bearing water pressure is held at about 700 psig above primary coolant pressure. Water make-up requirements of this system are normally from the feedwater system with redundant supplies via a bearing water make-up pump feeding condensate, and as a final alternative, an emergency positive displacement pump feeding condensate or fire water. The normal bearing water system is used during normal circulator operation. If this system is interrupted, the backup bearing water system using feedwater supply is automatically introduced. A third system, the emergency bearing water system, supplies sufficient bearing water to the circulator for the short time required for damage-free coastdown following a circulator trip upon loss of normal and backup bearing water systems [2].

A nitrogen pressurization system is used during water turbine operation when driving the pelton wheels with high pressure and high temperature feedwater. This system supplies nitrogen to the pelton wheel cavity to maintain it at 10-30 psi above the saturation pressure of the feedwater supply to the turbine. This system is utilized to prevent cavitation damage to the pelton wheels when operating on feedwater.

DEVELOPMENT TESTING OF THE HELIUM CIRCULATORS

In 1966, a facility was built near Boulder, Colorado, at PSC's Valmont Steam Electric Station (a fossil-fueled plant) to field test the basic design concepts of the circulators. Steam was obtained from the power plant to drive the circulators. The main test bed consisted of a pressure vessel sized to house a full-sized circulator. The environment in the test vessel could be controlled to closely reproduce the primary coolant pressure, temperature, and helium atmosphere conditions expected in an operating HTGR [7]. This facility was used for the following purposes:

(1) To check the aerodynamic properties of the helium compressor blading, inlet, and diffuser.

(2) To investigate noise levels emanating from the helium caused by compressor operation.

(3) To verify circulator bearing and rotor dynamic performance.

(4) To test the circulator shaft seals.

(5) To evaluate stresses and natural frequencies of the compressor and turbine rotor blades.

(6) To evaluate the circulator's operational capabilities when subjected to abnormal transients such as thermal shock of switching from steam to water turbine drive, overspeed of the circulator to 13,000 rpm, and rapid depressurization from normal primary coolant helium pressure to atmospheric pressure.

The results indicated that the circulator design was well suited to provide the primary coolant circulation requirements of an HTGR. After these developmental tests were performed, five production model circulators (four normal units plus a spare) were individually tested prior to installation at Fort St. Vrain. These units were run to full speed on steam and to approximately 8400 rpm on water turbine drive [1].

CIRCULATOR OPERATIONAL HISTORY

The circulator assembly is a conservatively designed machine with proven integrity. The circulators have been incorrectly identified with a significant fraction of the plant down time. Much of the time attributed to the circulators has in fact been a result of problems with the circulator auxiliaries, e.g., the bearing and seal water supply system. These problems were characterized by water ingress into the primary coolant system. The circulator machines have been much more reliable than perceived; moreover, the mechanical integrity of the circulator has been excellent.

While accumulating approximately 250,000 total combined (five machines) operating hours (based on water plus steam drive, Figure 4) out of 1,050,000 hours full-temperature design operational life, approximately fourteen separate incidents have required one or more circulators to be removed for repair, and one design modification was incorporated in-situ. These incidents are summarized in Table 2.

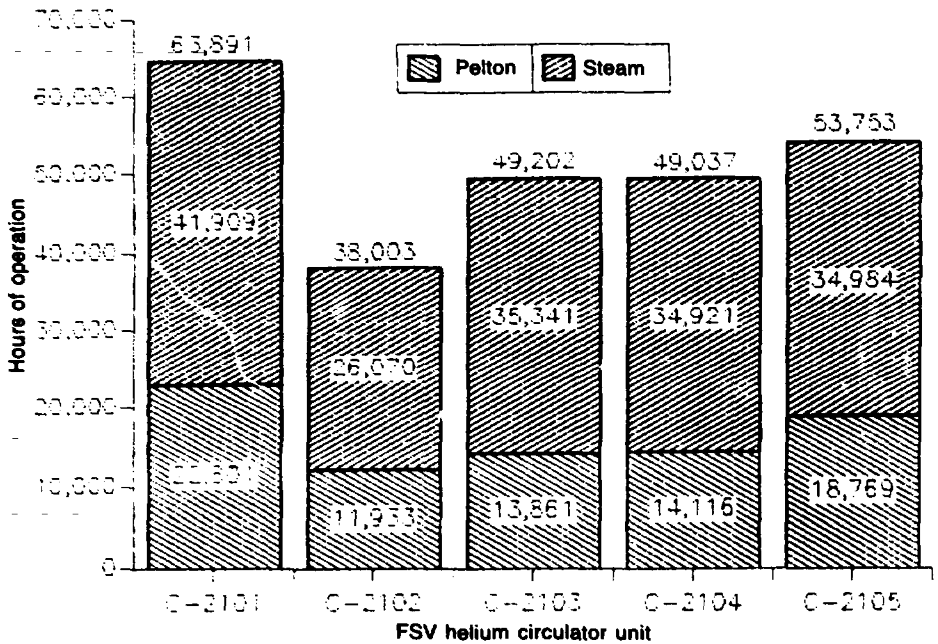

FIGURE 4 FSV Helium Circulator Hours of Operation [10]

TABLE 2

SUMMARY OF CIRCULATOR PROBLEM INCIDENTS [10]

INCIDENT PROBLEM	CIRCULATOR SERIAL NUMBER	INCIDENT DATE	INCIDENT RESOLUTION	FAILURE CATEGORY: DESIGN OR MFG. DEFECT	RANDOM FAILURE	EXTERNAL OR OTHER
Shutdown Seals						
Ruptured Bellows	C-2101	7/74	Improved press control	X		
Face Leak	C-2105	7/75	Improved control of brake sequencing	X		
Supply Line Leak	C-2101	8/75	Repaired to drwg		X	
Bellows Leak	C-2102	4/76	Mfg'g defect	X		
Bellows Leak	C-2105	2/80	Mfg'g defect	X		
Bellows Leak	C-2102	6/81	Design Mod	X		
Pre-Nuclear Pelton Wheel Cavitation	All	8/72	Incorporated pressurized nitrogen blanket on water system	X		
Nuclear Pelton Wheel Cracks	All	12/74	Wrought wheels installed in-situ	X		
Bearing Water Line Leak	C-2102	12/84	Mfg'g defect in bolt	X		
Stress Corrosion of Compressor End Bolts	All	1/85- 6/85	Changed material	X		
Primary Seal Leak	C-2103	9/76	Changed bolt mat'l, thread form, & torque (all machines)	X		
Insulation Cover Area Parts Failure	C-2101	8/87	To be determined	X(?)		X(?)
External Problems/Inspections						
Brg Water Strainer Failure	C-2104	8/73				X
Tech Spec Inspection	C-2102	3/79				X
Discharge Valve Damage	C-2104	1/84				X

The failure incidents are categorized in the last three columns of Table 2 headed "Design or Manufacturing Defect", "Random Failure" and "External or Other".

As indicated in the table, of the fourteen failure incidents there have been tentatively eleven design or manufacturing defect failures of circulators. One failure is considered a random failure and the remaining three are not attributable to the circulator design (i.e., the "External Problems/Inspections" category under the "Incident Problem" heading).

Of the eleven design or manufacturing defect failures tentatively attributed to the circulators, three are more directly related to external auxiliary system failures for which modifications corrected the problem.

(The three auxiliary system modificaitons are the improved pressure control for the shutdown seal bellows, the improved control of the brake/seal sequencing to prevent seal actuation while the rotor is turning, and the pressurization of the pelton wheel water cavity to prevent cavitation.)

Thus, only approximately eight incidents are clearly attributable to design or manufacturing defects in the circulator machine [10]. A description of the more significant circulator issues is chronologically described in the next sections.

CIRCULATOR OPERATION DURING HOT FUNCTIONAL TEST

Installation of the four circulators was completed in January 1972. Many construction and instrumentation difficulties were encountered, but these were largely associated with the circulator auxiliaries.

Prior to core loading, the hot functional test of the primary coolant system began in July 1972. Special oversized (pre-nuclear) water turbines driven by feedwater at 3500 psig were used to compress and thus heat the primary coolant to a maximum 625°F.

During the initial phases of the test, with circulators running at low speeds, and with large numbers of starts and stops, cavitation damage occurred on the speed control valves which regulate circulator speed by controlling water flow to the water turbines. Cavitation damage was avoided by redesign, but problems external to the circulators involving the valves appeared. Sustained operation resulted in sporadic low frequency, high amplitude vibration in the emergency feedwater piping causing pipe hanger and insulation damage. This condition was resolved by replacing the insufficiently stiff pneumatic operators on the valves with stiffer hydraulic units.

After a few hundred hours of individual circulator operation, one circulator indicated high shaft eccentricity. After verification of the eccentricity reading, the circulator was shut down. Several days later, another circulator automatically shut down due to an apparently spurious overspeed trip. When a restart was attempted, a very high eccentricity reading was indicated.

The hot functional test was interrupted and all four circulators' water turbines were visually inspected by removing the penetration piping. All four exhibited various degrees of metal damage believed to be due to cavitation. The two circulators that had indicated shaft eccentricity had each lost one or more turbine buckets. All four circulators were removed from the reactor vessel and were shipped to General Atomic Company (GAC) in San Diego, California for inspection and rework [3]. Figure 5 typifies the bucket damage that was sustained. Examination showed that the damage was due to severe cavitation leading to stress concentrations at the bucket roots with some resultant fatigue failures.

All of the turbine wheels had some damage, the severity correlating directly with the operating times. Of the two intact wheels, one was

FIGURE 5 Helium Circulator Water Turbine Wheel Bucket With Cavitation Damage

badly cracked. The cavitation damage was caused by implosive forces developed when vapor or gaseous bubbles collapsed adjacent to a solid surface, aggravated by the erosive tendencies of the hot feedwater. The damage was evidenced by crater-like pits which, in advance stages, were re-entrant and honeycombed. Damage in certain cases destroyed the tip of the splitter that divides the impinging water jet. On the bucket backsides, damage penetrated into the hub [4].

This cavitation damage was subsequently resolved by installation of the pelton cavity nitrogen pressurization system previously described.

A second hot functional plant test was successfully completed between May and August 1973.

CIRCULATOR OPERATION DURING LOW POWER PHYSICS TESTING

Fuel loading was completed in January 1974, followed by two months of low power physics tests [8]. The helium circulator performance startup test was conducted during April and May 1974. The test demonstrated adequate circulator operation using steam from the plant's auxiliary boiler as the driving force. For one loop operation, the circulator water turbine drives automatically started, as required by accident analyses, upon loss of both circulator's steam drives. Also, per design conditions, one water turbine driven circulator (powered under fire water conditions) provided greater than the necessary primary coolant helium flow for adequate shutdown core cooling.

In July 1974, a failure occurred to a static shutdown seal of a circulator. The shutdown seal is used to isolate the auxiliary system from the primary coolant. It is applied after the brake shuts down circulator rotation.

After removal of the circulator and installation of the spare, it was found that seal failure was due to inner bellows rupture from an apparent inadvertent overpressure and resultant overextension (Fig. 6).

To verify that the failure was not generic, all of the installed circulator seals were cycled twenty times without incident. Because of the heat treatment used on the seals, if they had been overpressured, failure would have occurred within a few cycles.

Further study of the removed circulator revealed two additional failures:

(1) Six of the water turbine buckets had microscopic cracks at the splitter.

(2) The curvic coupling joining the water and steam turbine assemblies exhibited deep cracking only on the water turbine cast Inconel 718 portion. The wrought 422 stainless steel steam turbine portion was flawless.

General Atomic Company initiated extensive metallurgical, engineering, and experimental testing efforts to determine the cause of the cracks [6]. These tests included fracture mechanics analyses, fracture toughness determinations, tensile, impact, stress corrosion, vibration loading, and thermal shock tests. Evaluation of the analytical and test data indicated that both failures were due to high frequency cyclic fatigue. The curvic coupling failure was caused by umbrella-like flexing stresses set up by steam hitting the circulator turbine blades at sonic velocities. This stress when applied to the Inconel 718 curvic coupling casting was of sufficient magnitude to exceed its tensile strength. Fracture mechanics analytical methods supported by experimental testing showed these cracks to be self arresting at all the required operating conditions, and they would therefore not impair circulator function [6].

FIGURE 6 Damaged Helium Circulator Shutdown Seal Bellows

It is believed that the coupling failures occurred during preliminary testing at Valmont where operation at the incorrect pressure ratio across the steam nozzles allowed a condition of cyclic pulsing in the steam at the turbine disk. Flexings of the disk were transmitted to the coupling.

The fatigue cracks on the water turbine wheel buckets were believed to be due to stress amplification caused by the water jets hitting the buckets coupled with high speed rotation. This loading is highly amplified as the circulator exceeds 8000 rpm. Normal, full circulator speed with primary coolant at atmospheric pressure is in excess of 10,000 rpm. Cracking of these buckets apparently occurred in less than ten hours at such high speed operation. To prevent failure reoccurrences, maximum circulator speed during water turbine operation was limited to 7000 rpm. Stress analyses indicate that sustained operation at this lower speed will not result in crack initiation and propagation. The accidents analyzed in the Final Safety Analysis Report (FSAR) have been reviewed by GAC with the conclusion that the temperature limits of the reactor core and primary coolant thermal barrier materials will not be exceeded during emergency water turbine operation limited to 7000 rpm.

In December 1974 all four water turbine wheels were replaced by new assemblies machined from inconel 718 forgings. The forgings are known to better resist cyclic fatigue damage [9]. There has been no evidence of fatigue cracking in those assemblies that have been inspected after normal operation.

CIRCULATOR PERFORMANCE DURING INITIAL RISE-TO-POWER

In March 1976, the shutdown seal of a circulator failed. The source of the leakage was determined to be a crack in the inner bellows of the assembly.

An investigation into the failure led to the conclusion that the crack was most probably initiated by repeated overextension of the bellows prior to installation in the circulator [5]. The qualification test specified by GAC for the seal vendor was changed to prevent any future seal test damage.

Plant operations continued through 1978 with generally satisfactory performance of the helium circulators. In 1979, as part of the Fort St. Vrain technical surveillance requirements, a complete circulator unit was removed from the PCRV and inspected for signs of abnormal wear or component degradation. This inspection included examination of bearing surfaces, seal surfaces, break system, buffer seal system, and labrynth seals. The helium compressor impeller, the steam turbine drive, and the pelton wheel were also inspected for both surface and sub-surface defects. Results of this inspection indicated that abnormal wear or component degradation had not occurred and that future inspection intervals of approximately ten years would be sufficient to monitor the condition of the helium circulators.

CIRCULATOR ISSUES DURING COMMERCIAL OPERATION

On January 8, 1980 while operating the plant at very low power, it was determined that a leak existed in the static seal actuating mechanism of the 1B helium circulator. This leak was subsequently determined to be internal to the machine, and it was subsequently removed and replaced with the spare helium circulator.

Upon disassembly it was determined that a crack existed in the bottom confluant of the outer bellows of the static seal assembly. Further examination indicated that this failure was caused by tension tearing of a groove apparently left by the forming tool during the manufacturing process. All spare seals were subsequently inspected and no evidence of similar damage was uncovered. This was determined to be an isolated manufacturing defect and not indicative of a generic problem.

The most recent helium circulator problem occurred on July 29, 1987. With the reactor at approximately 70% power, a circulator trip occurred following by a secondary coolant loop #2 shutdown. After reduction in power to reestablish loop #2, a high shaft wobble indication as well as high inner space helium flow was observed on the "D" (C-2101) helium circulator. The reactor was subsequently shut down, and in the ensuing month the circulator was removed and replaced with the spare.

A detailed investigation of the C-2101 circulator continues at the present time. However, the investigation has revealed that the insulation shield and corresponding labrynth seal had failed (Figure 7) dropping onto

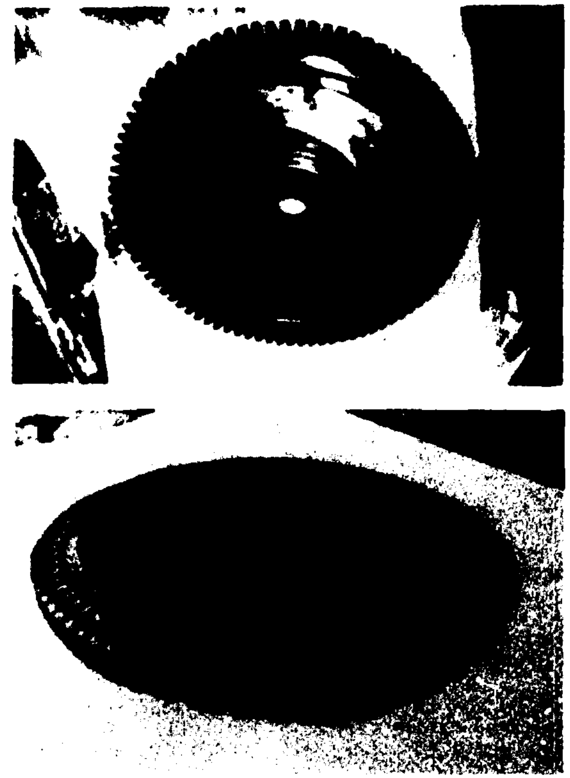

FIGURE 7 Views of Remnants of Insulation Cover On Rim Of Steam Turbine Rotor

the steam turbine wheel. So far, stress corrosion cracking has been determined to be a factor in the mechanical degradation of the labrynth seal mounting bolts and the steam ducting bolts. The cause of this cracking is felt to be due to caustic embrittlement possibly brought about by a combination of low level caustic carryover from regeneration of the secondary coolant demineralizers throughout the past 15 years, and the limited use of a sodium hydroxide base water treatment on the make-up to an auxiliary boiler added to the plant approximately five years ago to help satisfy steam needs during plant shutdown and low power conditions.

At a recent meeting with the NRC, a near-term program was identified where Fort St. Vrain would continue plant operation until the inspection of C-2101 is completed and the necessary spare parts are procured to allow replacement of all affected components in the circulators currently installed in the Fort St. Vrain PCRV. It was determined that the failure mechanism identified in C-2101 may have generic implications, but the failure would be confined to each circulator singularly and would not have the ability to allow one circulator problem to affect another circulator. It is anticipated that a plant shutdown of approximately three months' duration will be required beginning approximately March 1, 1988.

CONCLUSIONS

The Fort St. Vrain helium circulators and their auxiliaries are prototypical complex, one-of-a-kind components and as such, problems have been encountered which have played an important role in the poor operational performance of the plant. It is felt that the circulator assembly itself is a conservatively designed machine with generally proven integrity. However, because successful circulator operation requires nearly flawless performance of a complex circulator auxiliary system which includes several thousand valves and instruments while supporting such components as pumps, compressors, heat exchangers, and vessels, overall plant performance has been impaired.

Public Service Company of Colorado has considered a number of circulator design alternatives including the following: new circulators with magnetic thrust bearings, new circulators incorporating hydrostatic seals to prevent high pressure bearing water from entering the primary coolant system and, significantly modified auxiliaries so that each circulator stands alone without a multiplicity of inter-acting and inter-related sub-systems. Actions to replace or significantly modify the existing circulators and their auxiliaries are currently not being acted on, pending decisions concerning the long-term future of the Fort St. Vrain plant.

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