Structural Integrity Associates, Inc. Report
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Life Extension for Core Plate Plugs
at Brunswick Steam Electric Plant Unit 2

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Life Extension for Core Plate Plugs at Brunswick Nuclear Plant Unit 2

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All	All	1	9/5/12	Corrected erroneous proprietary information designations in References and throughout body of report.
All	All	2	11/1/12	Redacted GE proprietary information and replaced Reference 16.

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1.0 INTRODUCTION

In the mid-1970s, core plate plugs were installed in the bypass flow holes of the core support plates of BWR/4s. The plugs were intended to limit flow through bypass flow holes and reduce the flow induced vibration of in-core neutron monitors and start-up sources against the corners of fuel assemblies [1]. The spring loaded plugs were designed to withstand typical (~27.5 psi) and worst case transient (>45 psi) pressure differences across the core plate, ΔPs.

The plugs consist of five parts: shaft, body, pin, latch and spring (Figure 1-1). The first four are fabricated from solution annealed Type 304 stainless steel. The compression spring is Alloy X-750 in a spring temper. The spring is also age hardened for 4 hours at 1200°F.

Brunswick installed 77 of these plugs as noted in Reference 2. Sixty-four of the 77 were installed in each of the four holes surrounding 16 local power range monitors (LPRMs). A core map illustrating the location of the bypass flow holes and the LPRMs is given in Figure 1-2.

GE SIL Number 359, Revision 3 [1] notes that the mechanical life of core plate plugs is 12 effective full power years (EFPY), based upon "the probability of the Type 304 stainless steel latch fracturing during plug removal and resulting in a potential loose piece." Life limits have been revised several times [3, 4]. The life limits were based upon relaxation of the Alloy X-750 spring, intergranular stress corrosion cracking (IGSCC) of the spring or stainless steel structural members, and radiation embrittlement. The following sections provide a brief review of the degradation mechanisms.

Spring Relaxation. The Alloy X-750 spring that provides the preload to the plug will relax as a function of thermal and neutron exposure. The loss of preload may cause the plug to leak at a higher rate than the design value, producing possible flow induced vibration effects that can influence other components in the core. [[

]] [3].

IGSCC. The Alloy spring is also susceptible to IGSCC in a BWR coolant environment. Cracks in the spring will reduce the preload, possibly to the point that all preload is lost, i.e., complete spring failure. This does not necessarily create any loose parts. The consequences of IGSCC and loss of function of the plug are the same as for spring relaxation. [[

]] [4]. A prior estimate of core plate plug life as limited by IGSCC was 12 to 14 EFPY [1]. The prior estimates were based upon stress rule index calculations that assumed a constant load on the spring. Reductions in spring load, due to relaxation of the spring, lead to a lower stress rule index and longer predicted life.

Radiation Embrittlement. Removal of the plugs requires that it be ripped through the core plate hole from above. This operation produces a large deformation of the latch ears, which is on the order of 30% bending strain; ~ 15% total elongation. An embrittled latch that cannot accommodate that large deformation could fracture and result in loose parts in the lower plenum. [[ ]] [4].

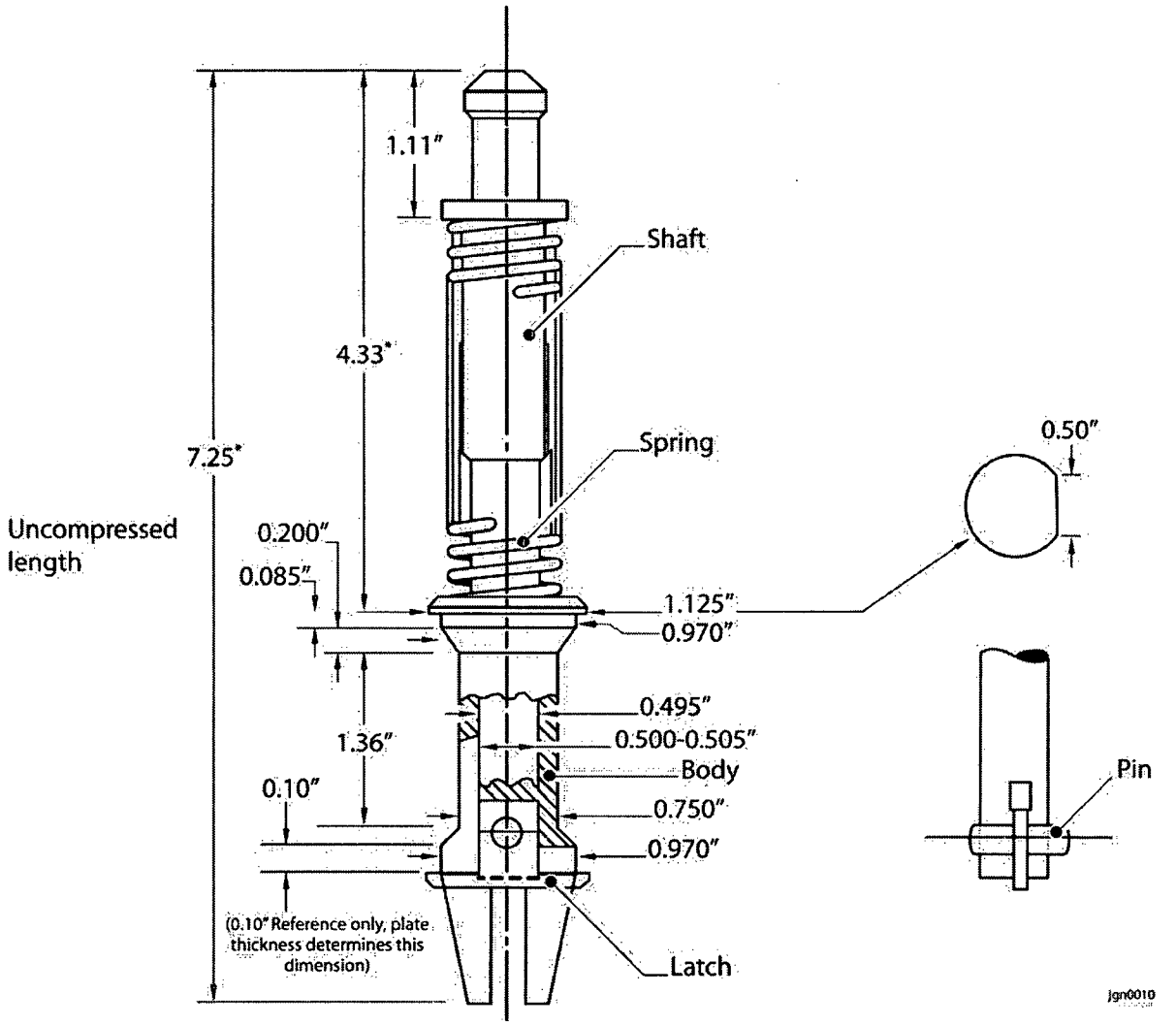

Figure 1-1. Core Plate Plug

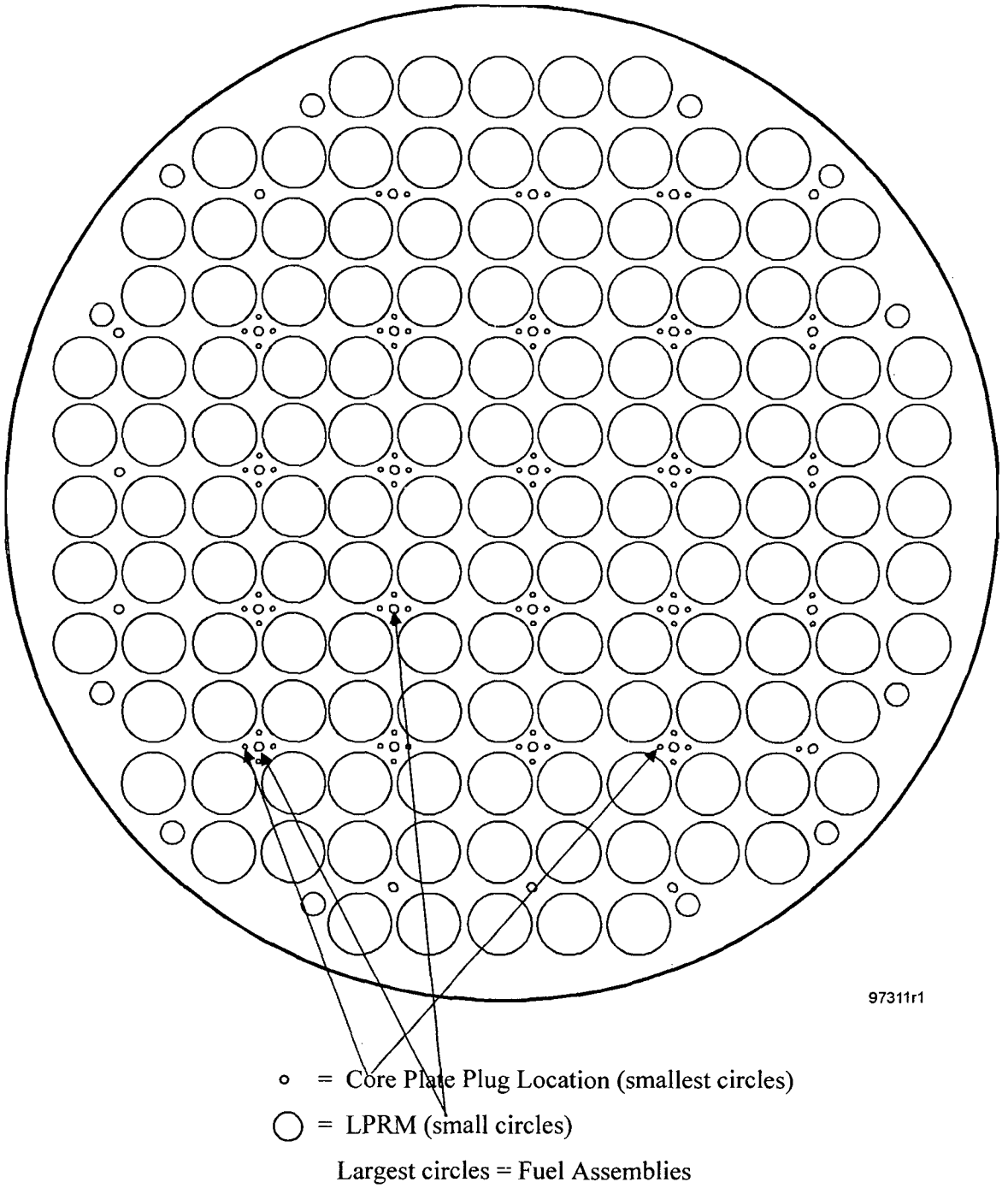

Figure 1-2. Brunswick Core Map Showing Core Plate Plug Locations

2.0 APPROACH

This assessment evaluates the core plate plug life and life limits from a different perspective than that provided in the GE analyses [3, 4]. The GE analyses evaluated the design life of core plate plugs and provided recommendations for replacement based upon estimates of degradation due to stress relaxation and IGSCC. This analysis assumes that the plugs will be left in place, then evaluates the degree of functionality and the potential for the generation of loose parts that may be expected at any time. This work is an independent evaluation of the potential degradation mechanisms and results from surveillance of core plate plugs that have been removed from service. This analysis considers Extended Power Uprate (EPUR) – 120% of the original licensed thermal power (OLTP) for Brunswick Unit 2.

2.1 Functionality

Concerns with the functionality of the core plate plug are primarily a question of the degree of functionality.

As noted in Section 1, the plugs were inserted into bypass flow holes in the core plate to limit flow through those holes and reduce flow-induced vibration of in-core neutron monitors and start-up sources against the corners of fuel assemblies.

Initially, the leakage flow past a properly installed core plate plug should be very low. As the plugs degrade, from relaxation or cracking of the spring or from cracking of other plug components, the leakage past the plug will increase and its functionality will decrease. The purpose of this report is to evaluate the degree of functionality of the core plate plugs at any time and to define the time at which their functionality is no longer acceptable.

The leakage past a plug that remains in place, but with a spring load of less than the design value, may be greater than that of a plug with the proper spring load. In Section 3, leakage is

evaluated as a function of spring load and plug movement for a single plug and is compared to the flow through the by-pass holes assuming that no core plate plugs are in place. These leakage rates may be used by plant personnel to assess the consequences of leakage from one or more plugs on other in-core components.

As noted above, relaxation of the core plate plug's Alloy X-750 spring **will** occur as a result of the thermal and neutron exposure of the plug. The rate of spring relaxation was calculated [5] using the method and neutron flux values described by GE in [4], with various amounts of thermal relaxation, and comparing those results to data on measured spring relaxation and measured spring constants from core plate plugs removed from service by GE [4].

The resulting loss of preload described above **may** cause the plug to leak at rates beyond the design value and could lead to flow induced vibration effects on other components in the core. Reference 4 describes an evaluation that includes relaxation of the spring temper Alloy X-750 springs in the 550°F water under fast neutron fluences considered typical of the core plate region.

The Alloy X-750 spring is also susceptible to IGSCC in the BWR environment. This report includes estimates of the time to IGSCC for the springs using the GE Stress Rule Index. [[

]] [4]. From the perspective of functionality, the consequences of cracks in the spring are a reduction in the preload; possibly to the point that all preload is lost. Thus, the consequences of IGSCC of the spring is a degradation in the functionality of the plug; the same as for spring relaxation. The leakage correlations described in Section 3 were also used to describe the loss of functionality of core plate plugs due to IGSCC of the Alloy X-750 springs.

2.2 Loose Parts

Since the spring and the body of the plug are susceptible to IGSCC, the potential for generation of loose parts was evaluated **while the plug remains in place**. Much of GE's basis for defining life limits on the core plate plugs is concerned with fracture of the Type 304 stainless steel latch during the removal of the plug. This report addresses the probability of failure of a spring, latch, or plug structural member with the plug in place. For parts that can fail by IGSCC during normal operation of the plug, the probability that those parts can move from their installed location during service is evaluated in this report.

The loose parts evaluation includes review of the core plate plug design, combined with through-thickness stress distributions and IGSCC data, to assess whether through-thickness failure of any of the plug components can occur without the plug being ejected.

The loose parts evaluation does not include an assessment of the potential for the generation of loose parts or the consequences of such loose parts that might occur during removal of a core plate plug. The elements of BWRVIP-06-A, Section 4, consideration of loose parts is not in the scope of this evaluation.

This report does not specifically address failure of core plate plug components by other mechanisms. For example, at a sufficiently high plug leakage, the plug may vibrate or "chatter" due to peripheral flow. With sufficient movement over time the plug latch ears may degrade by an erosion corrosion or fretting corrosion mechanism to the point that the plug may become dislodged. Therefore, it has been assumed that the end-of-life is that point at which the core steady state ΔP balances the ability of the spring (including effects of any spring relaxation) to seat the plug.

3.0 RESULTS

[[

]] [4].

The method used to calculate spring relaxation has relied upon conservative estimates of the original, maximum free length of the springs. The free length of springs following exposure has been compared to the specification maximum to estimate the amount of relaxation. The use of a minimum specified free length or an average value following slight exercising of the springs reveals that little or no relaxation of the springs had occurred. It should be noted that the

[[

]] [4].

[[

]] [4].

When core plate plugs were removed from Peach Bottom Unit 3 in 2002, GE performed surveillance activities on four of the plugs. These core plate plugs had been exposed for 17.4 EFPY [6]. Those surveillance activities demonstrate that:

- All metallic surfaces were free from flaws (no evidence of cracking, wear, or corrosion),
- Hardness of the latch material (which was heavily deformed by the removal operation) appeared to have been affected far more by the removal operation than by any irradiation hardening,
- Spring preloads and spring constants were determined (with results shown later in this report).

3.1 Spring Relaxation

Relaxation of the Alloy X-750 spring would be expected to result from initial exposure to elevated temperature, from continued high temperature exposure, and as a result of irradiation effects. Data were collected from the literature for all three effects [3, 4, 6, 7-12]. The GE reports [3, 4 and 6] were the only references that specifically discussed irradiation induced relaxation in a BWR environment. [[

]]

Following extended power uprate (120% of the Original Licensed Thermal Power (OLTP) for Brunswick Unit 2), fluences throughout the reactor, vessel including at the top of the core plate, were recalculated [13].

3.1.1 Thermal Relaxation

Alloy X-750 is an age hardenable nickel-base alloy intended for use at high temperatures, well in excess of 550°F in the BWR coolant. Data from Huntington Alloys International, the primary supplier of Alloy X-750 (as Inconel™ X-750), do not list thermal relaxation data on material in

either the spring temper or #1 temper wire[1] at such low temperatures (Figure 3-1) [7]. [[

]] [4, 14]. At higher temperatures (~800°F), thermal relaxation of #1 temper materials would be very low, on the order of ~2%. A simple comparison of yield strength at room temperature and at 550°F indicates that a maximum of 10% relaxation is expected [7, 8].

[[

]] [4]. This analysis compares the results of core plate plug surveillance [3, 4, 6] with the original GE evaluation discussed above [4].

3.1.2 Irradiation Induced Relaxation

All of the expressions for irradiation-induced creep show a linear dependence between strain rate and stress. The resulting expression for stress relaxation will be of the form:

$$\sigma/\sigma_o = A \quad \ln(\Phi t) + B \qquad \textbf{Eq. 2}$$

where: A and B = empirically determined constants in the irradiation creep expression

A plot of data from Causey [9], Walters [11], Hyatt (as reported in [12]), and the GE expression [1, 3, 4] is shown in Figure 3-2. All of those sources show that irradiation induced relaxation is consistent with the form of Equation 2. The plot also shows that GE's expression for relaxation generally bounds the extrapolation of those data, the majority of which were collected at much higher fluences, to the fluence level of interest. Note that for Figure 3-2, the plots for Hyatt and Causey were forced to a relaxation value of 5% at a fluence of 1 x 10^{19} n/cm^2. A simple fit to those data, i.e., a straight line in a semi-log space, without an "artificial" point at a low fluence such as 1 x 10^{19} n/cm^2 would predict that the stress relaxation was less than zero, a physical impossibility, at

[1] 1350°F/16 hour precipitation hardening treatment; recommended for optimum resistance to relaxation at operating temperatures from 700°F to 800°F

fluences of concern to the lower internals in the BWR. The "artificial" point, 5% relaxation at 1 x 10^{19} n/cm^2, serves to force the curve to a non-negative relaxation value at BWR fluences. The predicted relaxation and relaxation values from core plate plug springs are also shown in Figure 3-3. Those data are bounded by the GE curve and show the same fluence dependence as the other data.

3.1.3 Results from Surveillance

The observed spring relaxation for core plate plugs removed from service [3, 4, 6] has shown that:

- The method used to determine stress relaxation from measurements is very conservative,
- The revised GE estimate bounds the measured stress relaxation (using the conservative method noted above),
- Surveillance data are in better agreement with an expression of the form of Equation 1 where the thermal relaxation term is zero.

The surveillance reports compare the free length of the spring, following removal from the core plate plug, to the specification **maximum** for the free length of the spring. [[

]] [4]. The free length of springs is also known to change with no thermal or irradiation exposure after one or two cycles of exercise. The core plate plug spring receives at least one cycle of deformation during the insertion process and probably had received several more cycles in the course of plug assembly. During the assembly of the core plate plug, the spring is subjected to loading that is above the normal operational loads on the spring. This is expected to cause some plastic deformation which could lead to a change in the free length of the spring [14]. Thus, [[

]] [4]. Using a smaller value for the initial free length of the spring yields a value for relaxation in service that is even smaller than that reported by GE (see Figure 3-3). [[

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Surveillance activities performed on core plate plugs after 1, 1.8, 5, 10, and approximately 12 EFPY all showed that the spring constant was unchanged from the initially specified value of 30-33 lb/in. However, measured spring constants after 17.4 EFPY were significantly lower than the specified value (23-25 lb/in vs. 30-33 lb/in). No explanation for this apparent anomaly is offered in Reference [6].

Figure 3-4 is a plot of spring force vs. EFPY, using the earlier GE estimate for relaxation, the revised GE estimate and a best fit (logarithmic with time) to the surveillance data from References [3, 4 and 6]. The revised GE correlation (dashed line) and the best fit to the surveillance data (heavy solid line) are in very good agreement. The relaxed spring loads are greater than the total hydraulic force on the bottom of the plug[2] produced by a bounding ΔP for normal conditions of 28.45 psi[3] across the core plate for 30 EFPY. Under upset conditions (ΔP of 30.85 psi), the best fit to the surveillance data intersects the ΔP of 30.85 psi at around 21 EFPY. Even though Brunswick-2 is currently at 24 EFPY, it should be noted that upset conditions are both infrequent and short lived. The reduced spring load (below the upset ΔP of 30.85 psi) could lead to increased leakage past the core plate plug resulting in vibration and chattering of the plug for the short duration of the upset event. Following the upset event, the plant would return to normal operation, restoring conditions where the life of the core plate plug limited by spring relaxation would be 30 EFPY. The probability of the occurrence of such upset events is relatively small. Even the conservative design basis for transients only accounts for a few upset events that are extremely short in duration. The leakage associated with various levels of spring opening has been discussed as a part of an earlier calculation package [15], reproduced in Table 3-2 of this report.

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[2] Area = 0.785 in^2 per Reference [15]
[3] Bounding value used by BNP [16]

[[

]] The best fit curve to the surveillance data suggests that the initial spring load is approximately 38 pounds.

3.2 IGSCC of Spring

No reports of IGSCC of spring temper Alloy X-750 in the BWR environment were located in the open literature [17-27]. [[

]] [4, 14]. The material has been used extensively as lantern springs and finger springs in GE fuel bundles as well as in other applications. Typically, Alloy X-750 is the first choice for any flat or coil spring application where resistance to relaxation and corrosion resistance in a high temperature environment is required. McIlree [17] has described experience with Alloy X-750 in nuclear power systems and demonstrated that material in the hot finished, "equalized", #1 temper, and double heat treated conditions have exhibited failures in such systems, but that the highly cold worked then aged spring temper materials was more resistant.

Failures of Alloy X-750 bolts, pins and beams, and springs have been noted in BWR and PWR service qualification tests [18], however, the high strength spring temper, especially with a 1350°F aging treatment, has been more resistant to such failures. Spring temper material aged at a lower temperature (e.g., 1200°F) has exhibited greater susceptibility to IGSCC. The spring temper treatment (including 1350°F aging treatment) produces a microstructure consisting of a uniform dispersion of gamma prime and globular and cellular grain boundary carbides.

The most IGSCC resistant microstructure for Alloy X-750 has a gamma prime phase that is responsible for hardening in the grain interiors and a semi-continuous distribution of globular $M_{23}C_6$ carbides at the grain boundaries [20]. Cold working before aging increases the fraction of cellular (vs. globular) carbides. Cellular carbides produce a less ductile and more IGSCC susceptible microstructure.

Small amounts of cold work are extremely detrimental to IGSCC resistance [19-21]. The core internals spring temper (CIST) treatment , however, has been shown to be very IGSCC resistant, provided that aging after the high level of cold work was done at sufficiently high temperature (e.g., 1300°F or higher). Based on the spring aging conditions provided in References [4] and [14], IGSCC is a potential degradation mechanism applicable to Brunswick-2. However, the results of this analysis suggest that IGSCC is not a concern for Brunswick-2 core plate plugs for over 30 EFPY.

GE's evaluation of the predicted life of the core plate plug spring uses the Stress Rule Index (SRI) approach as described in Reference [4]. That analysis conservatively assumes that all of the stresses in the spring are primary loads, despite the fact that the spring is primarily loaded under deflection control. For a core plate plug where the preload always exceeds the core plate ΔP, the spring will experience a combination of primary stress plus deflection controlled loading.

[[

]] [4].

The revised GE analysis [4] has incorporated time-dependent, decreasing loads. That revised analysis treats stress (and SRI) as a constant during each of the time periods between core plate plug removals. That is, a "life fraction" is computed by dividing the actual time of exposure (in EFPY) by the life prediction per the SRI. [[

]]

The current analysis took a similar approach, however, the time periods over which stress and SRI were evaluated were made much smaller (1 EFPY), based upon the expressions derived for stress relaxation of the spring. The revised GE expression for spring relaxation and the best fit to

the spring relaxation determined from core plate plug surveillance (Figure 3-4) are in excellent agreement. In Table 3-1, the GE Revised Prediction and the Fit to the Surveillance data were each used to estimate spring load, spring stress (with all of the stress in the spring still treated as a primary stress), the SRI, and the resulting cumulative usage factor that that SRI would predict over each effective full power year. Stresses for the GE Revised Prediction were based upon the load vs. stress comparison provided for a single load in [4]. The stresses computed from the
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As noted previously, none of the core plate plugs that have been examined following up to 17.4 EFPY of service have revealed any evidence of cracking, and none of the springs with up to 11.7 EFPY of exposure exhibited any degradation of the spring constant. The spring constant for 4 of the 4 springs removed from the Peach Bottom Atomic Power Station was significantly less than 30-33 lb/in specification value, but that no evidence of any cracking detected on any of those four springs [6].

The stress rule correlations for IGSCC initiation do not take into account the less aggressive environment provided by moderate hydrogen water chemistry (HWC-M) or HWC with noble metals. The benefits of HWC-M or HWC plus noble metals for maintaining lower electrochemical corrosion potential (ECP) of components in in-vessel locations above the core plate have been demonstrated by in-plant measurements at several plants. HWC-M or HWC plus noble metals may have produced some benefit for stainless steel components of the core plate plugs as suggested by ECP measurements obtained in in-vessel locations above the core plate plugs [28-30]. There are no current data that demonstrate a benefit of HWC-M or HWC plus noble metals on IGSCC of Alloy X-750. In this analysis, no benefit of operation under HWC-M or HWC plus noble metals was assumed for either the spring or for the stainless steel parts.

3.3 IGSCC of Stainless Steel Components

The literature contains numerous reports of IGSCC failure of solution annealed stainless steel in the BWR core environment after long exposures. Most often, the failures have been associated with accumulation of fast fluences in excess of 5 x 10^{20} n/cm^2 [28]. The core environment affects the material condition, producing solute segregation of species such as phosphorus and especially silicon, thereby rendering the material more susceptible to intergranular attack and IGSCC as shown by exposure to aggressive nitric acid/acid dichromate environments. Further, some chromium depletion, as demonstrated by post-exposure sensitization tests (ASTM A262, Practices A and E [31]) has been demonstrated. Finally, the in-core environment is highly oxidizing as the radiolysis of water produces oxygen and hydrogen peroxide.

For most components of the core plate plug, IGSCC susceptibility is expected to be minimal since the stresses are very low (of the order of 1 ksi for most of the stainless components) and neutron fluences will be low. In addition, the austenitic Type 304 stainless steel parts are not welded subsequent to solution annealing. Thus, it is not expected that these parts are sensitized. Per the original BWR fleet bounding neutron flux value given in Reference [4], the top of the core plate plug shaft was predicted to require more than 30 EFPY to reach 5 x 10^{20} n/cm^2. Other parts of the plug will accumulate fast fluence at a lower rate. The very low stresses in the components in the top of the plug would still preclude SCC concerns with those components. The more highly stressed latch and pin are shielded by the core plate itself. Those components would not be expected to reach 5 x 10^{20} n/cm^2 for exposures of 30 EFPY.

3.3.1 Latch

The latch is the most highly stressed stainless steel component in the core plate plug, with maximum bending stresses of the order of 20 ksi. That maximum stress also occurs in a creviced area that can provide an accelerant to SCC initiation. Fortunately, the latch will accumulate fast fluence slower than any other part of the core plate plug due to its greater distance from the core and the shielding given by the core plate itself, so that influences of irradiation should not be a significant factor.

The latch is re-solution annealed after punching to eliminate any cold work effects from the punching operation [14]. The time to crack initiation for solution annealed, essentially unirradiated stainless steel, stressed to approximately 2/3 of its yield strength is of the order of 40 years. The stress levels corresponding to 2/3 of the material yield strength is well below the threshold for the IGSCC of uncreviced furnace sensitized stainless steel. The fact that BWRs operate on low ECP HWC-type environments and the absence of welds in the latch significantly mitigates IGSCC [32-33].

3.3.2 Other Stainless Steel Structural Components

Stresses in the other stainless steel components of the core plate plugs are far lower than those in the latch. For example, the constant load in the shaft is less than 1 ksi. The pin is the next most highly loaded member other than the latch. The peak calculated bending stress in the pin is approximately 1 ksi; a very small fraction of the yield strength. As noted in Section 3.3, irradiated stainless steel components, loaded to small nominal stresses, have cracked in the vessel in other applications, however, the susceptibility of the stainless steel components of the core plate plug are not considered to be any greater than those of unirradiated stainless steels exposed in the BWR system. The use of solution annealed materials should provide greater resistance than for vessel internal components, which contain weld heat affected zones.

3.4 Embrittlement of Stainless Steel

For plugs left in place, embrittlement of the latch is unimportant for anything other than comparisons of the critical flaw size, a_{crit}, to IGSCC. If the plug is not removed by ripping it through the core plate, the irradiation induced reduction in total elongation from >50% to something less than 15% is unimportant. Based on GE estimates of fast neutron flux at the top of the core plate and attenuation of that flux through the thickness of the core plate, i.e., to the latch, total elongations of >15% are expected at exposures of 30 years or more.

3.5 Flow Past Plugs

Leakage past a core plate plug was calculated for normal and for faulted conditions for four different stages of plug movement. These cases are shown in Table 3-2. These cases represent different geometric conditions and are independent of plant exposure.

The base case (spring opening = 0) showed that very minor leakage, less than 1 gpm, would be expected. This leakage arises from leakage flow between the shaft and body and past the seat under a spring force of 30 to 40 pounds.

Three different amounts of axial displacement of the plug out of the hole in the core plate plug were evaluated. Those displacements corresponded to lifting of the plug by 0.085 inch (the thickness of the seat area), by 0.293 inch (past the bottom of the seat), and 1.293 inches (well into the reduced diameter section of the plug body). The smaller displacements would be possible in the event of significant spring relaxation. In both cases, leakage flow past the core plate plug would be of the order of 20-25 gpm for normal operation and 21-26 gpm for upset conditions. The flow calculations show that the value does not really increase even if the plugs were displaced upward by another inch, to 1.293 inches above its normal position. It is also evident from Table 3-2 that the increase in flow rate for an upset event is insignificant. The flow rates past a displaced plug increase proportionally with pressure across the core plate. At a ΔP = 28.45 psi (normal operation), the flow is about 26 gpm. For upset conditions, at a ΔP = 30.85 psi, the flow is approximately 27 gpm.

With no core plate plug, Table 3-2 indicates that the flow rate through the core plate bypass hole is of the order of 151 gpm and 157 gpm for normal and upset conditions, respectively.

This "On/Off" behavior appears to be consistent with very detailed flow mock-up tests performed by GE [2]. Those tests showed that accelerations of local power range monitors (LPRMs) and other in-core devices were essentially unaffected by small changes in bypass flow conditions, (e.g., 3 of the 4 holes in the vicinity of the in-core instruments remained plugged), however, acceleration was dramatically different when all of the bypass holes (i.e., 4 of 4) were

completely unplugged. The case of failure and ejection of one plug in a pattern of four holes is bounded by the flow mock-up test performed by GE [2] and would not produce unacceptable instrument vibration levels. Still, the ejection of the core plate plug will cause an increase in the vibration levels at the nearby LPRM that should be detectable.

3.6 Loose Parts Considerations

The primary concern for loose parts is the complete ejection of the plug due to spring relaxation or IGSCC. Design of the plug appears to all but preclude that type of event.

With the bottom latch in place, the ΔP across the core plate pushes against the shaft and the body of the plug. If the spring is relaxed or broken, the shaft and plug body can be lifted by the pressure, and flow paths past the core plate plug seat and through the internals of the plug will be created. The core plate plug will remain in place, however; held against the bottom of the core plate by the latch. A broken spring could introduce loose parts into the vessel, however, the spring would have to fail in two locations that are near to one another, for example, in the same coil, at less than about half of the circumference, for part of the spring to become dislodged from the plug assembly. The probability that the spring will crack all the way through the wire in two places in the same coil is considered to be extremely small.

The shaft will not be ejected from the core plate plug so long as the shaft and either the latch or the pin remain in place, since either of those devices will prevent the movement of the shaft beyond the plug body.

Complete failure of the shaft at a location within the core plate, above the pin and latch but below the spring, will not necessarily result in a loose part, even though the upper part of the broken shaft, the spring, and the plug body will be unrestrained. The fluid pressure will continue to act on the end of the shaft and the plug body. Although, this force will no longer be resisted by a spring force, the shoulder on that shaft will restrain the spring and keep the spring from being ejected into the core.

A complete failure of the latch, the pin, or the core plate plug body is required for the plug to be ejected from the core plate. In any of those cases, the core plate ΔP acting on the end of the shaft and the plug body can eject the plug from the core plate.

Significant relaxation or cracking of the springs would produce a major loss of preload on the core plate plug assembly. Any movement of the core plate plug, upward and off the core plate will result in an increase in leakage under the ΔP across the core plate. As noted in Section 3.5, flow past the plugs would not increase very much (from a fraction of a gallon per minute to as much as 26 gpm for normal operation and 27 gpm in case of an upset event), depending upon the amount of plug movement. It is also evident from Table 3-2 that the increase in the flow past plug for an upset event is insignificant. In case of an upset event, that is both infrequent and short lived, the slightly increased leakage past the core plate plug could result in vibration and chattering of the plugs for the short duration the upset event occurs. Since the probability of such events is fairly low, it is anticipated that this slightly increased leakage past the core plate plug during the short duration of the event will not result in its damage or failure. Visual examination to verify that the plug has not been displaced upwards or damaged could provide assurance that a preload still exists on the plug and that the latch is not being exposed to large cyclic loadings. This examination will not, however, provide any guarantee that under operating conditions that the plug remains seated or that the latch is being cycled by a pulsating flow.

As noted in Section 3.5 in NEDC-21084 (Section 3.1.2.2.4) [2], the complete ejection of a single core plate plug has been evaluated and has been demonstrated to have no significant effect on core thermal-hydraulics.

Table 3-1. Stress Rule Index Calculations

Constant (Load to stress) =				3.304843					
Fit to Surveillance		-5.205	40.161						
		Spring Load, lbs		**Spring Stress, ksi**		**Stress Rule Index**		**Cumulative Usage (per. SRI)**	
EFPY	Yield Strength, ksi	GE Revised Prediction	Fit to Surveillance Data	GE Revised Prediction	Fit to Surveillance Data	GE Revised Prediction	Fit to Surveillance Data	GE Revised Prediction	Fit to Surveillance Data
0	194	35.1	40.2	116	116.0	0.598	0.598	0.081	0.081
1	194	32.6	40.2	107.8	116.0	0.556	0.598	0.137	0.161
2	194	31.6	36.6	104.6	105.6	0.539	0.544	0.187	0.213
3	194	30.9	34.4	102.1	99.5	0.526	0.513	0.231	0.253
4	194	30.3	32.9	100.0	95.2	0.516	0.491	0.272	0.286
5	194	29.7	31.8	98.2	91.8	0.506	0.473	0.309	0.314
6	194	29.2	30.8	96.6	89.1	0.498	0.459	0.344	0.339
7	194	28.8	30.0	95.1	86.7	0.490	0.447	0.377	0.362
8	194	28.3	29.3	93.7	84.7	0.483	0.437	0.408	0.384
9	194	28.0	28.7	92.4	83.0	0.476	0.428	0.438	0.403
10	194	27.6	28.2	91.2	81.4	0.470	0.419	0.465	0.421
11	194	27.2	27.7	90.0	80.0	0.464	0.412	0.492	0.438
12	194	26.9	27.2	88.9	78.6	0.458	0.405	0.517	0.455
13	194	26.6	26.8	87.8	77.4	0.453	0.399	0.541	0.470
14	194	26.3	26.4	86.8	76.3	0.447	0.393	0.564	0.485
15	194	26.0	26.1	85.8	75.3	0.442	0.388	0.586	0.499
16	194	25.7	25.7	84.8	74.3	0.437	0.383	0.607	0.512
17	194	25.4	25.4	83.9	73.4	0.433	0.378	0.627	0.525
18	194	25.1	25.1	83.0	72.5	0.428	0.374	0.647	0.538
19	194	24.9	24.8	82.1	71.7	0.423	0.370	0.666	0.550
20	194	24.6	24.6	81.3	71.0	0.419	0.366	0.684	0.561
21	194	24.3	24.3	80.5	70.2	0.415	0.362	0.702	0.573
22	194	24.1	24.1	79.7	69.5	0.411	0.358	0.718	0.584
23	194	23.9	23.8	78.9	68.9	0.407	0.355	0.735	0.594
24	194	23.6	23.6	78.1	68.2	0.403	0.352	0.751	0.605
25	194	23.4	23.4	77.4	67.6	0.399	0.348	0.766	0.615
26	194	23.2	23.2	76.6	67.0	0.395	0.345	0.781	0.625
27	194	23.0	23.0	75.9	66.5	0.391	0.343	0.795	0.634
28	194	22.8	22.8	75.2	65.9	0.388	0.340	0.809	0.644
29	194	22.5	22.6	74.5	65.4	0.384	0.337	0.823	0.653
30	194	22.3	22.5	73.8	64.9	0.380	0.334	0.836	0.662

Table 3-2. Leakage through Core Plate Bypass Holes[1]

Spring Opening, inches	Flow Rate, gpm (28.45 psid)	Flow Rate, gpm (30.85 psid)
0	0.81	0.84
0.085	19.91	20.63
0.293	25.66	26.71
1.293	25.38	26.45
(No Plug)	151.18	157.43

[1] Total leakage past shaft and body

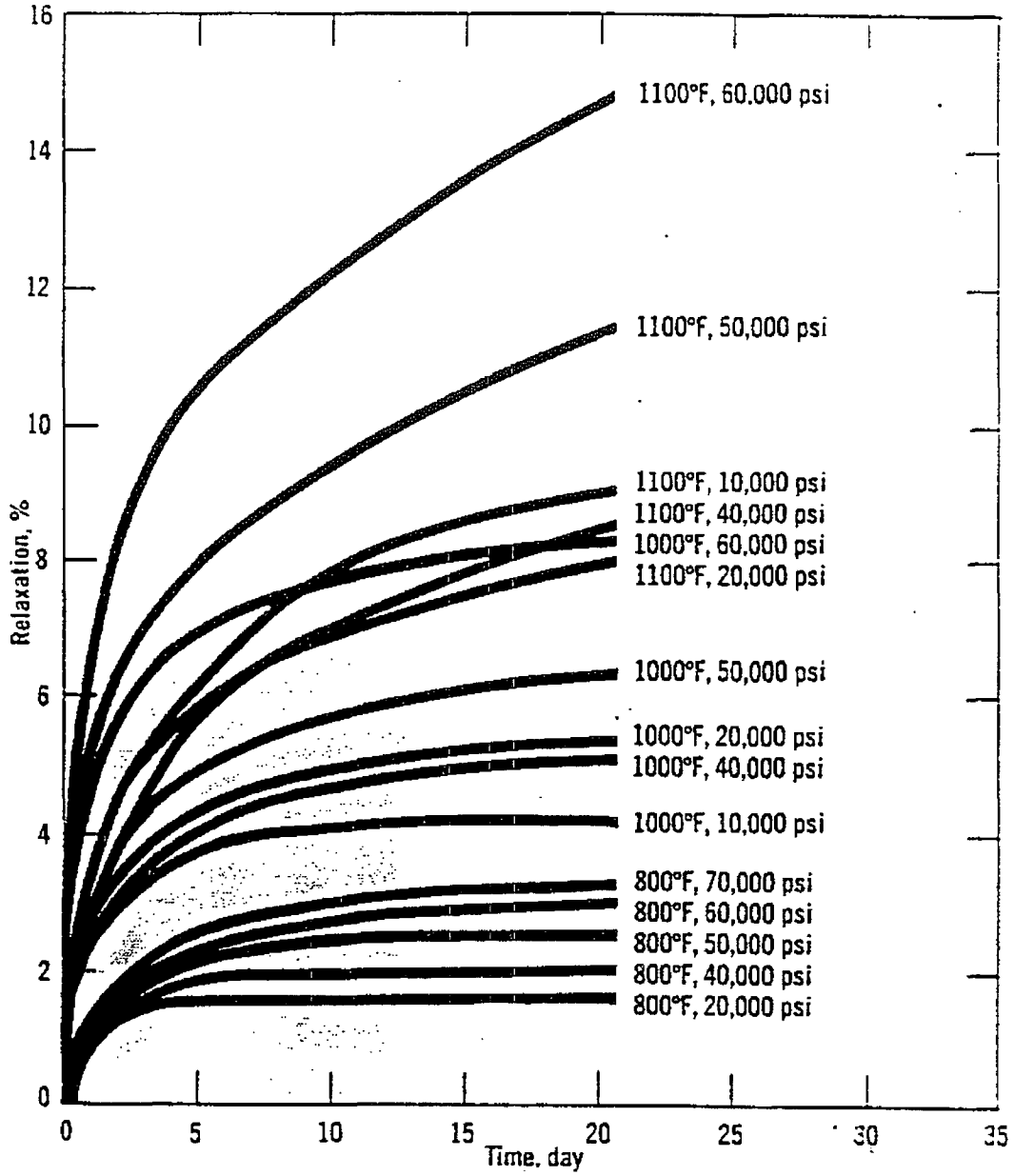

Figure 3-1. Thermal Relaxation of Alloy X-750 (from [7])

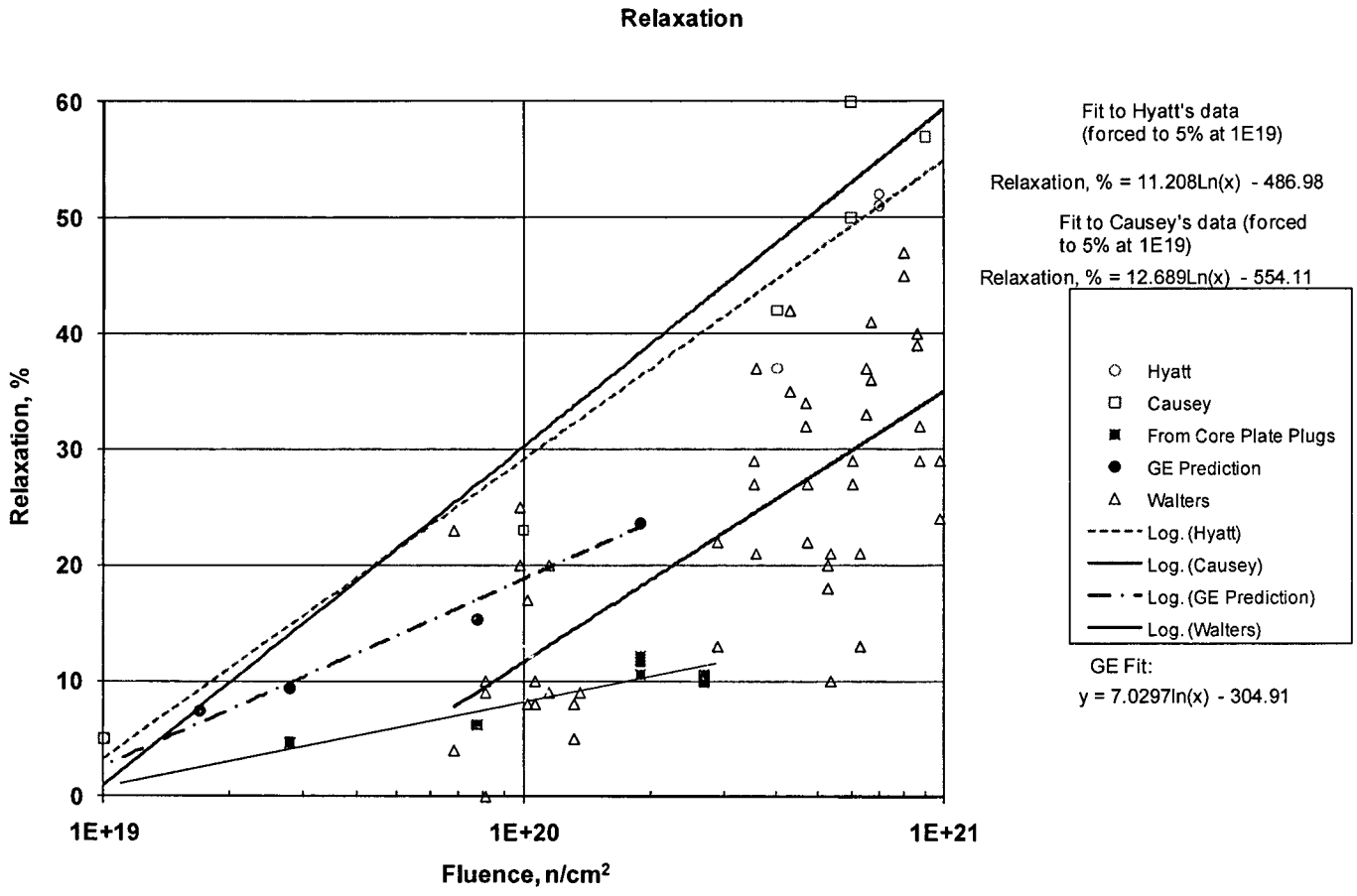

Figure 3-2. Irradiation Creep of Alloy X-750 (heavy black dashed line is approximate fit to surveillance data from core plate plugs)

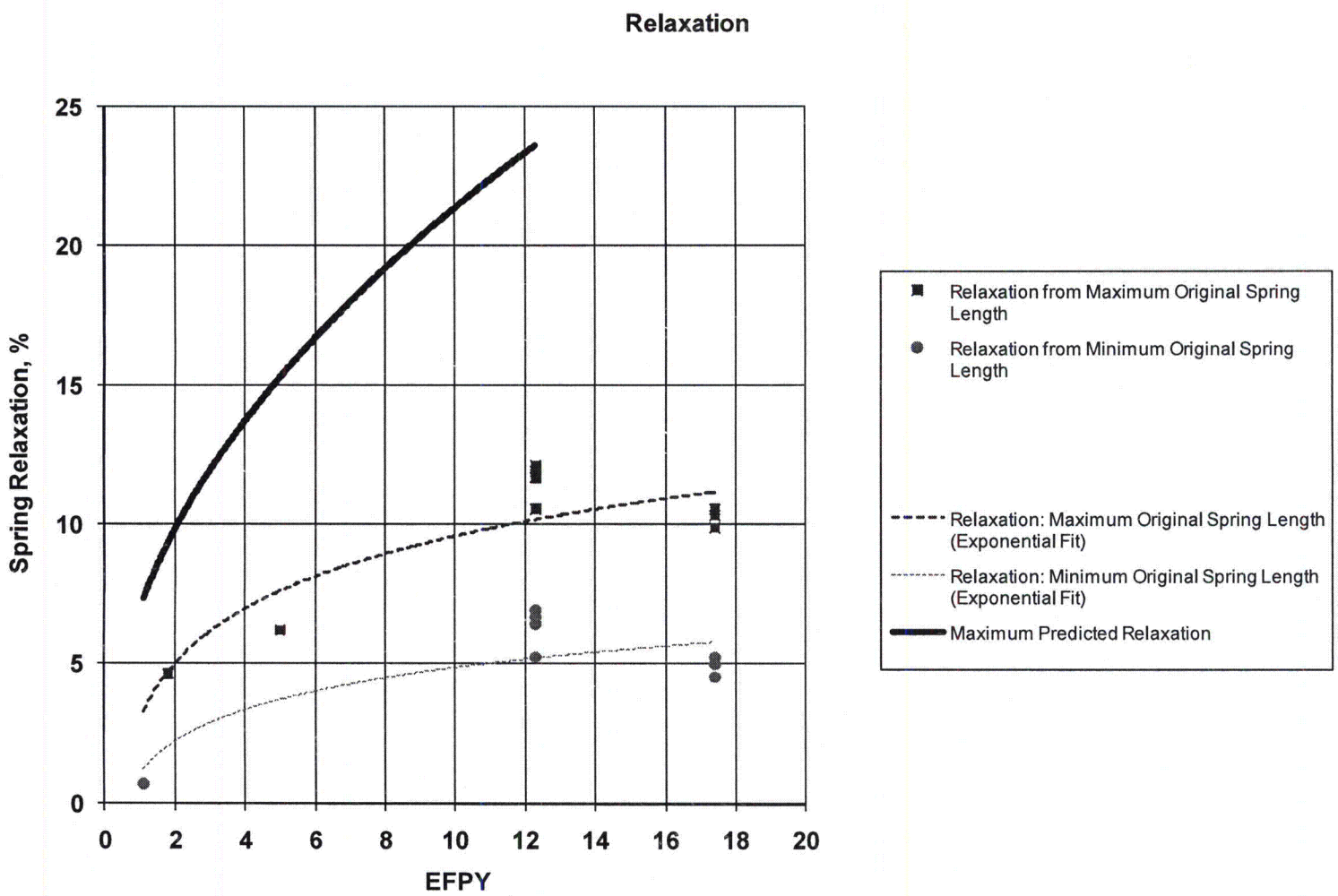

Figure 3-3. Spring Relaxation (Measured and Predicted) – Core Plate Plug

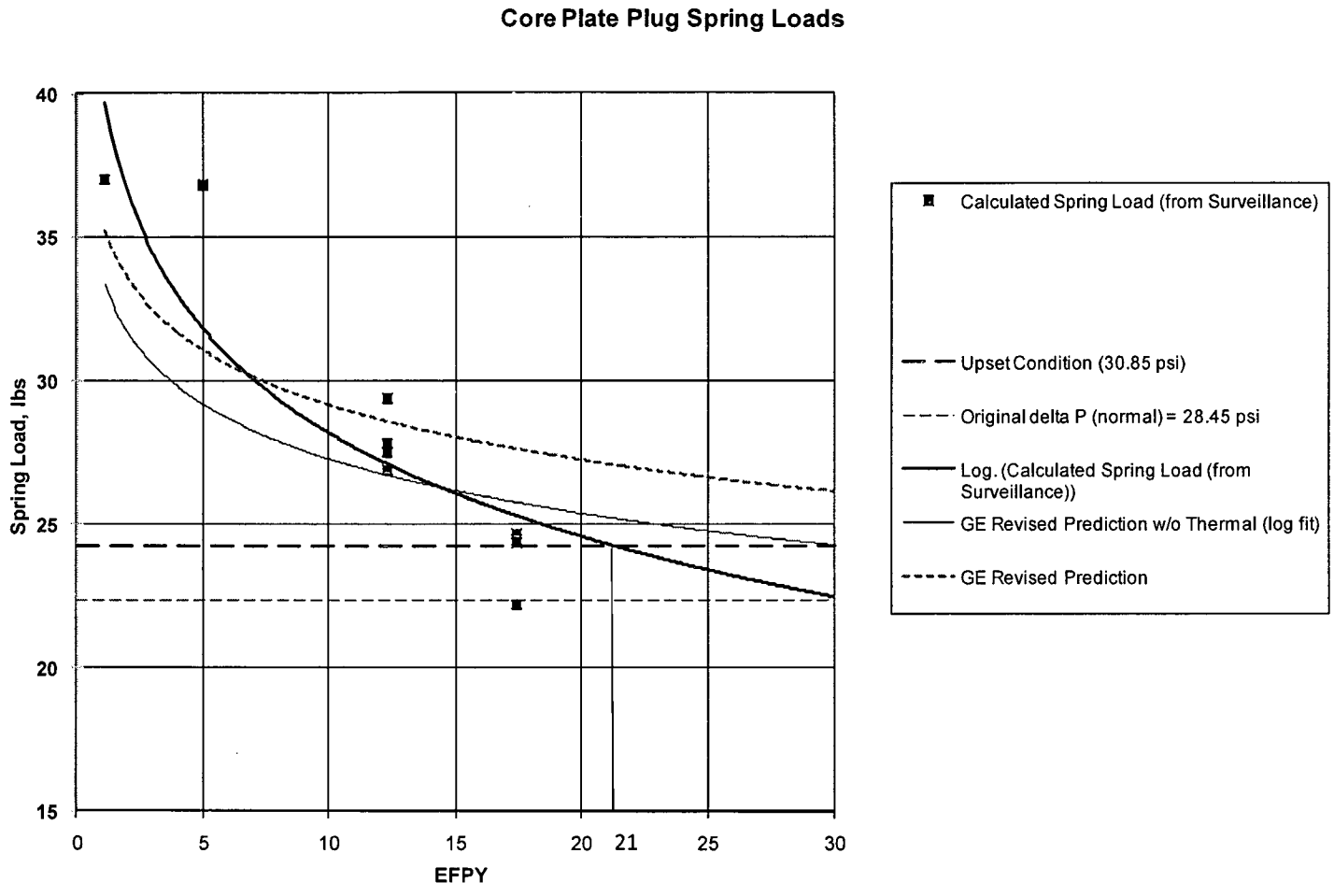

Figure 3-4. Core Plate Plug Spring Loads

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Figure 3-5. Time to Stress Corrosion Cracking for Alloy X-750 – GE Stress Rule Index Results (from [4])

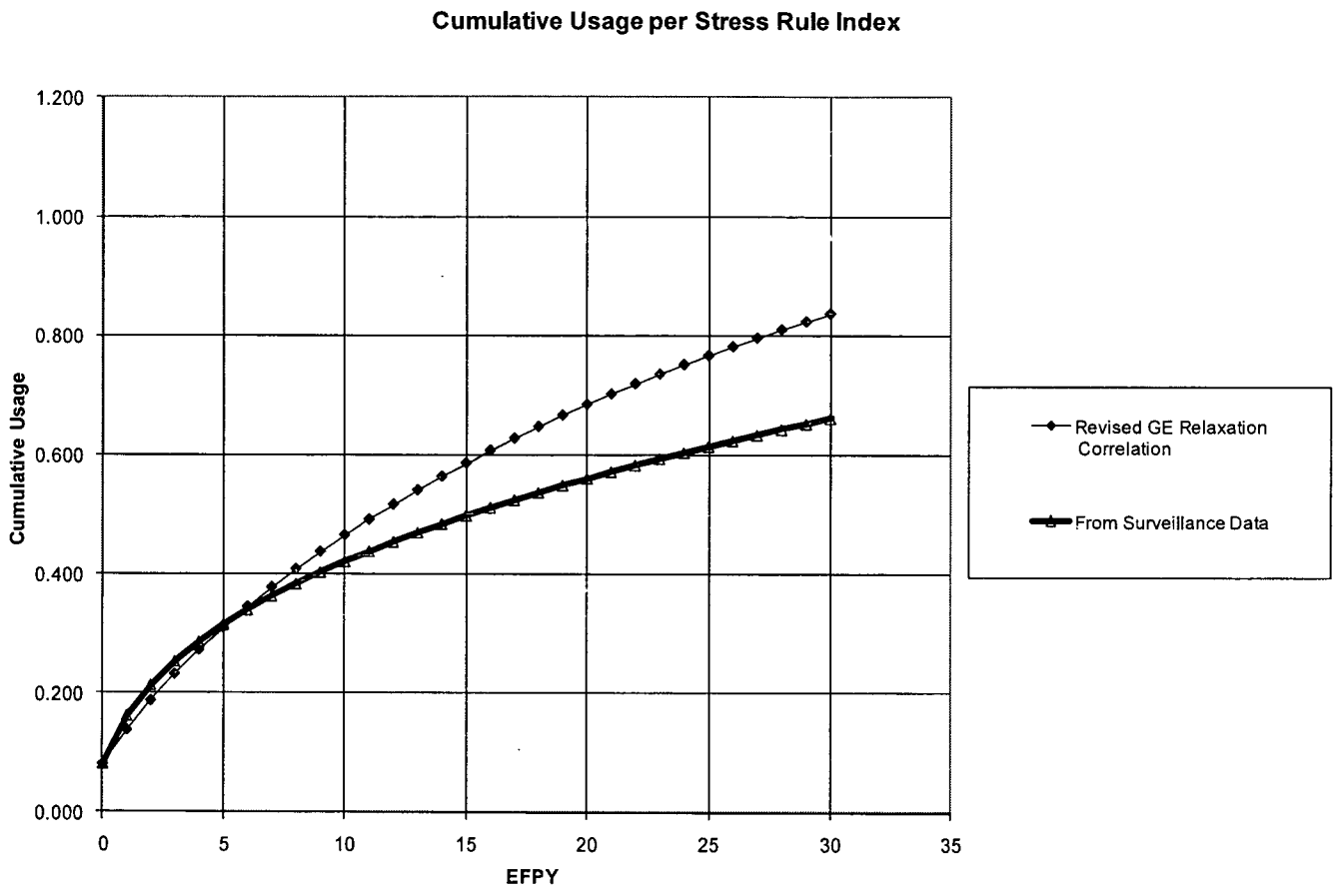

Figure 3-6. Cumulative Usage per Stress Rule Index

4.0 SUMMARY

This evaluation was performed based on the plant specific data including updated fluences and reactor internal pressure differences (accounting for extended power uprate – 120% of the original licensed thermal power) [13, 16] and the most recent core plate plug surveillance data obtained from the Peach Bottom Atomic Power Station [6]. Based on this current evaluation, it was observed that:

- For normal operation (ΔP = 28.45 psi), the life of the Brunswick-2 core plate plugs limited by degradation mechanisms including spring relaxation, IGSCC of the spring and IGSCC of other stainless steel components is 30 EFPY.
- For upset conditions (ΔP = 30.85 psi), the seating force applied by the spring would not exceed the force exerted on the bottom of the plug by the upset ΔP; thus, some amount of leakage may occur for upset events. Degradation of the spring and other stainless steel components in the core plate plug due to IGSCC is not expected to occur for over 30 EFPY.

  Although Brunswick-2 is currently at 24 EFPY, it is to be noted that upset conditions are both infrequent and short lived. Having demonstrated that irradiation embrittlement and IGSCC will not lead to failure of the spring or other stainless steel components for over 30 EFPY, the only possible effect would be a slight increase in the leakage past the core plate plug for the short duration of the upset event following which the plant would return to normal operation restoring conditions where the life of the core plate plug limited by spring relaxation would be 30 EFPY. Should an upset event occur, it is recommended that Progress Energy perform a visual examination of a sample of core plate plugs to rule out any damage that could have occurred as a result of the upset condition. It is also recommended that Progress Energy review plant monitoring data to record the ΔP reached during that upset event.

[[

]] [4]. However, measured spring constants after 17.4 EFPY were significantly lower than the specified value for the as-installed springs (23-25 lb/in vs. 30-33 lb/in). No explanation for this apparent anomaly was offered in Reference [6].

[[

]] [4]. [[

]] [4], based on IGSCC initiation.

This analysis took a similar approach as a GE calculation that previously yielded revised IGSCC life limits of > 14 EFPY, discussed above. However, the time periods over which stress and SRI were evaluated were made much smaller, based upon the expressions that were derived for stress relaxation of the spring. The revised GE expression for spring relaxation and the best fit to the spring relaxation determined from core plate plug surveillance (Figure 3-3 and 3-4) are in good agreement. Evaluating the SRI over each EFPY (with all of the stress in the spring still treated as primary stress), determining the SCC usage based on the SRI prediction, then determining the cumulative usage factor, shows that the spring life, as limited by IGSCC would be more than 30 EFPY (Table 3-1; Figure 3-6).

IGSCC of the stainless steel components in the core plate plug can become a concern, particularly at fast fluences of 5×10^{20} n/cm^2. Per the original BWR fleet bounding neutron flux value given in Reference 4, the top of the core plate plug shaft was predicted to require more than 30 EFPY to reach 5×10^{20} n/cm^2, with other parts of the plug accumulating fast fluence even slower. However, for the fast flux calculated for power up-rate [13], more than 30 EFPY would be required to achieve that fluence for the most highly exposed (and most lightly loaded) part of the plug. The very low stresses in the components in the top of the plug would still preclude SCC concerns with those components. The more highly stressed latch and pin are shielded by the core plate itself. Those components would not be expected to reach 5×10^{20}

n/cm^2 for exposures of 30 EFPY. Life based on SCC of the stainless steel components is greater than 30 EFPY.

Radiation embrittlement is not a concern for core plate plugs that are left in place. In addition, the austenitic Type 304 stainless steel parts are solution annealed and do not containing welds. Thus, it is not expected that these parts are sensitized. Radiation embrittlement is not a concern in terms of the reduction in toughness of the core plate plugs for over 30 EFPY.

Generation of loose parts will not occur unless a spring fails in two locations that are close together (<60° of circumference), and/or fatigue or IGSCC degradation mechanisms that could produce failure of the plug's latch, shaft, or pin. Based on the actual material conditions of the Alloy X-750 spring (heat treatment and tempering) and Type 304 stainless steel components (non-welded and solution annealed components), the probability of any of those events is considered extremely small for normal operating conditions. Should an upset condition occur, even though there could be leakage past the core plate plug for the short duration of the occurrence of such an event, the possibility of vibration of the core plate plug leading to vibration and chattering is low.

The complete plug can be ejected from the core plate in the event that the latch fails completely. Although that event is considered unlikely for the loadings considered here, cracking or high levels of spring relaxation that permit the spring to pulsate and the plug to chatter under the hydraulic loads can lead to accelerated failure of the latch. Based on this, consideration of loose parts in accordance with BWRVIP-06-A, Section 4 should be addressed by Progress Energy. Periodic visual examination to verify that all plugs are in their proper orientation is recommended.

Leakage resulting from a plug that remains in place, even if that plug is displaced from its normal position, is small (~20-26 gpm) in comparison to the flow that occurs through an unplugged bypass flow hole (>150 gpm). Vibration of nearby LPRMs, as might occur after the

ejection of one or more core plate plugs, would provide an on-line indication that the core plate plugs had been ejected and that an undesirable flow condition was present.

Core plate plugs should remain functional and will not present a loose parts concern for at least 30 EFPY.

5.0 CONCLUSIONS

This report has estimated a core plate plug life of 30 EFPY for normal operation, limited by spring relaxation.

Surveillance activities performed on the core plate plug could provide valuable information for future life predictions.

Periodic inspection of a sample of plugs, in place, for evidence of damage or displacement (VT-3) is an acceptable method of demonstrating that the plugs remain functional. The sample size should consist of approximately 10% of the LPRM locations where core plate plugs are installed. Performance of such inspections on a 10% sample size is recommended at every refueling outage.

Should an upset even occur, it is recommended that Progress Energy review the ΔP measured across the core plate during that event to assess if the actual upset event ΔP was sufficiently high to predict some amount of leakage flow.

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