Assessment of Causes for Degrading Fuel Performance at Darlington NGS

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ABSTRACT

Fuel performance at the Darlington nuclear generating station has historically been excellent. Until recently, the majority of these few fuel defects have been attributed to fretting by heat transport system debris. The minority have been linked to manufacturing issues.

Recently, Darlington has experienced an increase in the number of fuel defects. Although the defect rate remains low with respect to industry standards, this defect experience is considered to be unacceptable given current industry expectations and the OPG zero defect policy.

Nine fuel defects have been discharged since 2007 from the four Darlington reactors. This represents a fuel defect rate of just 0.35 defects per year per reactor. At the time of this writing three additional defects are suspected to be in core.

Although a definitive defect cause has yet to be identified, these fuel performance issues appear to be due to the coincidental degradation of manufacturing and operational factors, thereby decreasing the margins to fuel failure due to fuelling power ramps. All of the confirmed defected bundles have been long bundles and all experienced a relatively high power ramp when shifted from Position 2 to Position 6. High bundle uranium masses and low internal clearances are thought to be significant contributing factors. Bundle burnups at the time of the power ramps were low and these bundles were not identified by existing power ramp defect predictive tools.

Our assessment has resulted in a number of recommendations which are designed to mitigate these adverse conditions by restoring the margins to power ramp failures. These recommendations impact broadly across a number of organizations including reactor physics, fuel design, fuel manufacturing, reactor design, inspections and PIE.

INTRODUCTION

Fuel performance at the Darlington nuclear generating station has historically been excellent. While there have been very few defects, historically the main issue was attributed to debris fretting with a minority linked to manufacturing issues. Since 2007, Darlington has experienced an increase in the number of fuel defects. Although the defect rate remains low with respect to industry standards, this defect experience has been considered to be unacceptable given current industry expectations and OPG “zero defect” policy. In response to this operating experience (OPEX) a joint OPG / fuel manufacturer working group was established to investigate and recommend solutions to this problem.

Fuel defects represent an adverse condition to reactor operations with the following impacts:

- Increased operator and maintainer doses.
- Reduced fuel and plant reliability.
- Potential for fission product release to the environment.
- Impact on the reputation of the corporation.
- Administrative impacts due to audit findings and identification of Areas for Improvement (AFIs).
- Challenges to Operations, Fuel Handling and Engineering in the removal of defective fuel.

Nine fuel defects have been discharged since 2007 from three of the four Darlington reactors. This represents a fuel defect rate of 0.35 defects per year per reactor. If all reactors are considered and on a bundle usage basis, this is a defect rate of approximately 0.006 percent. Since each bundle contains 37 elements and with no bundle had contained more than a single defected element, the defect rate on an element basis remains exceedingly low (~ 10^{-6}). At the time of this writing three additional defects are suspected to be in core.

To date the investigation has been successful in determining a defect cause for only one of these 9 defected fuel bundles. This bundle was found to have defected due to fretting by a piece of debris in the heat transport system. The defect causes for the other bundles have not yet been determined. This report describes the investigations which have been performed and/or are still in progress. Key observations and conclusions are provided.

At this stage in our investigation a variety of factors appear to be implicated in these fuel performance issues. Taken separately, each of these factors may not have been sufficiently adverse to result in the current fuel defect experience. However, the coincidence of two or more factors would result in degraded margins to failure and might significantly increase the risk of this poor fuel performance. The following adverse factors have been identified:

- Low radial and axial fuel to fuel sheath/endcap clearances.
- Increasing Uranium mass in long bundles.
- Slightly more severe fuelling power ramps than anticipated in the original core design. This is in part due to removal of 8 adjusters from core early during the operating history of Darlington. We are also investigating the possible irradiation degradation of the reactivity worth of the remaining adjusters.
- Power ramps assessment tools which are not able to predict this poor fuel performance, as presently configured.

Elusive issues often require investigations that have long timelines, but it is not acceptable to operate at risk of fuel defects while awaiting conclusive determination of defect cause. Sufficient information is now available to develop reasonable corrective actions. Darlington management has accepted these corrective actions and mandated the investigative team to develop a recovery plan. The last section of this report provides detailed recommendations which are intended to improve fuel performance.

Recommendations fall into the following broad categories:

- Reactor operations
  - Bundle usage
  - Scheduling of routine fuelling
  - Predictive tools
- Reactor design
  - Adjuster loading
- Fuel design – OPG specifications
- Fuel manufacturing – maintenance/improvement of required clearances
- On-site fuel inspections and off-site examinations in hot cells.

BACKGROUND

The identification of the existence of defected fuel elements in the cores of Darlington reactors is by use of the gaseous fission product (GFP) monitoring system and/or by analysis of heat transport system grab samples. These techniques are very sensitive and allow the identification of single defected elements containing very small sheath penetrations. Such identifications trigger sustained efforts to locate and remove the defects from core.

Defect location relies on the use of the feeder scanning (FS) system. Unfortunately, FS is only effective during a short window of time after reactor shutdown. In the absence of FS data, defect location is by correlation of reactor fuelling histories to trends in heat transport fission product concentrations. This process is inefficient; nonetheless, defected fuel bundles are successfully discharged at Darlington and identified for inspections in the irradiated fuel bay (IFB).

After discharge, suspect fuel bundles are sent to the West IFB for underwater inspections. IFB inspection techniques are effective in identification of the defected fuel element however, in most cases these visual techniques are not capable of identifying the cause of the defects. The identification of defect cause generally requires post-irradiation examinations (PIE) in hot-cells. The timeline for PIE is generally quite long, usually requiring one or more years from receipt of the irradiated fuel shipment to completion of the examination.

Of the nine defected bundles discussed in this report, elements from seven have been shipped to the Chalk River Laboratories for PIE (Table 1). The suspect defect bundle from channel 1L20 was discharged to the Darlington East IFB and cannot be inspected or shipped. Inspections have now started for the most recent discharge of defect suspect fuel from Channel 2L20 and the defected bundle has been identified.

PIE remains incomplete at the time of this writing. The majority of work that has been completed is for defected fuel elements. Although there have been some very interesting and possibly important observations, these have not yet been validated against base-line examinations on adjacent intact elements. Confirmatory PIE on the relevant intact elements has recently been reprioritized and should be completed by the end of 2013. Similarly, other investigations have now been initiated and will be completed in the short term. A detailed recovery plan has been issued for Darlington. This plan will be revised as additional data becomes available.

OVERVIEW

Table 1 identifies the defected bundles and provides key irradiation dates. Also provided are the dates of the first fuel defect indications and the identities of the defected elements. The elements that have been shipped for PIE are identified. The following key points are observed:

- All defected bundles are long bundles. Eight of the bundles are of the 37R design and one is 37M.
- All bundles were initially loaded into Position 2 and then shifted to Position 6.
- All but one defected elements were outer elements. An intermediate element defected in the bundle from 1F15.
- The bundle from 1J20 defected due to debris fretting. Visual inspections in the IFB were not able to identify the primary defect cause for the other bundles but did observe secondary deuteride damage in all cases.
- Excluding 1J20 (debris fretting), the initial defect indication from 4 of the bundles were observed when the bundles were resident in Position 6, the remaining 4 provided indications after being shifted to Position 10. These observations are thought to indicate the opening of areas of secondary deuteriding damage to the coolant, but not the time of the creation of primary sheath damage.

Irradiation histories are provided in Figure 1. The times of the first defect indications are also provided. Timelines for residence of these bundles in-core in the defected condition are provided in Figure 2.

ASSESSMENTS OF POWER RAMPS

It is noteworthy that all of the defected bundles had experienced the Position 2 to Position 6 fuelling shift. Although the burnups for these bundles were low at the time of the shift, these shifts represent some the most severe fuelling power ramps experienced at Darlington as measured by power increase and final bundle power.

Figure 3 displays the final bundle power and burnups for all bundles which experienced power increases due to fuelling of these channels while the defected bundles were in-core. This data is superimposed on a background of data representing the bundle powers and burnups of all the bundles in a typical Darlington core. It can be seen that the Position 2 to Position 6 shifts do represent some of the most severe operating conditions.

Bundle and fuel element power ramps are assessed at OPG using the CAFÉ (1986) formulism. CAFÉ’86 is based on experimental power ramp data from Chalk River Laboratories (CRL) with

CANLUB fuel elements, and benchmarked against the improved power ramp performance of CANLUB fuel at Pickering and at Bruce A. In this model the probability of a defect occurring in a fuel element (p) is expressed as a function of the variables which describe the fuel state following a power ramp; the final element linear power (P; kW/m), the change in element linear power (ΔP; kW/m), and the fuel element burnup (ω; MWh/kgU):

$$p = \left(1 + e^{-A}\right)^{-1}$$

where

$A = -17.6 + 0.186\,P + 0.117\,\Delta P + 0.012\,\omega$

for

$P\ (\mathrm{kW/m}) > 61.3 - 0.0257\,\omega$

$\Delta P\ (\mathrm{kW/m}) > 26.1 - 0.0319\,\omega$

Normally, CAFÉ is not considered to be applicable below an element burnup of approximately 75 MWh/kgU. Also, the applicability conditions provided above for P and ΔP disable CAFÉ at low burnup.

These conditions for the use of CAFÉ rendered it incapable of predicting power ramp defect probabilities for the Darlington defected bundles. Operational fuelling tools and guidelines based on CAFÉ did not identify these fuelling operations for special scrutiny by the station fuelling engineers.

Historically, the basis data used for the development of CAFÉ did not include power ramps at low burnups. The conditioning windows described above were imposed so as to not impair operational flexibility where supporting data was unavailable.

We chose to test the response of the documented CAFÉ methodology to the suspected defects at Darlington by removing the application windows. The results of this “open” calculation are provided in Figures 4, 5, 6 and 7.

These assessments demonstrate that a statistical fit of historical 37 element power ramp defect data would provide the expectation of high power ramp defect probabilities for some bundles which have experienced Position 2 to Position 6 shifts at Darlington. The historical applicability windows would have to be adjusted to a lower burnup. Complete removal of these windows is not supported by the data. Bundles shifted from Position 1 to 5 also experienced substantial power ramps, but these bundles did not defect. There appears to be a burnup threshold below which fuel elements are resistant to power ramps; however this threshold is lower than presently established, at least for the fuel bundles irradiated at Darlington.

Figures 4 to 7 also display parameter thresholds which are based on this OPEX and which have now been incorporated into fuelling guidelines to reduce the risks ramp defects. These are considered to be "soft" guidelines which may sometimes be violated in the interest of good core management, but in which case remedial measures will be imposed to manage subsequent power ramps and to monitor fuel condition. The following power ramp guidelines have been developed for Position 2 to 6 shifts:

- Avoid final bundle powers after the fuel shift of > 760 kW
- Avoid increase in bundle power due to the shift > 500 kW
- Avoid final to initial power ratios of > 2.6
- Avoid "open" CAFÉ' single outer element defect probability of > 0.6 percent.

The extent of this operational condition should not be overstated. Historical Position 2 to Position 6 fuelling power ramps for all Darlington units have been examined from 2000 to July 2013, and all shifts which exceeded the criteria provide above were identified. Each fuel channel is fuelled approximately every 3.5 to 4 months, so on average there would be from 40 to 50 fuellings of each of these fuel channels during these 13 years. Figure 8 displays the result of our assessment. Some fuel channels experienced a great number of these severe power ramps, yet there have been only 8 suspected power ramp fuel defects. The probability of defecting a bundle is not high; however our response to this problem has been proactive.

INSPECTIONS AND PIE OBSERVATIONS

In bay (on-site) fuel inspections have confirmed the identities of the defected bundles and elements which have been identified in Table 1, but unfortunately with the exception of 1J20 (the debris fretting defect), only secondary damage was observed and defect cause could not be assigned. This uncertainty has motivated an extensive program of post-irradiation examinations (PIE) in AECL hot-cells. These examinations are still in progress.

Although still incomplete, PIE has provided evidence that supports our assessment that high fuelling power ramps and element powers may be implicated in these fuel defects. These observations are discussed below.

The great majority of PIE completed to date has been on defected elements. Validation and benchmarking assessments on intact elements have for the most part not been completed yet. Nonetheless, concerns for safe reactor operations and management directives demand that constructive measures be taken now to reduce the impact of any adverse conditions and to reduce the risk to operations. These actions will also be discussed later in this paper.

Low Diametral Clearance – Potential for SCC Type Defect

PIE has revealed a primary defect which appears to have been caused by stress corrosion cracking (SCC) at the center line of outer element 7 of 2O19. One of the PIE sections of this defect is provided in Figure 9. It can be seen that the penetration line follows a meandering path which is typical of SCC. In this case the SCC path passes through a void in the braze eutectic, and then passes through the spacer pad material.

Other sections of the 2O19-7 defect indicate fuel pellet to sheath crowding in the radial direction (i.e. low diametral clearance) and little evidence of CANLUB. However, these observations need to be validated by examination of intact neighbouring elements and by further review of manufacturing data to examine the typical frequency of voids in the braze eutectic.

Similarly, defected element 2K14-14 showed evidence of incipient cracks on the sheath inner surface close to a bearing pad (Figure 10). The defect cause for this element has not yet been determined.

Low Axial Clearances – Potential for Endcap Crowding

PIE has provided indications that end-pellet to endcap axial clearance may be insufficient, and that pellet crowding of the endcap may be a contributing factor to these fuel defects. Unfortunately, these indications have so far been on defected elements and need to be validated via PIE on neighbouring intact elements. This supporting work has been scheduled.

Pellet crowding has been observed at both ends of elements 1O10-8 and 2O19-7 and at one end of 2K14-14 (PIE of the other end is not available). Pellet crowding in 2O19-7 is illustrated in Figure 11. In this case the fuel pellet is observed to be residing in contact with the endcap. This observation will be validated by PIE on an intact neighbouring element.

Evidence of pellet crowding in 1O10-8 is illustrated in Figure 12. In this case there are accompanying indications that these conditions may have led to hydride migration and propagation of a weld artefact notch, similar to previous experience at Ontario Hydro in the mid 1980s at the Bruce A station (Figure 13). These historic defects were assessed to have been the result of endcap crowding and the resulting strain in the endcap weld. In that case elements failed due to hydride migration to the stress riser at the weld notch. The fuel manufacturer for these historic defects and the manufacturer of the Darlington fuel are not the same. In this Darlington PIE data the evidence is complicated by the occurrence of secondary deuteriding in the same notch. Unfortunately the intact neighbouring elements which accompanied this shipment for PIE have been disposed and are no longer available for validation examinations. We will not be able to clarify these observations by further PIE, however we will examine high mass unirradiated bundles to provide some clarity regarding these conditions.

High Fuel Powers and Temperatures

PIE of elements 2O19-7 and 1J20-9 has revealed extensive columnar grain growth in the fuel pellet and the formation of central voids. These examinations were performed in areas close to areas of secondary damage. Comparative examinations at the undamaged parts of the elements or on intact neighbouring elements were not performed or were not available.

Extensive fuel grain growth and void formation is an occasional observation in defected fuel elements, and is thought to be aggravated by fuel oxidation and reduced thermal conductivity of the fuel pellets. However, these observations can also be indications of high operating powers and require validation via PIE on intact neighbouring elements. These examinations are scheduled.

OTHER FACTORS

Fuel Design and Fuel Manufacturing

The OPG specification for the axial gap is 1.5 mm (nominal), with a range from 1.0 to 3.8 mm. This represents the “total” axial gap inside the fuel element, excluding the pellet dishes. The bases for this specification are the requirements to provide sufficient room for fuel stack expansion during irradiation, while limiting the size of the gap to preclude sheath collapse when the fuel bundles are loaded into the pressurized heat transport system.

The nominal element diametral clearance is specified to be 0.08 mm, with a range of 0.03 to 0.15 mm. This specification leaves the actual minimum diametral clearance uncertain and dependent on the specifications for sheath outer diameter, sheath thickness, CANLUB thickness and pellet outer diameter. In the OPG specification the actual diametral clearance is permitted to be chosen by the manufacturer to facilitate loading of pellets into the sheath.

OPG is taking actions to review the design specifications for axial clearance and diametral clearance to ensure that adherence to these will result in the production of fuel with clearances which are adequate to the irradiation conditions at Darlington. The OPG specification for the braze quality will also be assessed. Concurrently, OPG will be reviewing manufacturing processes and records to confirm that bundles with adequate clearances are being manufactured.

It is of interest that all defected bundles have been of the long bundle variety. These bundles are 12.7 mm longer than the standard length bundles used at Darlington. Examinations of uranium mass data provided by the manufacturer on shipment records provide some evidence regarding this observation. Note, these data provide average bundle uranium masses calculated on a pellet lot basis so they do not represent individual bundle masses, however these should provide reliable trends if taken on a shipment basis.

Figure 14 provides uranium masses for standard and long bundles on a shipment basis. These trends indicate that the uranium masses of long bundles have increased over the past decade, where the masses for standard length bundles have stayed approximately constant. If fuel pellet stack lengths are calculated using design centered values, this increase in Uranium mass is equivalent to approximately 0.7 mm, or approximately 70 % of the minimum axial clearance specified by OPG.

OPG is presently conducting a more thorough investigation of individual bundle mass records. The objective of this investigation is to determine if there is a reliable correlation between bundle mass increases and the Darlington fuel defect experience.

Adjuster Configuration and Age

A contributing factor to the occurrence of fuel defects may be local flux increases and the resulting bundle power increases in the locations of adjuster rods which have been locked out-of-core since the early days of Darlington operation. The severity of fuelling power ramps are assessed to have increased when these 8 adjusters were removed from core. Nonetheless, Darlington operated almost defect free for many years after the adjuster reconfiguration in the late 1990s. Assessments conducted in support of the reconfiguration revealed a large margin between the anticipated Darlington fuelling power ramps and power ramps which had been successfully experienced during the early years of operation of the unadjusted Bruce A reactors. However, it is reasonable to suggest that other factors such as low as-manufactured internal clearances may now be making these fuel bundles more susceptible to high bundle powers and power ramps.

Figure 15 displays the configuration of the vertical reactivity devices of a Darlington reactor. The identities of the 8 adjuster which have been locked out of core are indicated. Also indicated are the locations of the fuel channels from which defected bundles have been discharged. There appears to be a correlation between the locations of the defect channels and the locations of the missing adjusters. The strongest correlation is between columns 19 and 20, from which both AA8 and AA24 have been locked out of core, and defects discharged from channels 1J20, 1L20, 2L20 and 2O19. Defect channels 1O10, 1F15, 2K14 and 4V12 are adjacent to locations where single adjusters have been removed. Only defect channel 4K08 is not directly adjacent to the location of a missing adjuster, however it is only separated from such a location by one lattice pitch.

The adjusters in the Darlington reactors have been in use since the reactors were first commissioned. Recent analyses indicate that in the worst case, adjuster reactivity worth may have decreased by up to 16 percent due to these extended irradiations. These estimates are scheduled to be validated later this year when the reactivity worth of all in-service Unit 2 adjusters will be directly measured. The impact of these reactivity changes on bundle powers and fuelling power ramps is being evaluated. Although the impact is anticipated to be small, a non-trivial impact is none-the–less anticipated. Additional work is planned after the adjuster reactivity measurements become available.

CONCLUSIONS

An extensive review has been conducted of factors that may have contributed to the recent occurrence of fuel defects at Darlington. Although a definitive single cause has not been identified, there exists an accumulation of evidence linking this adverse OPEX to the following:

- A degradation in the margin to power ramp failure due to one or several of the following design / manufacturing factors:
    - Increased uranium masses in long bundles.
    - Insufficient axial clearances.

  - Insufficient radial clearances and related issues with the quality of the CANLUB coating.
  - Voiding in the braze eutectic.

- An increase in the severity of power ramps during routine fuelling operations due to the removal of 8 adjusters from each reactor. Although this change was made close to 20 years ago, a drift in manufacturing tolerances as demonstrated in bundle mass trends and internal clearance issues may now be making these fuelling ramps problematic.
  - A degradation of the reactivity worth of the adjusters due to prolonged irradiation may be contributing to this issue.
- Inability of the CAFÉ based predictive tools in use by the Darlington fuelling engineers to calculate defect probabilities for the atypical low burnup power ramps which have been found to be of concern at Darlington.

RECOVERY PLAN

The mandate of this investigation was to determine a path forward to the restoration of fuel performance at Darlington to the required “zero defect” standard. Although important supporting investigations remain in progress (mainly PIE, fuel inspections and manufacturing related), a detailed recovery plan has been developed and is now being implemented at Darlington.

Although OPG will take the lead for execution of this recovery, the remediation plan will require the efforts and involvement of a number of important other groups including the fuel manufacturer and AECL hot-cells.

The recovery plan has the following main components:

Short Term

- Modification of the new fuel loading rules to avoid putting long fuel bundles in position 2, when possible. To support unavoidable long fuel bundle loading into position 2:
  - Ensure subsequent fuelling of the channel is planned to limit the power ramp of the bundle to an acceptable level, where possible.
  - Develop guidelines to restrict long bundles with highest uranium masses from being loaded into position 2.
- Review of current fuel loading of all units to identify high uranium mass long bundles which have been loaded into position 2 and limiting of subsequent power ramps where necessary.
- Implementation of detailed pre-simulation guidelines for Fuelling Engineers to avoid most severe power ramps for fuel bundle movement from position 2 to position 6. This will include use of the existing CAFÉ with modified burnup applicability windows.

Medium Term

- Assessment of the impact of adjuster reconfiguration and reactivity degradation.
    - Measurement of adjuster reactivity worth at the next planned outage.
    - Assessment of the impact of restoring a 24 adjuster configuration.
- Review and revision of the OPG fuel design specifications; evaluation of manufacturer compliance for:
    - Fuel pellet to endcap axial clearance.
    - Fuel pellet to fuel sheath diametral clearance.
    - Quality of the braze eutectic.
- Destructive and non-destructive examinations of selected high Uranium mass long bundles to determine pre-irradiation / as-manufactured condition.
- Completion of PIE tasks which are needed to support this assessment including:
    - Benchmarking examinations of intact elements which were adjacent to the defected elements.
    - Examinations of recently discharged defected elements for root cause determination.
- Reassessment of the CAFÉ correlation to include the recent Darlington experience, including reassessment the burnup applicability windows.

Long Term

- Equipping the Darlington East irradiated fuel bay with a fuel inspection facility and inspection of the suspect fuel bundles from 1L20 which are stored there.
- Investigation of the feasibility of installing modern inspection facilities at Darlington so that more detailed examinations may be performed on-site without the need for irradiated fuel shipments.
- Investigation of the economic and operational benefits of restoring Darlington reactors to a 24 adjuster configuration.
- Repair / refurbishment of the GFP and the feeder scan defect identification systems.

REFERENCES

This paper draws from a recent internal Ontario Power Generation report which extensively references internal documentation. Some of this material may be available externally or may be available for release if requested.

Table 1: Defected Fuel Bundles, Irradiation Dates, Shipment Dates

Unit / Channel	Unit 1 Chan O10	Unit 1 Chan L20	Unit 2 Chan O19	Unit 4 Chan K08	Unit 1 Chan J20	Unit 2 Chan K14	Unit 4 Chan V12	Unit 1 Chan F15	Unit 2 Chan L20
Bundle Type	37R long	37R long	37R long	37R long	37R long	37R long	37R long	37R long	37M long
Defect Element Number	8	NA	7	13	9	14	4	26	15
Discharge Position	10	10	10	10	6	10	10	10	10
Date of 1st Defect Indication	16 Jun'07	8 Sep'07	22 Apr'10	11 Oct'11	9 Aug'11	21 Oct'11	10 Mar'12	31 Mar'12	4 Apr'13
Time from 2-6 shift to defect indication (days)	162	142	78	123	0 (debris)	102	120	172	165
Load Date to Pos. 2	4 Aug '06	10 Jan'07	25 Sep'09	14 Mar'11	27 May'11	18 Apr'11	24 Jun'11	6 Jul'11	25 Jun'12
Shift Date to Pos. 6	5 Jan '07	19 Apr'07	3 Feb'10	10 Jun'11	10 Aug;11	11 Jul'11	11 Nov'11	11 Oct'11	22 Oct'12
Shift Date to Pos. 10	11 Jun'07	14 Sep'07	26 May'10	11 Oct'11	NA	18 Nov'11	24 Feb'12	20 Jan'12	30 Jan'13
Discharge Date	1 Oct'07	1 Dec'07	6 Nov'10	27 Oct'11	13 Sep'11	2 Feb'12	2 Jun'12	10 May'12	15 May'13
Shipment Date for PIE	Jan. 2008	NA	Oct. 2011 May 2013	July 2012	July 2012 May 2013	July 2012	May 2013	May 2013	NA
Elements Shipped	7, 8, 9, 23	NA	7 (2011), 6 (2013)	13, 14	9 (2012), 10 (2013)	13, 14	3, 4	25, 26	NA

Figure 1: Irradiation histories and post-defect residence times

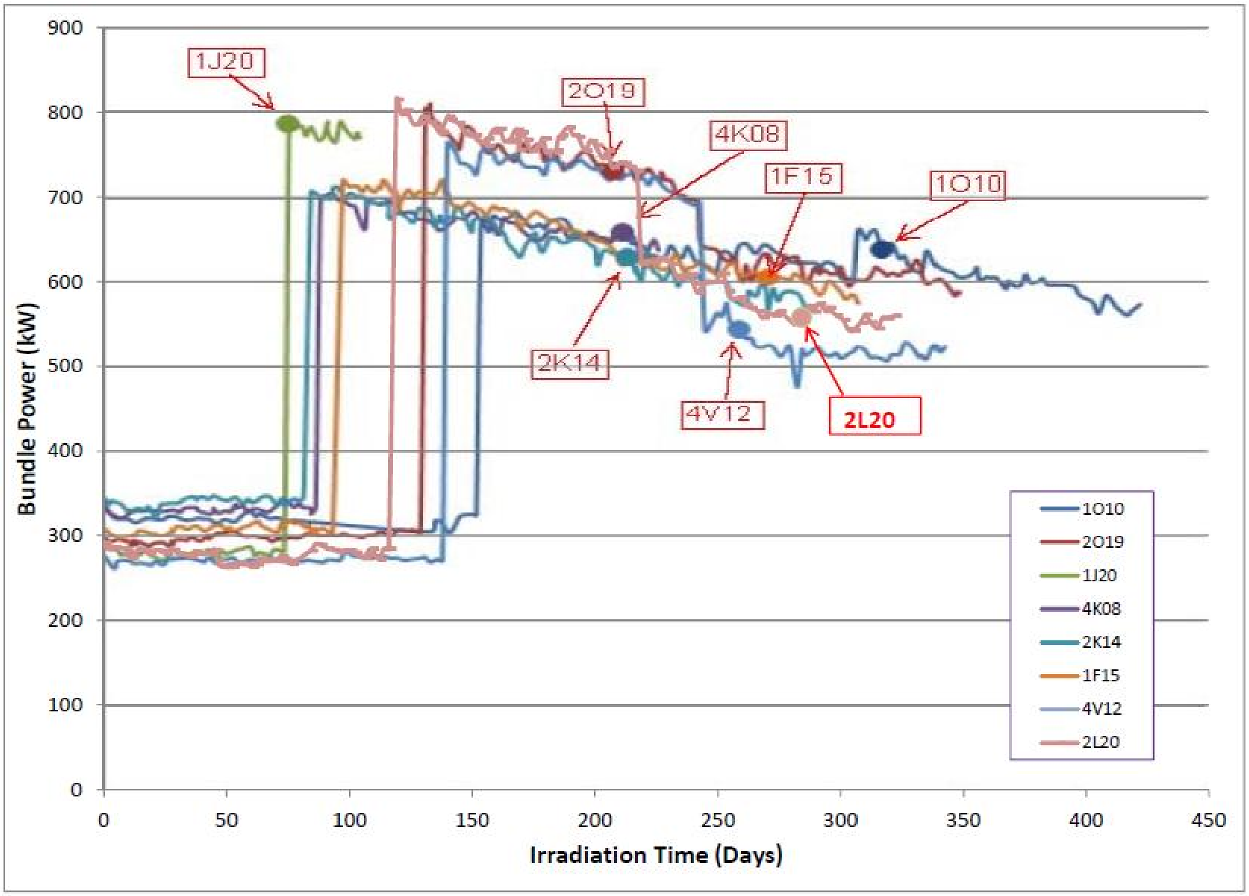


Figure 2: Timeline for occurrence of fuel defects at Darlington

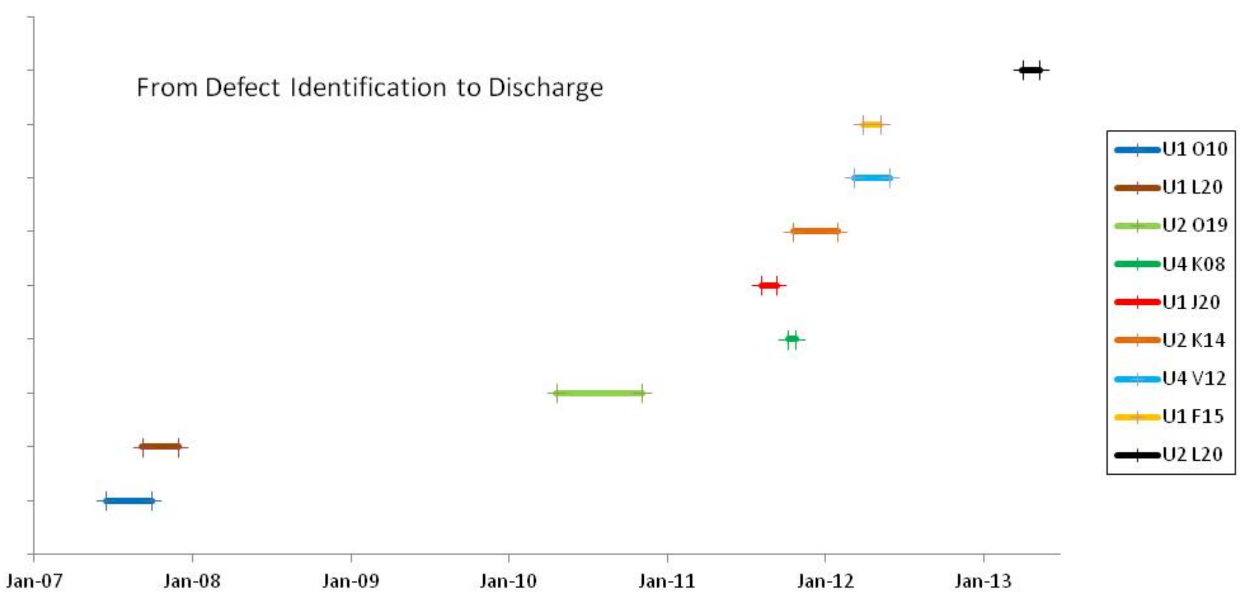


Figure 3: Fuelling power ramps

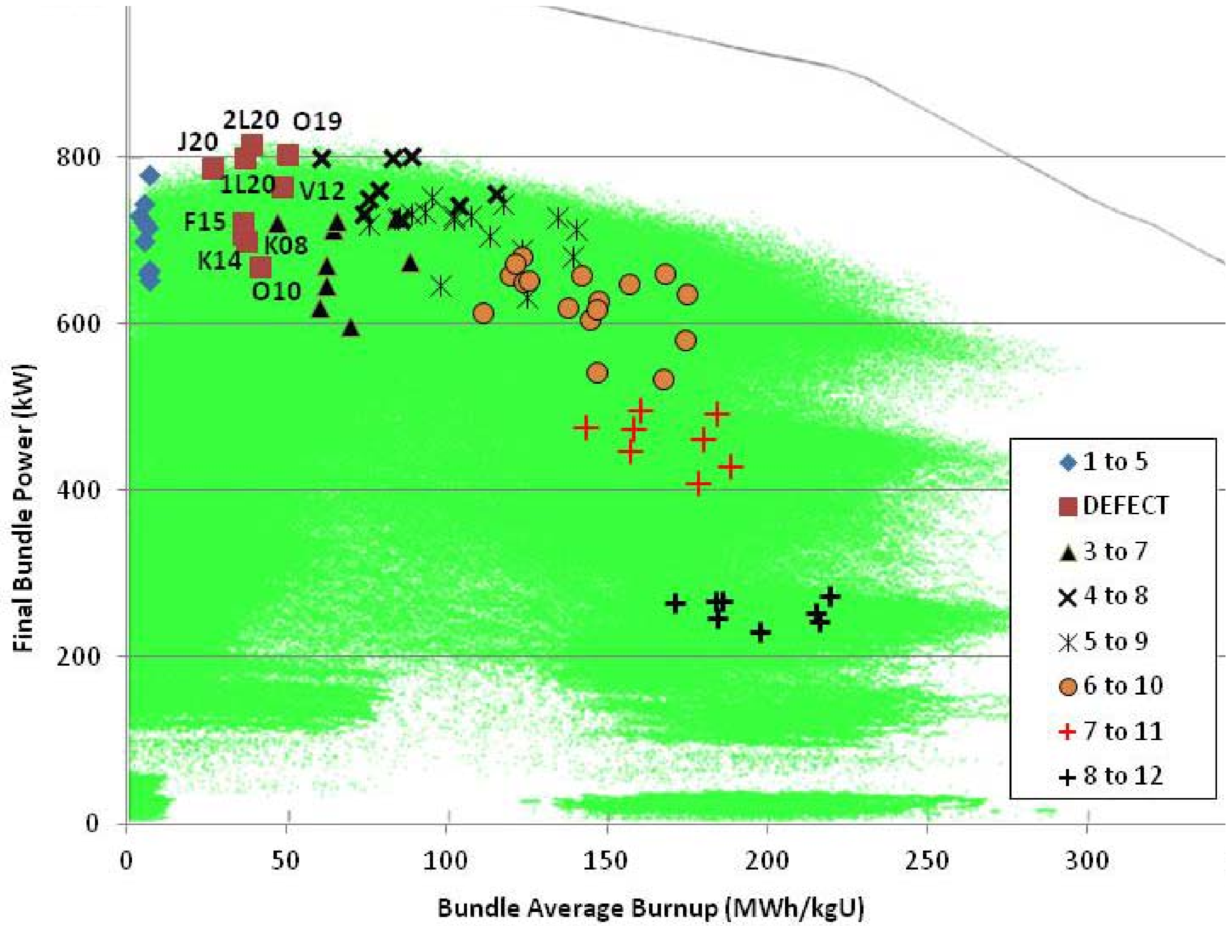


Figure 4: Bundle average burnup vs. “open” CAFÉ outer element defect probability

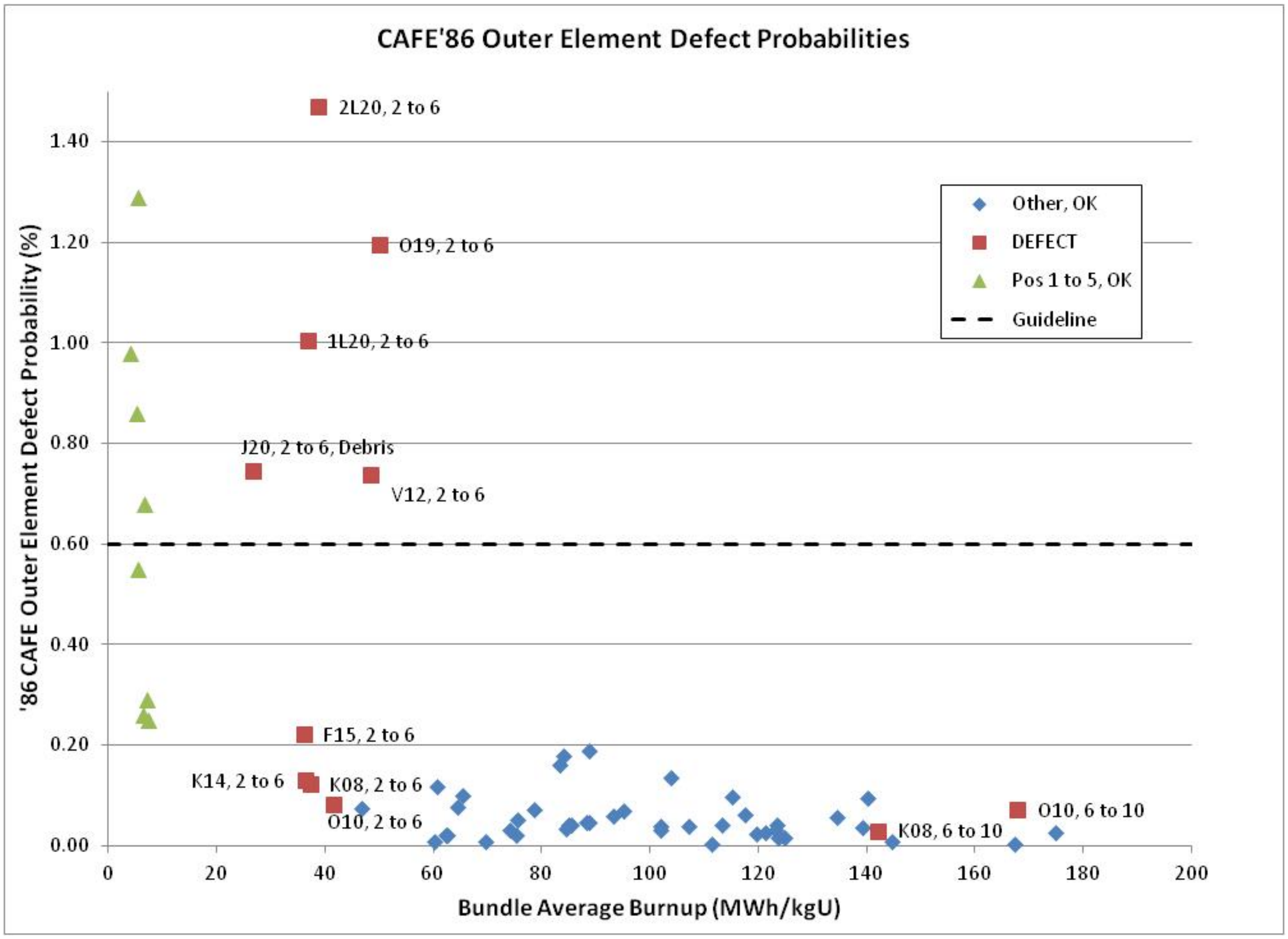


Figure 5: Final bundle power vs. “open” CAFÉ outer element defect probability

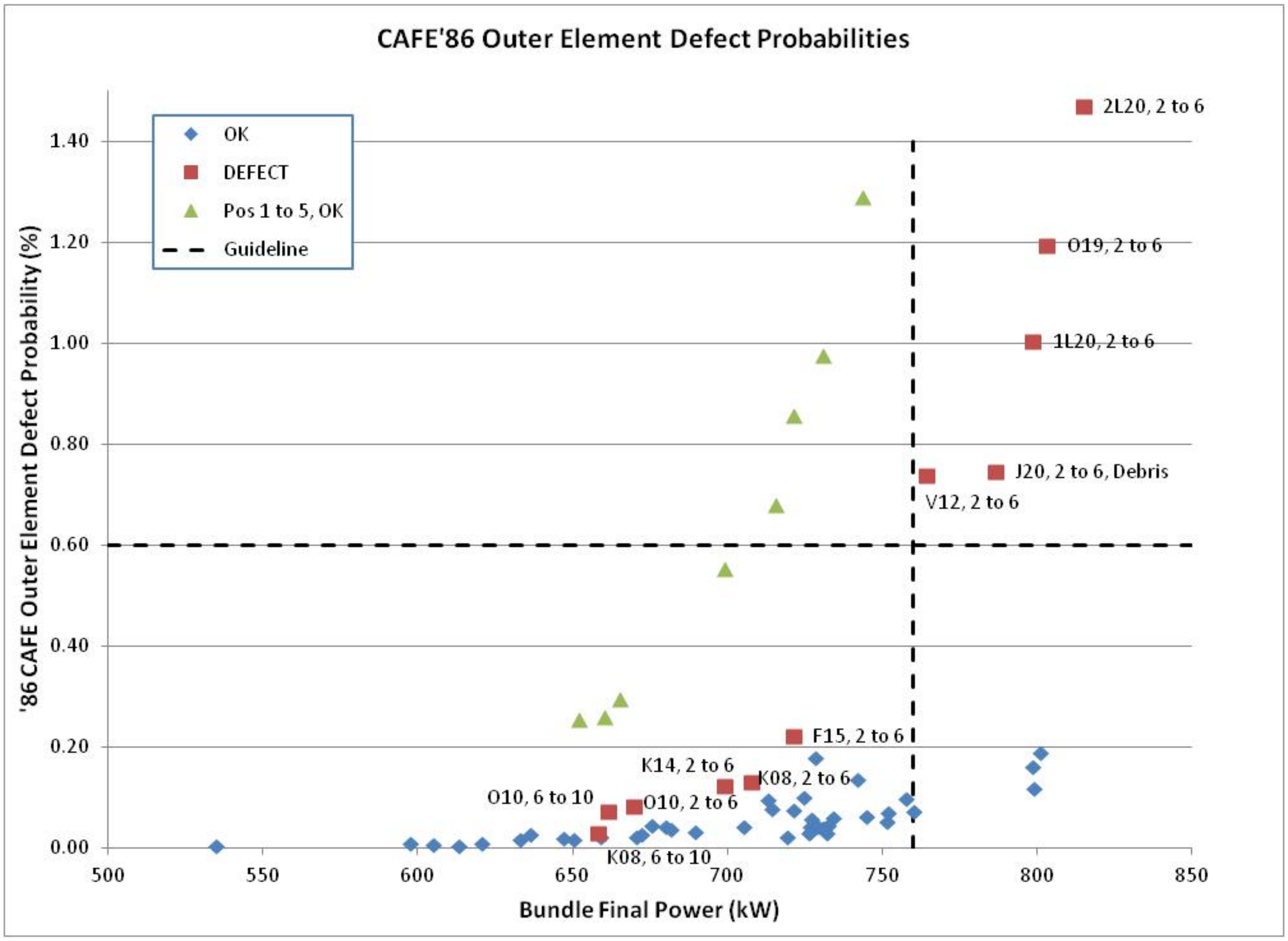


Figure 6: Bundle power increase vs. "open" CAFÉ outer element defect probability

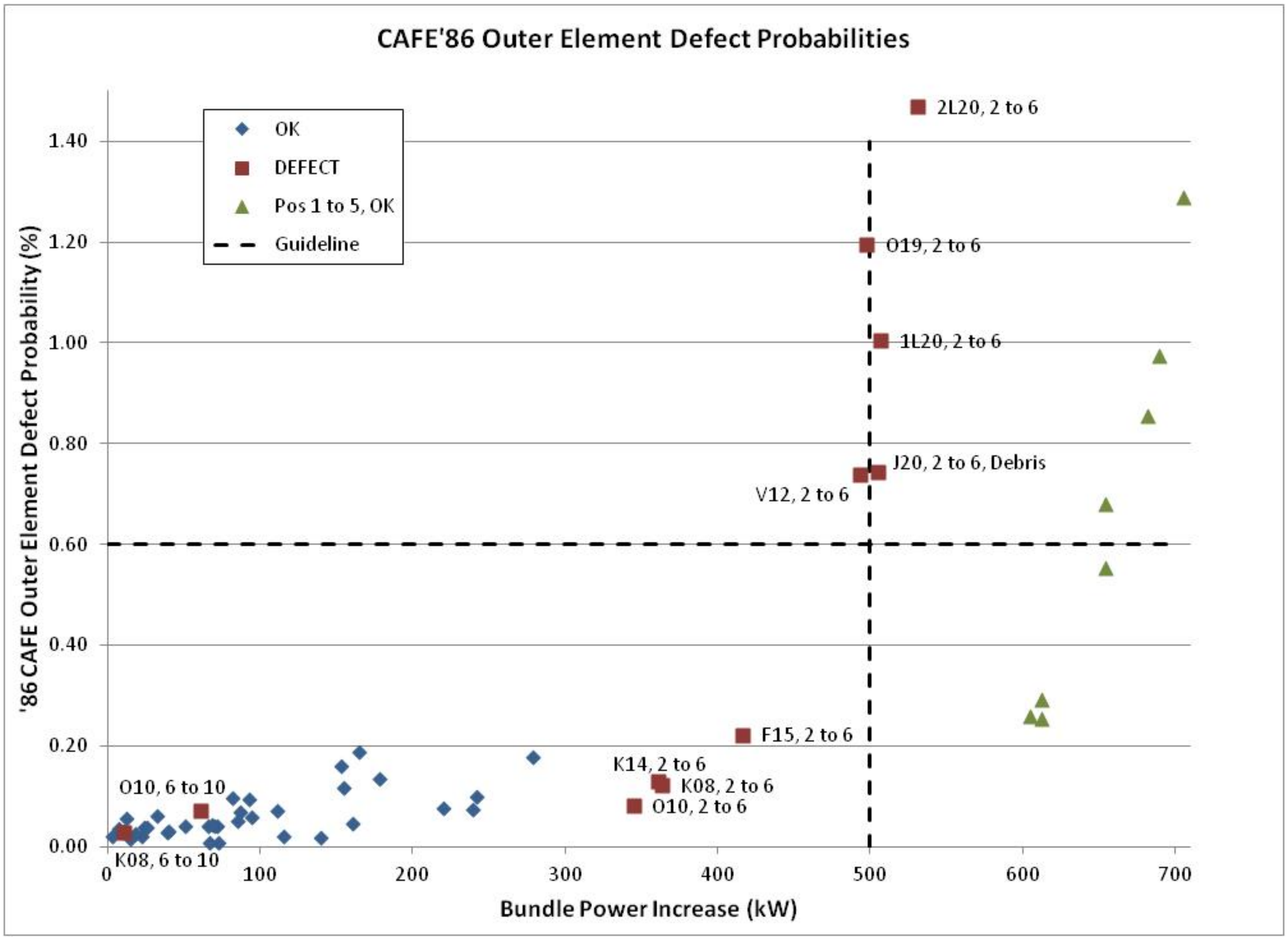


Figure 7: Final to initial power ratio vs. "open" CAFÉ outer element defect probability (excluding Position 1 to 5 shifts)

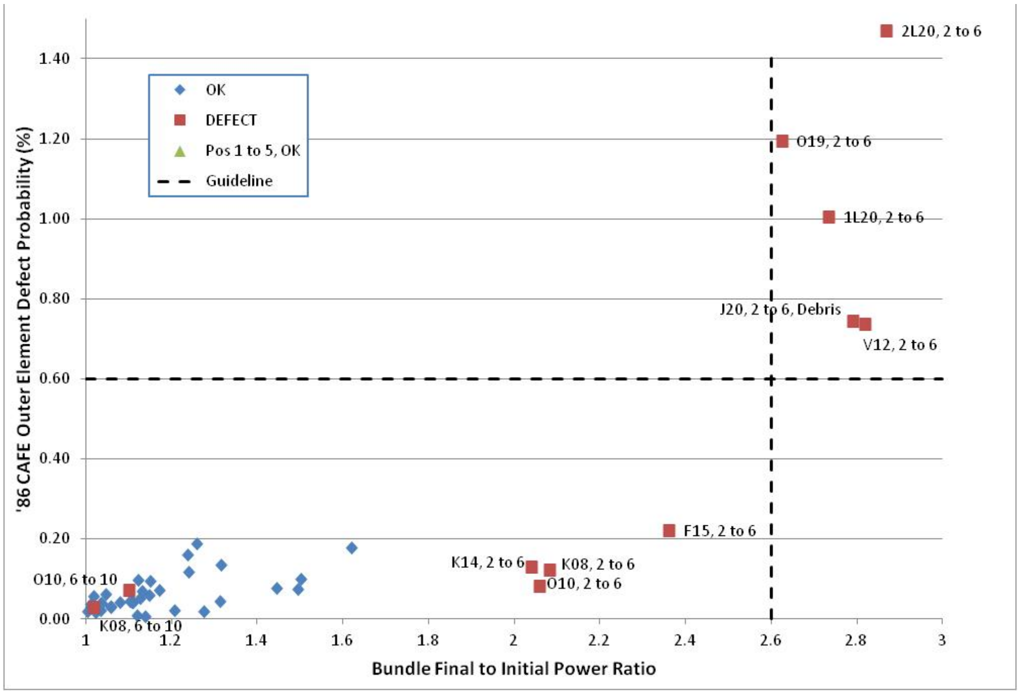


Figure 8: Frequency of fuellings which exceeded Position 2 to Position 6 ramp guidelines since 2000

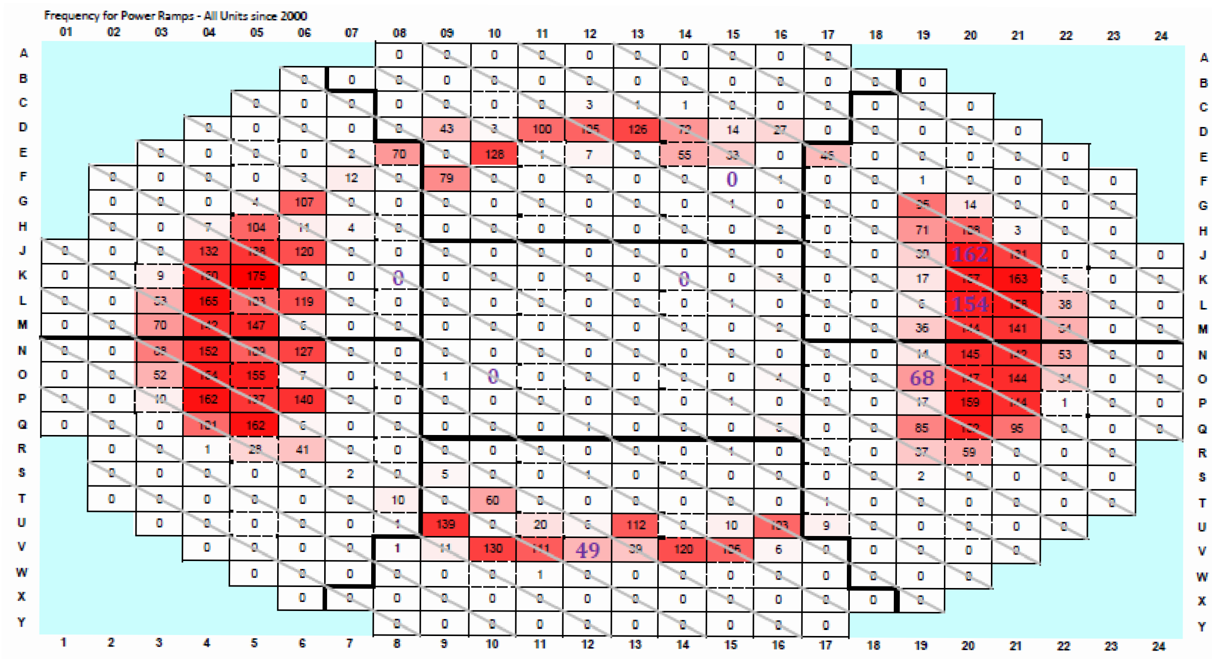


Figure 9: Possible SCC penetration at spacer pad on outer element 7 of 2O19

Figure 10: Possible incipient cracks on the sheath inner surface close to a bearing pad of 2K14 element 14

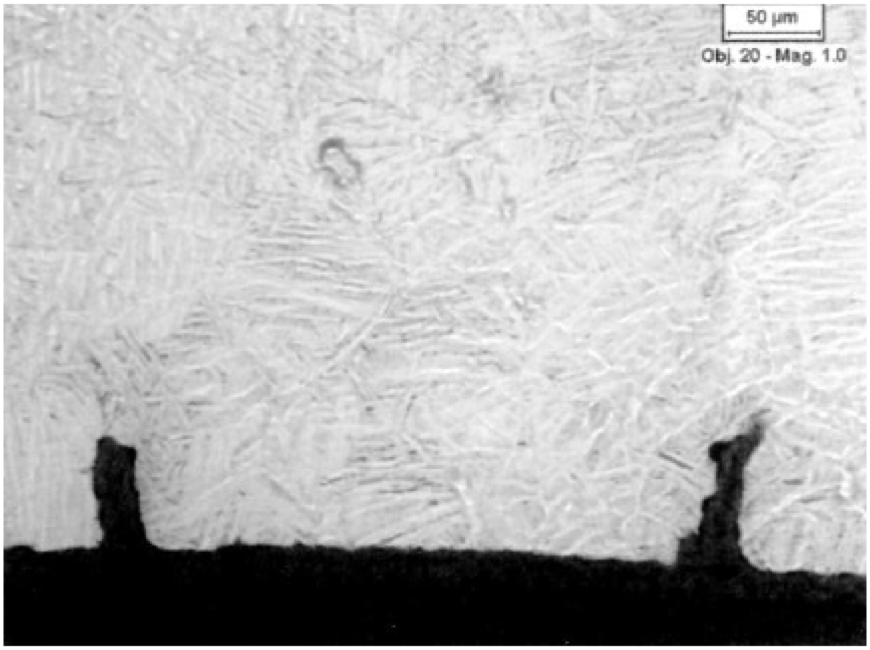


Figure 11: Pellet to endcap crowding in 2O19-7

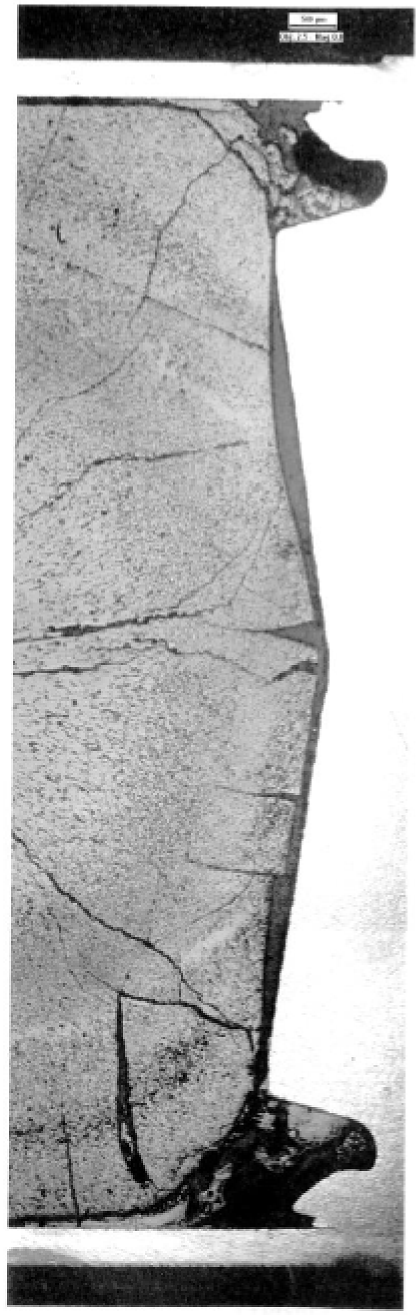


Figure 12: Contact of fuel stack with endcap in 1O10-8

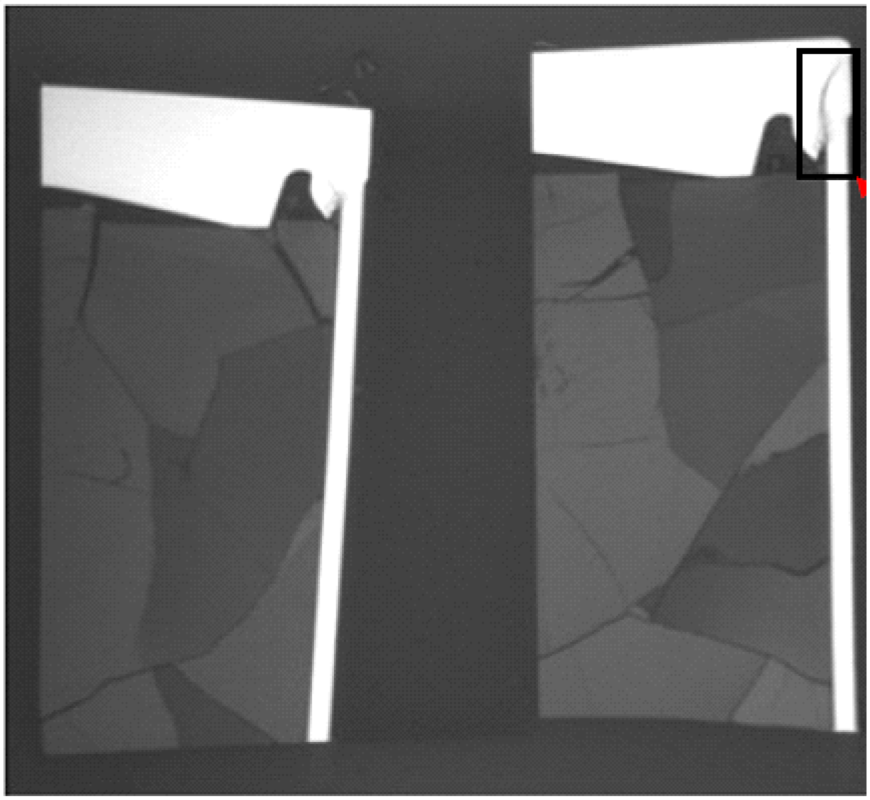


Figure 13: Circumferential cracking in 1O10-8

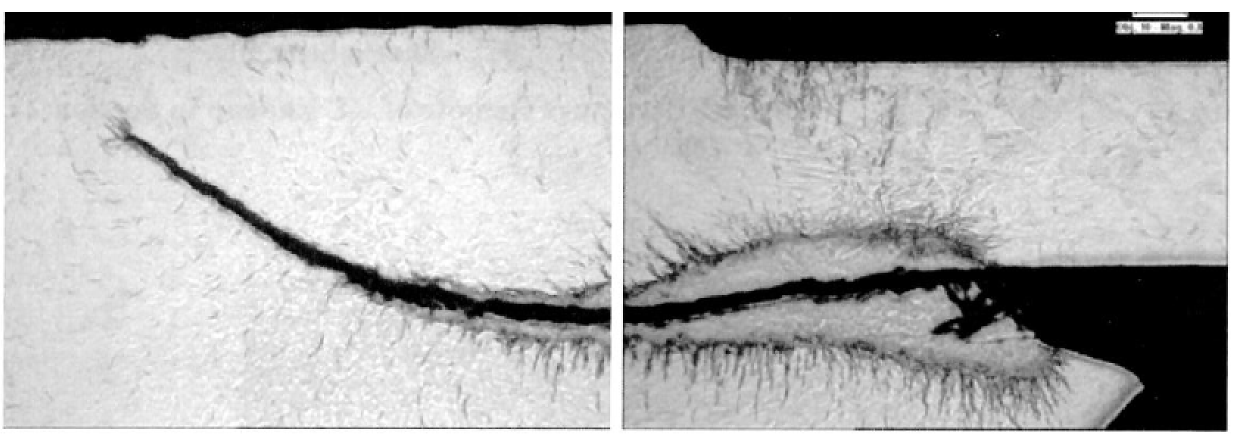
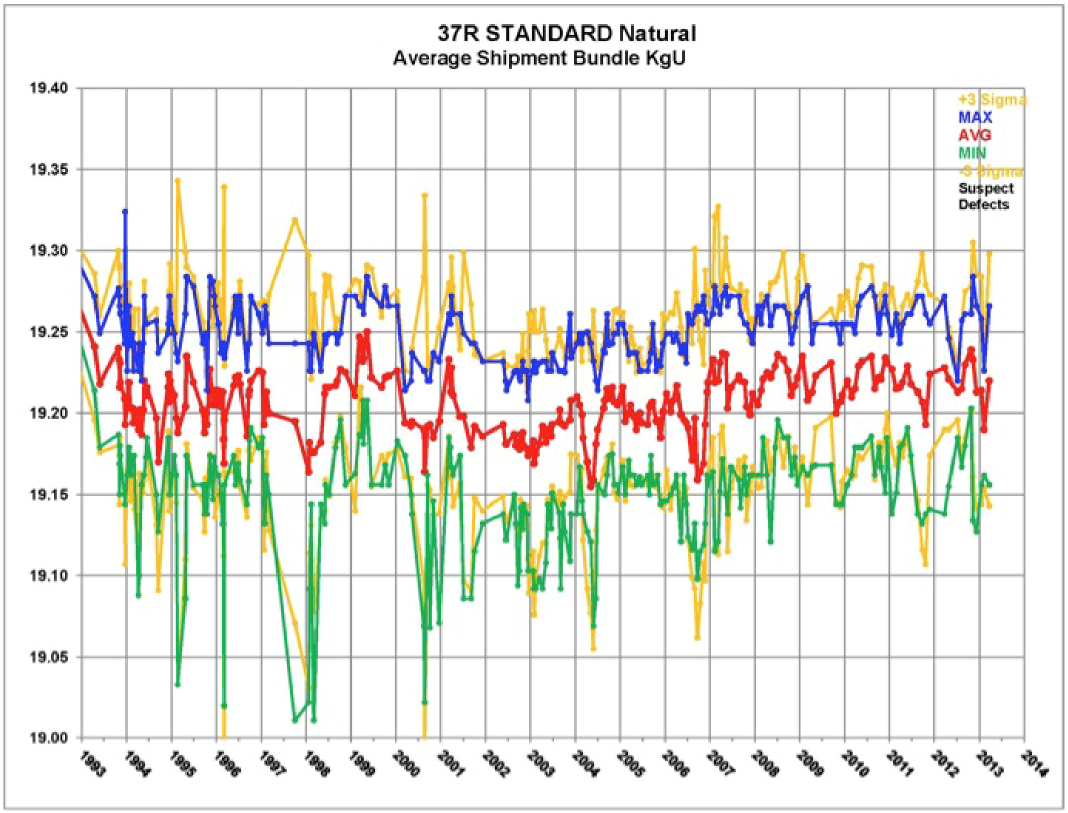


Figure 14: Bundle shipment Uranium masses for standard and long bundles



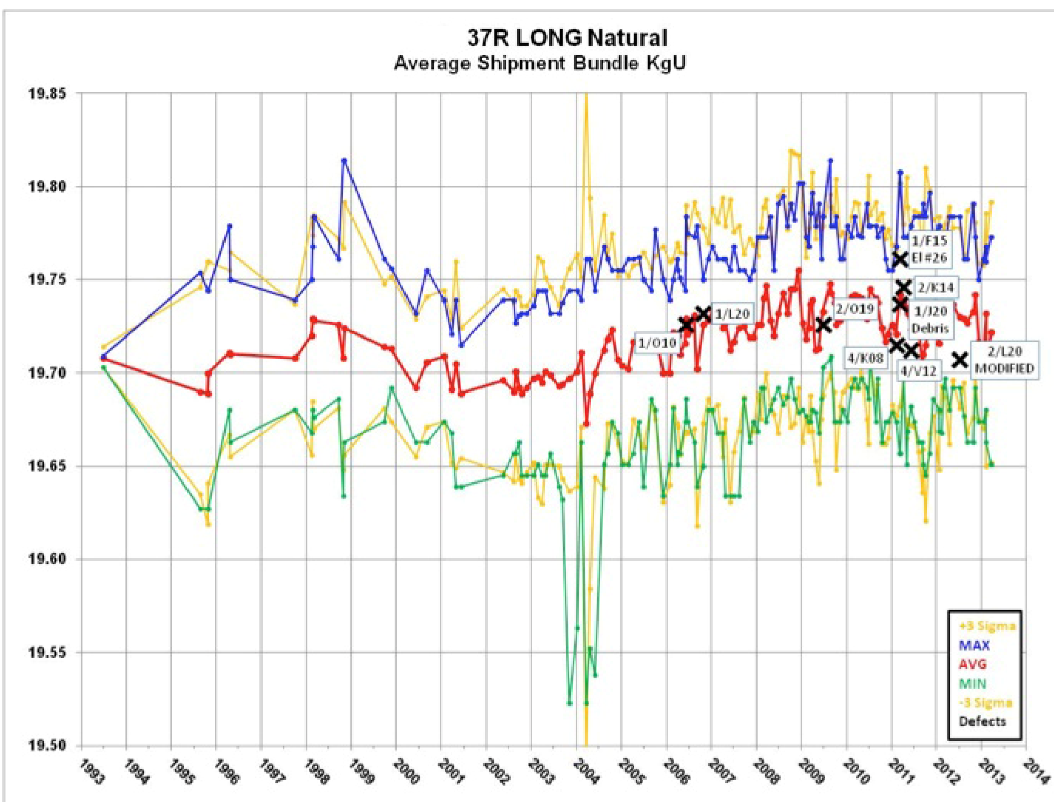


Figure 15: Top view of Darlington reactivity mechanisms showing locations of locked-out adjusters