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Prairie Island Nuclear Generating Plant
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Operation of Prairie Island Unit 2
with Suspect Mechanical Steam Generator Tube Plugs

Following the rupture of a mechanically expanded steam generator tube plug at North Anna Unit 1, Northern States Power Company began to evaluate the potential for a similar event at the Prairie Island Nuclear Generating Plant. The North Anna incident was found to be attributed to circumferential primary water stress corrosion cracking (PWSCC) of a mechanically expanded steam generator tube plug. It was discovered that the suspect plug (fabricated from Inconel 600 alloy) had not received the proper heat treating operation to prevent the occurrence of PWSCC. Following a review of material certifications, it was determined that forty eight plugs from the same heat as the failed North Anna plug were installed in the Prairie Island Unit 2 steam generators (eight in Steam Generator 21 and forty in Steam Generator 22). Of these forty eight plugs, twenty four (24) are installed in hot leg sections of the steam generators (area most susceptible to PWSCC due to higher operating temperatures).

Following the shutdown for the current Prairie Island Unit 2 refueling outage, plant personnel performed a visual inspection of all twenty four suspect hot leg plugs. The visual inspection was performed to identify any plug locations where the plug and/or tube ends were wet. If circumferential cracking of the suspect plugs had occurred, primary coolant water could have leaked into the steam generator tube while the reactor coolant system (RCS) was pressurized. Following depressurization and draining of the steam generator, water would slowly drain back out of the steam generator tube causing a wet plug end. Twenty one wetted tube plugs have been pulled at other plants. Of these twenty one tubes, fourteen have been found to have some cracking due to PWSCC. Laboratory test results of plugs removed from service have shown that PWSCC cracking is predominantly axial. All twenty four suspect plug locations inspected in the Prairie Island Unit 2 steam generator hot legs were found to be dry during this inspection. This gives one indication that the plugs are not cracked at this time.



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Westinghouse Electric Corporation performed a series of calculations to determine the point where a potential circumferential PWSCC crack may develop which leaves a 0.005 inch remaining ligament. These calculations considered the time that the plugs have been installed, plug microstructure and temperature scaling effects based on hot leg temperature (Prairie Island operating temperatures are approximately 32°F lower than those at North Anna. Therefore PWSCC will be slower to set in at Prairie Island.) The results of the Westinghouse analysis show that cracking due to circumferential PWSCC would not be considered a problem at Prairie Island Unit 2 for another 1176 effective full power days. The upcoming fuel cycle (PI Unit 2, Cycle 13) will encompass approximately 470 full power days.

The Westinghouse calculations were benchmarked with plugs removed from steam generators at the Kewaunee plant. This plant is similar to Prairie Island Unit 2 in operating temperatures, primary coolant chemistry and operating history. As the model predicted, no plugs from the Kewaunee unit showed evidence of circumferential PWSCC cracking.

Based on the results of the Westinghouse calculations and visual inspection, replacement of the suspect steam generator tube plugs would not be prudent at this time. Replacement of the plugs with current replacement techniques would result in significant occupational exposure. Currently, any plug removal must be done manually from inside the steam generator. It is estimated that the replacement of the forty eight suspect plugs would result in an occupational exposure of 12 to 24 man-rem. Westinghouse expects to have a fully qualified and field tested remote plug pulling system available by the next Unit 2 refueling outage (currently scheduled for August to September, 1990). Delaying replacement of the suspect plugs would allow Northern Sates Power to take advantage of this technique, thus saving significantly in occupational exposure. Necessary action to close out this issue for Prairie Island Unit 2 will be taken prior to the start up of Prairie Island Unit 2 Cycle 14.

A safety evaluation based on the results of the above referenced calculations has been prepared by Westinghouse Electric Corporation. The safety evaluation addresses the issue of operating Prairie Island Unit 2 for an additional fuel cycle prior to replacement of the suspect tube plugs. This safety evaluation is included as Attachment 1 to this letter. Based on, 1) the results of the Westinghouse calculations, 2) the lack of evidence of PWSCC cracking as found by visual inspection for wet plugs, and 3) the comparison of Prairie Island Unit 2 results with industry data, the operation of Prairie Island Unit 2 for an additional fuel cycle does not pose any undue safety concerns.

Please contact us if you have any question related to this submittal.

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Attachments
1) Prairie Island Unit 2 Steam Generator Mechanical Plug Integrity - Safety Evaluation

ATTACHMENT 1

Prairie Island Unit 2
Steam Generator Mechanical Plug Integrity
Safety Evaluation

# PRAIRIE ISLAND UNIT 2
# STEAM GENERATOR MECHANICAL PLUG INTEGRITY
# SAFETY EVALUATION

## 1.0 INTRODUCTION

During routine maintenance operations several utilities have reported observing water dripping from steam generator tube ends plugged with Westinghouse plugs. These observations can be attributed to a number of different sources: 1) high humidity, 2) residual water from either above the expander or from a leak path formed between the sealing lands on the outer diameter of the plug and the inner diameter of the tube, or 3) the occurrence of primary water stress corrosion cracking (PWSCC) in the plug shell.

The plugs in question are mechanically expanded plugs. The plug contains a tapered expander inside of an internally tapered shell. As the expander is pulled down a portion of the plug increases in diameter which results in an interference fit between the outside surface of the plug and the inside diameter of the tube. Ridges or lands formed on the outside surface of the plug improve the sealing capability of the plug and physically indent the inside surface of the tube.

Of the three reasons identified above for water dripping from the plugs, only two (items 2 and 3) potentially involve pressure boundary integrity. This evaluation, completed in accordance with 10 CFR 50.59 criteria, addresses the operation of Prairie Island Unit 2 with steam generator (SG) tube mechanical plugs which may develop primary water stress corrosion cracking. This evaluation does not address, in detail, the potential that a leak path can exist between the sealing lands on the outer diameter of the plug and the inner diameter of the tube as this case is not expected to be limiting. To date, as reported by Northern States Power Company, neither leaking mechanical plugs nor PWSCC of the mill annealed tubing has been observed at Prairie Island Unit 2.

## 2.0 REGULATORY BASIS

Once a tube has been plugged, the combination of the tube and the plug form the pressure boundary separating the primary and secondary systems. The subsequent boundary is subject to the relative conditions and considerations of both. Since the tube is no longer inspectable its condition is unknown. If the tube has been plugged due to a through-wall indication, then only the plug remains as a barrier/pressure boundary separating the primary and secondary systems. The question then becomes one of addressing the maintenance of the integrity of that barrier/pressure boundary during normal, upset, and accident condition loadings.

Plant Technical Specifications contain a limit on allowable primary to secondary leakage during normal operation. This limit can be used to determine acceptable leakage from a plug. For pulled tube locations, compliance with the Technical Specification limit will assure that the assumptions in the accident analyses are not adversely affected by the operation of the steam generator with plugs potentially experiencing primary water stress corrosion cracking.

## 3.0 EVALUATION

Intergranular carbide precipitation has been determined by corrosion testing to be a strong contributor to stress corrosion cracking resistance. This enhanced microstructure is obtained by a specific mill annealing temperature and subsequent thermal treatment. Metallurgical examination of a number of mechanical plugs removed from operating plants show intergranular cracks above and below the expander. Characterization of the microstructure indicated minimal intergranular carbide precipitates. Westinghouse believes the minimal intergranular carbide precipitation was caused by the use of a low mill anneal temperature, thereby providing insufficient carbon in solution to precipitate during thermal treatment. A total of 48 plugs have been installed in the Prairie Island Unit 2 steam generators since October 1986 which are made of Alloy 600 material with a minimal intergranular carbide precipitation grain boundary microstructure.

In the evaluation of the safety implications of the the occurrence of PWSCC within a mechanical plug, consideration is given to: 1) the case of the leakage path remaining unrestricted thus permitting communication of fluid between the channel head and the inside of the tube, and 2) the case of the leakage path becoming restricted in a manner which simulates a check or one-way valve.

3.1 Plug Leak Path Does Not Behave as a Check Valve

3.1.1 Partial Through-wall Tube Degradation Discussion

Metallurgical examination of eleven plugs made of Alloy 600 material with a minimal intergranular carbide precipitation microstructure, which were removed from a plant with operating conditions similar to Prairie Island Unit 2, exhibited no primary water stress corrosion cracking above the expander. There were two plugs which exhibited short axially oriented indications below the expander. These indications appeared following flattening of the sectioned plugs and were approximately 50 to 75 mils in length and 10 mils in depth. The plugs at Prairie Island Unit 2 have been in service for a comparable period of time and at an equivalent temperature. Therefore, it is expected that the plugs would be, at most, similarly degraded and, as such, mechanical plug integrity would be expected to be maintained under all plant condition loadings.

Prior to the tube leak event as a result of plug top release at North Anna Unit 1, a minimal amount of circumferential cracking had been observed in removed plugs resulting from PWSCC. The observed cracking was present in a small fraction of the circumference of the plug shell (less than a 30 degree arc) prior to leaking. It was previously concluded that a plug would not completely separate circumferentially before a leak path would exist to fill a tube and equalize the pressure across the plug. This remains the expected scenario for any potential PWSCC which may occur at Prairie Island Unit 2. Moreover, for the limiting condition of a nonthrough-wall degraded tube when it was removed from service, it is Westinghouse's engineering judgment that should a circumferentially oriented, through-wall crack develop in a steam generator tube plug, the crack would be limited in azimuthal extent and capable of withstanding normal, upset, and accident condition loadings.

### 3.1.2 Through-wall Tube Degradation and Pulled Tube Discussion

Typical installation of a mechanical plug would result in at least partial contact around the plug circumference with the tube inner diameter at the second land above the expander. The radial gap between the plug shell and the tube ID would not be expected to be continuous at this location. Should circumferentially/axially oriented cracking occur in the plug shell immediately above the first land above the expander top, postulating a radial gap of 0.0001 inch at this land, the annulus would function as a leak limiting orifice and the maximum primary to secondary leakage would be approximately 24 gpd. If the radial gap were assumed to be 0.0005 inch, the expected leakage would be approximately 500 gpd. It is judged that the leakage would be readily detectable by primary to secondary leakage monitoring and the leakage rate would permit a controlled and orderly plant shutdown.

Cracking is not expected above the top land on the plug shell. This region received little cold work during fabrication and it has a low applied stress due to applied pressure during operation. Therefore, it has a low potential for SCC because one of the three parameters required for SCC, i.e., high stress, is largely absent.

For the case of a mechanical plug installed in the pulled tube location, if the plug experiences axially oriented cracking it would be expected to maintain its structural integrity during normal, upset, and accident condition loadings. Based on metallography from plugs that were removed from service at other plants, the typical length of an axial crack in the plug shell is 0.25 inch. It is Westinghouse's engineering judgement that any primary to secondary leakage occurring as a result of plug degradation would be expected to be enveloped by the leakage issuing from a tube with a free span crack of equal length. Based on leakage test data for a tube wall thickness of 0.048 inch and a similar primary to secondary pressure differential, it is estimated that a crack in the standard tube plug shell would have to attain a length of 0.47 inch before the Technical Specification allowable limit of 500 gpd would be reached. No leakage would be expected to emanate from within or below the expander region of the plug shell. For the potential occurrence of a circumferentially oriented crack, experience shows that cracks that have occurred are typically less than $30^{0}$ in azimuthal extent (approximately 0.25 inch). The leakage during normal operating conditions would be expected to be comparable to an axial crack of equivalent length. Cracking of this magnitude would readily withstand steam line break loadings.

### 3.2 Plug Leak Path Behaves as a Check Valve

Based on an isolated field occurrence with a different type of steam generator tube plug, a leaking plug may lead to a fish-mouthed ruptured tube as a result of overpressurization of the non-active tube. In this single occurrence, water was postulated to enter an initially air filled tube through a leak in the plug or the plug/tube interface during the beginning of the plant heatup cycle. With higher pressure on the primary side, a pre-existing crack may be forced open allowing the in-leakage of water through the plug into the tube. Eventually, higher pressure inside the tube resulting from the volumetric expansion of the water once the tube goes water solid could force the crack closed, trapping the fluid mixture in the tube (the cracked plug is postulated to act as a check valve or flow diode) as plant heat up progresses. Even if the crack did not completely close during heatup, the relative times for in-leakage versus out-leakage could allow out-leakage during heatup and still result in the potential for overpressurization due to the thermal expansion ofthe water remaining in the tube. The potential consequences of the flow diode effect are a condition leading to eventual expansion and fish-mouthed type tube rupture (and the potential for subsequent primary to secondary leakage through the cracked plug) and the possibility of interaction with adjacent active tubes leading to primary to secondary leakage from the neighboring tube.

Calculations show that more than one cycle of pressurization is necessary to obtain the required net volume increase to result in fish-mouthed type rupture of the non-active tube. The number of cycles necessary to create a fish-mouthed type rupture a tube depends on several factors including:

the initial conditions of the trapped mass, water out-leakage if any during plant heatup, the amount of trapped air, etc.

The probability of the occurrence of the check valve/flow diode effect as a result of a potentially degraded mechanical plug in the Prairie Island Unit 2 steam generators has been qualitatively evaluated and is judged to be acceptably low. To date, there has been no field experience to suggest that the flow diode effect can occur in leaking mechanical plugs. Upon inspection of non-active tubes following removal of leaking mechanical plugs at other plants, no evidence of volumetric expansion of the plugged tubes was found during eddy current testing.

In the unlikely event that the flow diode effect would result in a tube wear mechanism on an adjacent active tube, it is Westinghouse's engineering judgement that the resultant worst case scenario would be a single tube rupture event, the consequences of which are evaluated in the Prairie Island Unit 2 Final Safety Analysis Report.

## 4.0 CONCLUSION

An assessment of the future operation of Northern States Power Company's Prairie Island Unit 2 with 48 mechanical plugs (24 Hot Leg Plugs) which are manufactured from Alloy 600 material that may be susceptible to primary water stress corrosion cracking has been completed. Specifically, the consequences of postulated mechanical plug degradation in a non-active tube and a pulled tube location have been assessed and judged to be acceptable.

In light of the above, operation of Prairie Island Unit 2 is not expected to increase the probability of an analyzed accident or result in a previously unanalyzed accident. Based on metallurgical examination results, should cracking occur during subsequent plant operation, the degradation on the plug shell would be expected, conservatively, to be limited in circumferential extent. Eleven plugs made from minimal intergranular carbide precipitation heats of Alloy 600 were pulled from the steam generators of a plant with similar operating conditions during the current outage and no cracking was found above the plug expander. Therefore, as Prairie Island Unit 2 has similar operating conditions to this plant and the duration that the plugs have been in service are comparable, little or no cracking would be expected in the plugs. Should cracking have occurred, the integrity of a potentially through wall cracked plug would be expected to be maintained during normal, upset, and accident condition loadings.

Additionally, Westinghouse has evaluated the potential that a plug which has experienced primary water stress corrosion cracking may lead to a ruptured tube as a result of the overpressurization of a non-active tube. To date, there has been no field experience to suggest that the "flow diode effect" can occur in a leaking mechanical plug. In the unlikely event of interaction with adjacent active tubes as a result of the flow diode effect, the worst case scenario is the occurrence of a single tube rupture event which is within the licensing basis of the plant.

Concomitantly, the margin of safety of the plant as defined in the bases of any technical specification has been evaluated and is not reduced. For the condition of the tubes removed from service using mechanical plugs which may have become degraded, pressure boundary integrity would be expected to be maintained during normal, upset, and accident condition loadings. As a plug top release event similar to that which occurred at North Anna Unit 1 is not expected at the Prairie Island Unit 2, a large primary to secondary leakage event would not be expected. However, should a large primary to secondary leakage event occur, an orderly, controlled plant shutdown should be readily achieved.

Therefore, subsequent plant operation of Northern States Power Company's Prairie Island Unit 2 with potentially degraded mechanical plugs does not represent an unreviewed safety question pursuant to 10 CFR 50 59 criteria.