STEAM GENERATOR WATER HAMMER TECHNICAL EVALUATION
PRAIRIE ISLAND POWER STATION

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CONTENTS

I. INTRODUCTION

An evaluation was performed for the Prairie Island Power Station (PIPS) feedwater systems. The purpose of this evaluation was to assess the effectiveness of the means to reduce the potential for water hammer in the feedwater systems (steam generator water hammer) during normal and hypothesized operating conditions. The steam-water slugging phenomenon in the feedwater systems (specifically, the feedrings and associated horizontal feedwater piping) was considered in this review. A known steam generator water hammer has not occurred at the PIPS, or at plants having similar auxiliary feedwater line inlet geometries.

The potential for steam generator water hammer is eliminated if the feedwater system is maintained full of water. Hence, this evaluation was based on the effectiveness of the means to maintain the feedwater system full of water during normal and hypothetical transient operating conditions.

The information for this evaluation was obtained from: 1) discussions with the licensee, 2) licensee submittals of September 2, 1975[1], January 29, 1976[2], and December 30, 1977[3], 3) the "Prairie Island Nuclear Generating Plant Final Safety Analysis Report"[4], 4) "An Evaluation of PWR Steam Generator Water Hammer", NUREG-0291[5], and 5) Westinghouse Technical Bulletin, NSD-TB-75-7[6].

A description of the feedwater systems at the PIPS (Unit Nos. 1 and 2) and their general operation are presented in Section II. The means to reduce the potential for water hammer in the feedwater systems are presented in Section III, including a discussion of their effectiveness during operating conditions conducive to water hammer. Conclusions and recommendations are presented in Section IV concerning the adequacy of the means to reduce the potential for steam generator water hammer at this facility.

II. FEEDWATER SYSTEM

1. DESCRIPTION

Each of the two feedwater systems for the PIPS was designed to provide an adequate supply of feedwater to the secondary side of the two steam generators in each unit during all operational conditions. Feedwater is supplied to the main feedwater pumps by the heater drain pumps and by the condensate pumps via the low pressure heaters. Feedwater from the main feedwater pumps is supplied to a main header via the high pressure heaters. The main header splits into two 16 inch feedwater lines to supply a 10 inch feedring inside each steam generator. Feedwater is discharged downward through holes uniformly distributed on the bottom of the feedring in each steam generator.

The two main feedwater pumps in each unit share common suction and discharge headers. Each pump is rated for a flow rate of 8600 gpm at 2070 feet total developed head (TDH). The electric pump motors are normally supplied with power by the turbine generator via the unit auxiliary transformer. In the event of a turbine trip, offsite power supplies the pump motors via the reserve auxiliary transformer.

The auxiliary feedwater system in each unit provides feedwater to the steam generators for residual heat removal during reactor startup and shutdown, low power operation, and in the event of loss of main feedwater flow. Auxiliary feedwater is supplied to each steam generator via a single three inch line that connects (inside the containment building) to the horizontal main feedwater line adjacent to each steam generator. The auxiliary feedwater line joins the main feedwater line at points located 3 feet 6 inches, 3 feet 8 inches, 3 feet 11 inches, and 3 feet 6 inches from the outer surface of the steam generators numbered 11, 12, 21, and 22, respectively. Each auxiliary feedwater line connects perpendicularly to the main feedwater lines in a horizontal plane which passes through the axial centerline of the main feedwater lines.

In each unit, auxiliary feedwater can be supplied by two redundant systems employing an electric motor driven pump in one system and a turbine driven pump in the other system. Each pump normally supplies feedwater to both steam generators. The motor driven pump usually operates with offsite power supplied via the reserve auxiliary transformer. A backup power supply is provided by the diesel generators.

The motor driven and turbine driven auxiliary feedwater pumps are each rated for 220 gpm at 3000 feet TDH. Normal feedwater supply to the auxiliary feedwater pumps of either unit is from the associated 150,000 gallon condensate storage tank. A backup water supply is provided by the plant's cooling water system.

2. GENERAL OPERATION

During normal power operation of the reactor, the main feedwater system supplies feedwater to the secondary side of the steam generators for heat removal from the reactor coolant system. The feedwater flow is regulated by individual regulating valves in the main feedwater lines to each steam generator. The positions of the valves are automatically controlled based upon steam generator level, steam flow, and feedwater flow.

During plant shutdown, startup, and for feedwater flow requirements below about 2% of maximum (maximum feedwater flow required at full reactor power), feedwater is supplied by the motor driven auxiliary feedwater pump. Feedwater flow is manually regulated to maintain adequate water levels in the steam generators.

For feedwater requirements between about 2% to 10% of maximum flow, a main feedwater pump is started and the motor driven auxiliary feedwater pump is shut down. Feedwater is manually controlled and supplied via low flow bypass lines which bypass the main feedwater regulating valve in each main feedwater line. The bypass valves allow more accurate and responsive feedwater flow control than would be possible with the larger main regulating valves during low power (and low feedwater flow) operation.

As turbine load is increased and feedwater flow requirements are between 10% to 15% of maximum, feedwater control is shifted to the main feedwater regulating valves under manual control. Above feedwater requirements of 15% of maximum flow, automatic control of the main feedwater regulating valves is initiated. The second main feedwater pump is started when feedwater flow of about 45% of maximum is required.

Automatic initiation of auxiliary feedwater flow will result upon receipt of one or more auxiliary feedwater pump startup signals. The motor driven pump starts on: 1) the coincidence of two out of three steam generator low-low water level signals from either steam generator, 2) the tripping of both main feedwater pumps, or 3) a safety injection signal (SIS). The turbine driven pump starts on: 1) the coincidence of two out of three steam generator low-low water level signals from either steam generator, 2) the tripping of both main feedwater pumps, 3) an SIS, or 4) a turbine trip coincident with the loss of one of the two offsite power sources.

Plant design specifications allow for a maximum delay of one minute from receipt of any auxiliary feedwater pump startup signals to delivery of auxiliary feedwater to the steam generators. Subsequent to automatic initiation of auxiliary feedwater flow, administrative controls require manual control and regulation of the flow to specified limits. Manual flow control is continued to bring the water levels above the feedrings and to maintain an adequate water inventory in the steam generators.

III. MEANS TO REDUCE THE POTENTIAL FOR WATER HAMMER

1. DESCRIPTION

The following are means currently recommended to reduce the potential for steam generator water hammer:

1. The installation of "J" shaped discharge tubes[5] on all steam generator feedrings and plugging of all bottom discharge holes in conjunction with the prompt automatic initiation of auxiliary feedwater flow upon loss of main feedwater flow and/or steam generator feedring uncovery.

2. Administrative controls[5] to limit auxiliary feedwater flow to less than 150 gpm during periods of steam generator feedring uncovery.

3. The reduction of the effective horizontal section of main feedwater piping at the entrance to all steam generators to less than eight feet[6].

The current PIPS feedwater system design fully incorporates item 2. Presently, no modifications are planned by the utility because there have been no steam generator water hammers at this facility.

The potential for water hammer is eliminated if the feedrings and feedwater piping are kept full until feedring recovery. This requirement can be satisfied during conditions conducive to water hammer by employing "J" shaped discharge tubes in conjunction with prompt automatic initiation of auxiliary feedwater flow. "J" shaped discharge tubes are not currently employed at the PIPS.

The present PIPS main feedwater piping geometry adjacent to each steam generator consists of a horizontal run from the steam generator to the first downward turning elbow in each line. The horizontal runs are 6 feet 6 inches, 6 feet 9 inches, 8 feet 6 inches, and 7 feet 10 inches for feedwater loops 11, 12, 21, and 22, respectively. The vendor recommendations are not met for Loop 21 since the piping length exceeds eight feet.

Tests conducted at Indian Point Unit No. 2 have indicated that reduced feedwater flow to steam generators with uncovered and draining feedrings reduces the potential for steam generator water hammer. Evidence of water hammer was observed in two loops with steam generators having uncovered and drained feedrings when feedwater was delivered at greater than 200 gpm per steam generator under hot standby test conditions. No water hammer was observed in tests when the auxiliary feedwater flow rates were below 200 gpm. The events occurred in the two loops with the shortest horizontal piping runs which are about 4 feet and 7 feet. The horizontal piping runs in the other two loops are 10 feet and 12 feet.

Results of tests conducted at Doel No. 1 in Belgium indicate a lower threshold flow of auxiliary feedwater is conducive to water hammer under certain conditions. A water hammer event occurred in a steam generator (or possibly, its associated horizontal piping) while auxiliary feedwater was being supplied at a rate of only 40 gpm. The steam generator was "hot" but at only 45 psia at the time of the event. The event occurred in a loop with a very long (about 18 feet) horizontal section of piping adjacent to the steam generator. The tests at Doel indicate that steam generator water hammer is possible at even very low feedwater flow rates with reduced steam generator pressures.

The water hammer in these tests were hypothesized to be the result of turbulent, wavy flow patterns in the horizontal feedwater piping (or feedring) creating a water slug that "sealed" the piping and isolated a pocket of steam. Subsequent collapse of the condensing steam pocket caused the slug to accelerate, resulting in water hammer upon slug impact.

The existing PIPS auxiliary feedwater piping geometry allows auxiliary feedwater to be admitted to the horizontal main feedwater piping adjacent to each of the steam generators. Although unconfirmed by testing, this geometry may eliminate conditions conducive to steam generator water hammer.

2. EFFECTIVENESS DURING TRANSIENTS AND CONDITIONS CONDUCIVE TO WATER HAMMER

The normal and hypothetical transients and conditions conducive to steam generator water hammer are discussed in this section. With the exception of subsection 2.4 entitled "Operator Error", each subsection describes a transient resulting from a single initiating event or failure with the unit (either No. 1 or No. 2) in normal power operation. Potential component or system failures as a direct result of a hypothetical steam generator water hammer are accounted for in the analysis.

A single criterion was the basis for evaluating the effectiveness of the means to adequately reduce the potential for steam generator water hammer. This criterion is to maintain the feedwater system full of water during the time from the initiating event resulting in feedring uncovery to subsequent feedring recovery and stabilized steam generator water inventory.

2.1 Reactor Trip

A reactor trip with the plant in normal power operation would result in a turbine trip and cause the water level in all steam generators to collapse to a level below the feedrings. Within 60 seconds of the resulting steam generator low-low water level signals, the motor driven and turbine driven auxiliary feedwater pumps would automatically start and supply auxiliary feedwater to the steam generators. If the initiating event for the reactor trip did not close the main feedwater regulating valves, the valves would close upon receipt of: 1) low primary coolant average temperature (T_{ave}) signals, 2) steam generator high-high water level signals, or 3) an SIS.

Main feedwater flow (above about 1500 gpm per steam generator) would be sufficient to maintain the feedwater system full of water following a reactor trip. However, since main feedwater flow is normally interrupted shortly after a reactor trip by low T_{ave} signals, auxiliary feedwater flow is required to restore steam generator water levels.

The maximum auxiliary feedwater flow (about 220 gpm per steam generator) is not sufficient to maintain the feedrings and associated horizontal piping full of water during periods of feedring uncovery. Therefore, since auxiliary feedwater is used to recover the feedrings following a reactor trip, the conditions conducive to water hammer may exist in all feedwater loops.

2.2 Loss of Main Feedwater Flow

The main feedwater supply could be interrupted due to the 1) loss of offsite power, 2) malfunction or tripping of the main feedwater pumps, 3) loss of suction to the main feedwater pumps, or 4) closure of the main feedwater regulating and/or isolation valves. A reactor trip would occur upon receipt of the resulting steam/feedwater flow mismatch signals and low steam generator water level signals. The reactor trip would cause the water levels in all steam generators to collapse to a level below the feedrings. The motor driven and turbine driven auxiliary feedwater pumps would start upon receipt of the subsequent low-low steam generator water level signals. Auxiliary feedwater would then be used to refill the steam generators and recover the feedrings.

Auxiliary feedwater flow is insufficient to keep the feedwater system full of water after the loss of main feedwater flow. Thus, the conditions conducive to water hammer may exist in all feedwater loops.

2.3 Loss of Offsite Power

A complete interruption of offsite power would result in a reactor trip, a turbine trip, and startup of the diesel generators. The motor driven and turbine driven auxiliary feedwater pumps would start up to supply feedwater to the steam generators upon receipt of the resulting steam generator low-low water level signals. The redundant auxiliary feedwater systems are fully functional without offsite power since the diesel generators independently supply necessary electrical power to each of the systems. Auxiliary feedwater would be used to restore the water level in the steam generators and recover the feedrings.

As was the case for a reactor trip or the loss of main feedwater flow, the interruption of offsite power would result in similar conditions in the feedwater systems. Auxiliary feedwater flow will not keep the feedrings and feedwater piping full during steam generator refill. Thus, the conditions conducive to water hammer may exist in all feedwater loops.

2.4 Operator Error

The potential for water hammer in the feedwater system increases if uncovered feedrings are allowed to drain substantially after an event causes the steam generator water levels to drop below the feedrings. Admission of feedwater into the drained feedrings and horizontal feedwater piping could then result in water slugging and subsequent water hammer. The uncovery of one or both feedrings is most likely when the plant is operating at low power or during startup since feedwater is being regulated manually, rather than automatically.

If uncovery of the feedrings occurred due to operator error, substantial drainage of the feedrings and horizontal piping would result in less than one minute. Auxiliary feedwater flow would not be sufficient to keep the feedrings and piping full of water during any period that the feedrings are uncovered. Thus, the conditions conducive to water hammer may exist in all feedwater loops.

2.5 Steam Line Break

The potential for water hammer events resulting from or concurrent with the rupture of a steam line inside containment of either unit was considered. The sequence of events following such a failure was evaluated to determine if the break would result in the 1) blowdown of the remaining steam generator and/or 2) inability to supply auxiliary feedwater to the unaffected steam generator.

The rupture of a steam line would automatically result in an SIS causing a reactor trip, a turbine trip, and isolation of all main feedwater lines. The loss of main feedwater flow to the steam generators would result in the automatic startup of the motor driven and turbine driven auxiliary feedwater pumps upon receipt of low-low steam generator water level signals. Feedwater would then be supplied for subsequent refill of the unaffected steam generator and recovery of the feedring.

The turbine driven auxiliary pump would be fully operable since it would receive adequate steam for driving power even if one of the two

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interconnected steam lines for the pump turbine was supplied by the blowndown steam generator. Check valves in each supply line would prevent "crossover" blowdown through the supply lines from the unaffected steam generator to the associated blowndown steam generator.

Auxiliary feedwater flow is not sufficient to keep the bottom discharge feedring and associated horizontal piping full of water in the feedwater loop with the steam generator not affected by the steam line break. Since the conditions conducive to water hammer may exist in this unaffected loop, the potential may exist for a rupture of the main feedwater piping. The rupture of a feedwater line due to a water hammer would result in the blowdown of the second steam generator. Blowdown of the second steam generator in conjunction with the blowdown of the first steam generator could result in containment building overpressurization. Also, with both steam generators out of service, the capability for heat removal from the reactor coolant system would be seriously impaired.

2.6 Loss-of-Coolant Accident

The potential for feedwater water hammer during a postulated loss-of-coolant accident (LOCA) in either unit was examined because 1) a water hammer could increase the consequences of a LOCA and 2) the plant protective actions during a LOCA could result in conditions which are conducive to water hammer if the feedwater system is not kept full of water.

A LOCA would result in an SIS, a reactor trip, a turbine trip, and subsequent isolation of the feedwater system. The startup of the motor driven and turbine driven auxiliary feedwater pumps would result and feedwater would be supplied to the steam generators within 60 seconds of the reactor trip. Refill of the steam generators and recovery of the feedrings would occur in a manner typical of a reactor trip or the loss of offsite power.

The potential for blowdown of a steam generator during a LOCA exists because of feedwater water hammer. Blowdown of a steam generator in conjunction with a LOCA could result in more severe containment building pressurization than would occur during a LOCA.

The conditions in the feedrings and feedwater piping resulting from a LOCA would be very similar to those resulting from a reactor trip. Thus, the conditions conducive to water hammer may exist in both feedwater loops of the affected unit.

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IV. CONCLUSIONS AND RECOMMENDATIONS

The assessment of the capability of existing means to reduce the potential for steam generator water hammer during various hypothesized transients and conditions was discussed in Section III. This assessment has shown that under conditions which are most conducive to water hammer in the feedwater systems (specifically, uncovered and draining feedrings and feedwater piping subjected to admission of cold auxiliary feedwater), the means to reduce the potential for water hammer at the PIPS are inadequate to maintain sufficiently full feedrings and feedwater piping until feedring recovery occurs.

On the basis of this evaluation, we recommend installation of top discharge feedrings in all steam generators. However, the PIPS, along with other plants with similar auxiliary feedwater line inlet geometries, has not reported a steam generator water hammer to date. We therefore recommend (as an alternative to steam generator feedring modifications) the implementation of a test program to qualify the effect of the PIPS auxiliary feedwater line inlet configuration on the inducement of steam generator water hammer. The test program need not be conducted by the responsible utility.

V. REFERENCES

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