DARLINGTON N12 EVENT INVESTIGATION: UNIT 1 & 2 FUEL AND FUEL CHANNEL INSPECTIONS

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IN-REACTOR FUEL OBSERVATIONS

On 30 November 1990, a routine recycle fueling operation was attempted on channel N12 of Darlington Nuclear Generating Station Unit 2 (DNGS-2). This involved the insertion of a fuel carrier containing two low burnup bundles from channel Y08 into N12. Only a partial insertion could be achieved, and the refueling operation was aborted. Installation of a maintenance cap on the N12 channel endfitting in late December allowed recovery of the fueling machine from the reactor.

By January 12, the contents of the affected fueling machine had been discharged to the irradiated fuel bay, and the underwater inspection of the fuel and fuel carrier was complete. The inspection identified fragments of fuel elements embedded in the leading end of the fuel carrier containing fuel bundles #12 and #13 from Y08. The Y08 fuel was deformed from the fragments but otherwise intact. This indicated that the #1 bundle from channel N12 had either "slipped" through the latch or had "come apart" in-service. Removal of the shield plug during the refueling operation then allowed washout of the damaged N12 fuel into the end-fitting, where it was fragmented during the attempted insertion of the fuel carrier containing recycle fuel from Y08.

Following the discovery of damaged fuel from D2N12, extensive fuel and fuel channel inspection and examination programs were undertaken.To 01 March 1992 we have done:

- in-situ video inspections of: 45 DNGS-2 and 12 DNGS-1 bundle #1 (latch) endplates, and the D2N12/13 inlet endplate,
- in-bay inspections of more than 323 bundles representing 58 DNGS-2 channels, and 399 bundles from 116 DNGS-1 channels,
- in-bay inspections of 8 BNGS-B bundles from 5 channels,
- in-bay disassembly of 21 bundles,
- hot-cell examinations of 33 complete bundles, 15 elements from 8 other bundles and 1 fragment,
- CIGAR inspection of 4 DNGS-2 pressure tubes, and
- removal of D2K13 fuel channel.

Figure 1 for DNGS-2 and Figure 2 for DNGS-1 show core maps of: channels given in-situ video inspections, channels from which fuel has been inspected in-bay, and channels from which fuel has been examined in the hot-cells.

FUEL DAMAGE CHARACTERIZATION

The following summarizes the most significant fuel damage observations and results obtained from the in-bay fuel inspections and hot-cell examinations, to 01 March 1992.

Endplate Cracking

The first indication of fuel damage from DNGS-2 came from the in-bay inspection of the fuel fragments removed from channel D2N12. In-situ video inspection of position #1 latch endplates quickly identified bundle D2Q12/01 as having one complete crack, and D2K12/01 as having many cracks.

The first DNGS fuel shipment for hot-cell examination consisted of the largest D2N12 fragment and the position #13 bundle from D2J12 high flow channel. This selection was made because the fuel was already available in the bay. The second DNGS shipment was D2Q12/01. It was selected on the basis that a lesser damaged bundle would give clearer information on primary defect cause; whereas the more dramatically damaged D2K12 bundle would likely have significant secondary damage effects.

The D2Q12/01 bundle had one complete crack and two partial cracks in the downstream endplate, all three cracks occurred at the intersection of the three main radial webs and the intermediate circumferential web. During bundle disassembly in the hot cells, two partial cracks were also found in the upstream endplate on the inner circumferential web. Figure 3 shows the schematic location of all these cracks. Scanning electron microscopy (SEM) of the D2Q12/01 crack fracture surface quickly identified the failure mode as low amplitude/high cycle fatigue.

The third DNGS shipment was bundles D2Q12/02 and D2Q12/13 to scope possible fuel damage along the channel. The fourth DNGS shipment was D2K12/01 and D2K12/02, to confirm initial examination results on the more extensively damaged D2K12 fuel.

To 01 March 1992, the Darlington fuel damage investigation has shipped and examined: 19 DNGS-2 bundles, 8 DNGS-1 bundles, 4 BNGS-B bundles, 15 elements from 8 other DNGS-1 bundles, and one fragment from D2N12.

Most cracks initiate on the inner endplate surface near the endcap to endplate resistance weld notch, which is a localized high stress area. In addition, in every channel with cracked fuel, the position #1 bundle has at least one crack at the radial and intermediate web intersections of the downstream endplates. Therefore, these high stress areas are likely the critical locations to crack first. A detailed discussion of the fuel examination fractography results is given in (1).

Spacer Pad Wear

The fragment from D2N12 was the first DNGS fuel examined in the hot-cells at AECL-CRL. The SEM results indicated that the failure mode was due to fatigue by vibration. At the time, the stereo microscope examination of D2J12/13 was just being completed. It was decided to disassemble this bundle to look for any evidence of vibration effects. Significant spacer wear was observed.

Historically, fuel bundle examinations focused on fuel failure root causes, or characterization of fuel discharged as part of the normal operating routine. As a result there was little available wear information on any initial load fuel, to compare with the D2J12/13 spacer wear results. To derive comparison data six BNGS-B Unit 6 first charge bundles were retrieved and partially disassembled in the bay, and two of the remaining partial bundles were shipped for detailed hot-cell examination. These BNGS-B first charge bundles showed approximately the same amount of spacer wear as D2J12/13.

Hot-cell bundle disassembly and spacer pad wear maps became a standard part of the DNGS fuel examination program. Bundles: D2Q12/13, D2K12/13, D2K12/08, D2K12/02, D2K12/01 and D2K13/13; all showed extreme spacer wear. These bundles all had at least one pair of spacer pads with enough wear to allow contact between a spacer pad and the sheath of the adjacent fuel element.

The spacer wear distribution is shown in Figures 3 and 4 for D2Q12/01 and D2Q12/13. The "black dots" are each spacer pair where at least one pad had sufficient wear to give full surface contact with the adjacent pad. In bundle position #1, the wear is predominantly between the inner and intermediate element rings. In position #13 the wear is still primarily between rings of elements (inner to intermediate and intermediate to outer); but the wear is more widespread throughout the bundle.

In general, between elements on the same ring the spacer pad wear was rough, and under SEM examination showed evidence of transverse motion. Between elements on adjacent rings the wear damage was much smoother and showed evidence of combined axial and transverse motion. This implies that within these bundles the rings of elements were moving with respect to each other, whereas elements on the same ring interacted through transverse motion. Detailed results are presented in (2).

Bearing Pad Wear

Three channels in DNGS-2 (four bundles) have been observed to have severe bundle position #13 wear on the upstream outboard bearing pads:

- D2K12/13 (initial load),
- D2K13/13 (initial load),
- D2K13/13 (second residence, shifted from D2K13/09), and
- D2J13/13 (initial load).

The upstream outboard bearing pads on the initial load bundle #13 in each of these channels have been completely worn away to the fuel sheath (100% "step"), on sequential outboard bottom bearing pads. The second residence bundle in D2K13/13 had two outboard bottom bearing pads with a 50% "step" worn away in approximately five weeks of operation. These three channels also contained the most extensively cracked fuel in downstream locations. This wear occurs as a result of relative motion between the inlet fuel bundle and the stainless steel spacer sleeve support at the end of the pressure tube. The worn bearing pad then displays an easily seen "step" when viewed in profile.

There are a number of distinct wear areas on the severely worn bearing pads. The direction of motion in each area is different, ranging from almost axial to almost transverse. In these cases of severe wear, the bundle motion is complex and varied (2).

As part of the fuel inspection program, observations of full face bearing pad wear are noted and recorded. In general, full face wear is more frequent at the channel inlet and decreasing in the downstream direction. In-bay inspections and hot-cell examination of selected elements indicate that bearing pads which do not interact with the inlet spacer sleeve do not have a significant amount of material worn away.

Endplate Wear

Endplate to endplate wear of discernible depth has been observed in both DNGS-2 (channels 2K12, 2K13, 2J13, 2Q12 AND 2H11) and DNGS-1 (channel 1H13). In general, the heaviest endplate wear is found on bundles near the outlet end of the channel, occurring primarily on the inner circumferential and radial webs. The channel inlet bundles tend to have a more evenly distributed wear pattern.

Endplate "Doming"

In the DNGS and BNGS channel the fuel string is held in place by fuel latch. The latch fingers support most of the outer elements of the position #1 bundle. The support areas are the downstream outermost endcap surfaces. The endplates and non-outer elements are not directly supported. Large drag forces act on all bundle components in the downstream direction. With time, the position #1 bundle will tend to change shape to a "domed" (convex) downstream endplate and a "dished" (concave) upstream endplate. This phenomenon will affect all other bundles to a lesser extent.

The downstream endplates of DNGS-2 position #1 bundles are domed by up to 1.6 mm. (This value is similar to that measured on BNGS-B position #1 fuel). Lesser doming has been measured on bundles from other DNGS-2 channel positions. No doming has been observed on DNGS-1 position #1 fuel. It is possible that the apparent difference in doming characteristics between DNGS-2 and DNGS-1, may be due to small manufacturing differences between fuel suppliers.

FUEL METALLURGICAL EXAMINATION

A total of 27 DNGS bundles have been shipped for hot-cell examination. To investigate the crack fracture surfaces, the bundles are first given a detailed visual inspection. Then the visible fracture surfaces are photographed, and peel tests are performed on the most susceptible welds to look for incipient cracks. These welds are those close to the intersection of radial; and circumferential welds.

A total of 68 fractures have been identified. In general the crack initiation site is associated with the location of element to endplate welds. The spigot at the end of the element is attached to the endplate by a resistance weld. As part of the welding process, a notch is formed between the spigot and endplate. All but three of these fractures initiated near, but not at, the tip of the weld notch.

The cracks showed (1) fatigue striations, typically less than one micron, and little evidence of shear lips. These observations are consistent with low amplitude high cycle fatigue cracking occurring at stresses just above the fatigue limit. The surface roughness of the DNGS fractures were compared to fatigue specimen fractures and again indicated that the fractures occurred near the fatigue stress limit. In most cases beachmarks are seen on the fracture surfaces, indicating some change in the fatigue conditions with time. In a few instances crack arrest marks were seen, where cracks have stopped progressing for sometime then restarted. The complete cracks generally propagated from the inner to the outer endplate surface. The direction of crack propagation was usually along a curved path which did not conform to typical microstructural boundaries.

Many fracture surfaces have had oxide thicknesses measured by Fourier Transform Infra-Red (FTIR) spectroscopy, with checks using standard metallography. In almost all cases there is a significant oxide layer of uniform thickness, indicating that the cracking progressed quickly as compared to the oxide build-up. There is some uncertainty in the time estimates due to the non-linear growth characteristics of the oxide layer.

PRESSURE TUBE FRETTING

Following the observation of extreme bearing pad to spacer sleeve wear in some DNGS-2 bundles in position #13, pressure tube inspections were performed to identify fret marks using CIGAR ultrasonic probes. The results are summarized as follows:

- D2K13 was inspected at the last two inlet bundle positions (#12 and #13). Most of the significant indications corresponded to the location of centre pads of bundle #13.

  The ultrasonic indications ranged from no appreciable depth to 0.5 mm deep with circumferential widths of approximately 10 mm. This wide mark was subsequently determined to be the superposition of two distinct bearing pad fret marks located adjacent to each other, and a third set of shallower fret marks. These three fret marks appear to correspond to the three bundles which resided in position #13 during DNGS-2 operation. The examination of one of the replication mouldings showed "layering" or "ridge" type features. This may indicate that there were three or four distinct fretting periods experienced by the bundle and pressure tube.

- D2K12 was given a full length CIGAR inspection. A total of 60 indications were detected, of which seven were dispositionable. Most of the indications occurred at the channel inlet end bundle positions #10 to #13, and most of these are associated with the centre plane bearing pads. The maximum depth was 0.2 mm, corresponding to the location of a centre bearing pad of bundle #13. At the outlet end, most of the indications are associated with the bundle upstream and downstream bearing pads. This may indicate a different mode of bundle motion at either end of the channel.

- D2Q12 was given a full length CIGAR inspection. There were no bearing pad fret marks of measurable depth.

- D2C10 was inspected at the last two inlet bundle positions (#12 and #13). There were no dispositionable marks, all observations were less than 0.1 mm.

SUMMARY OF INSPECTION AND EXAMINATION RESULTS

Some DNGS fuel bundles have experienced excessive vibration resulting in: endplate cracking, significant spacer pad wear and endplate to endplate wear along the fuel channel.

Some DNGS fuel bundles have developed low amplitude high cycle fatigue cracks in and through the endplates at high stress locations. Cracked endplates have been confirmed in position #1, #2, #3, #4, #5, #8 and #9 fuel bundles, with the extent of cracking decreasing in the upstream direction from bundle #1. Cracked endplates have been detected in eight Unit 2 channels and two Unit 1 channels.

Oxide thickness measurements indicate that the cracking progressed quickly as compared to the rate of oxide formation.

Endplate wear occurs preferentially at the upstream and downstream ends of the channels, with the most severe wear occurring in the downstream bundle positions.

Some position #13 (flow inlet) fuel bundles experience excessive vibration and movement resulting in extreme spacer pad wear and extreme bearing pad to spacer sleeve wear. These fuel channels show the most extensive endplate cracking at the flow outlet end.

All channels confirmed to have significantly damaged fuel are in columns 12 and 13, and within rows J and R.

Endplate hydrogen/deuterium embrittlement, manual fuel loading and manufacturing error have been eliminated as significant contributors to the observed fuel damage.

BNGS fuel exhibits less spacer wear, no notable endplate to endplate wear and little bearing pad to spacer sleeve wear, as compared to DNGS-2 fuel.

The position #1 fuel bundle endplate fatigue cracking pattern shows that the centre seven elements of the bundle could separate from the remainder of the bundle. The geometry and fracture faces of the endplate fragment retrieved from D2N12 are consistent with this result. (Separation of the centre seven D2N12/01 elements was later confirmed by bay inspection of the D2N12/01 "bundle" on 16 March 1992)

ACKNOWLEDGEMENTS

This paper presents a very brief summary of data and results contributed by very many people at Ontario Hydro and Atomic Energy of Canada Limited. Because of time limitations, much of this information has not been issued in a form which can be referenced. A start in issuing these results can be seen by some of the companion papers at this conference.

REFERENCES

(1) Hosbons RR, Surette BA and Rose DH, "Fractographic Examination of Darlington End Plate Fractures", RC-797, February 1992.

(2) Fisher NJ and Pettigrew MJ, "Examinations of Fretting Damage in Darlington Generating Station Unit 2 Fuel Bundles", RC-635, December 1991.

FIGURE 1

DARLINGTON NGS UNIT 2 - CHANELS CONTAINING BUNDLES WITH CRACKED ENDPLATES (CONFIRMED IN FUEL BAY AND / OR HOT-CELLS)

REACTOR EAST FACE

(UPDATED TO 1 MARCH 1992)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	
A										B						B									A
B						B											C		B						B
C								B		B		C	CB		CB										C
D												CB	B												D
E			B								CB	C	C												E
F							CB					B		C		BE									F
G											C	B	B							C					G
H			CB							C	B	CBE	B	B											H
J						B	C				C	BE	CBE					C							J
K										C	B	CBE	BE	CB											K
L											CB	B	CB	B	CB			CB							L
M						C							B	C	C	B			C					C	M
N										C		CBE	B		C										N
O												B		B											O
P											C		CB												P
Q												CB	BE					C						B	Q
R						CB		B	C				CBE	B			B	C							R
S		B			C							C	B								C				S
T										B															T
U							C				B			B											U
V																									V
W										B															W
X																									X
Y								B		B															Y
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	

SOUTH NORTH

LEGEND:

C = IN-SITU VIDEO INSPECTION USING CIGAR TOOLING

B = UNDERWATER INSPECTION IN THE IRRADIATED FUEL BAY

E = HOT-CELL EXAMINATION AT CRL OR WRE

= CHANNELS CONTAINING FUEL BUNDLES WITH CRACKS ARE SHADED

FIGURE 2

DARLINGTON NGS UNIT 1 - CHANELS CONTAINING BUNDLES WITH CRACKED ENDPLATES (CONFIRMED IN FUEL BAY AND / OR HOT-CELLS)

REACTOR EAST FACE

(UPDATED TO 1 MARCH 1992)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	
A										B															A
B								B									CB								B
C								B		B		B			B										C
D										B		B													D
E											B			C											E
F								CBE				B	BE				B	B							F
G										B	B	B		B		B	C								G
H						B	B	B	B		BE	B	B	B		B		B							H
J						B	B		B			B	B					B							J
K				B			B	B		B	B	CBE	BE	B			B	B							K
L				B	B	B	B	B	B	B	B	B			CB		B	B	B		B				L
M												BE	BE												M
N				B			B	B				CBE	B	B			B								N
O				B		B	B	BE			B	B	C B	BE			B	B							O
P					B				B	B		B	B		B					B	B				P
Q										B		CB	B	B	B	B									Q
R							B		CB	B	B	B	B	B	CB	B					B				R
S											B	B		CB	B										S
T										B		BE	B			B									T
U																									U
V										B					B										V
W						B																			W
X											B	B													X
Y												B													Y
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	

SOUTH NORTH

LEGEND:

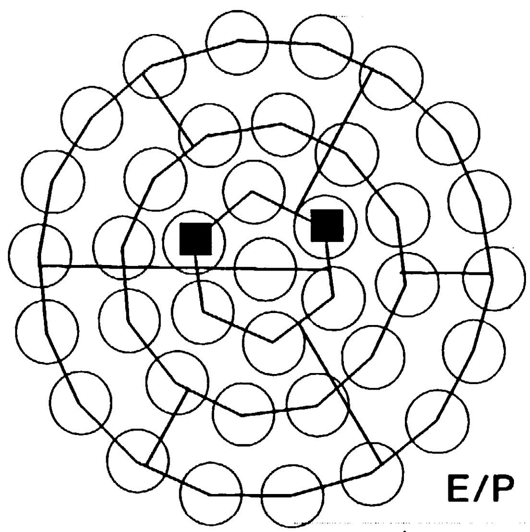
C = IN-SITU VIDEO INSPECTION USING CIGAR TOOLING

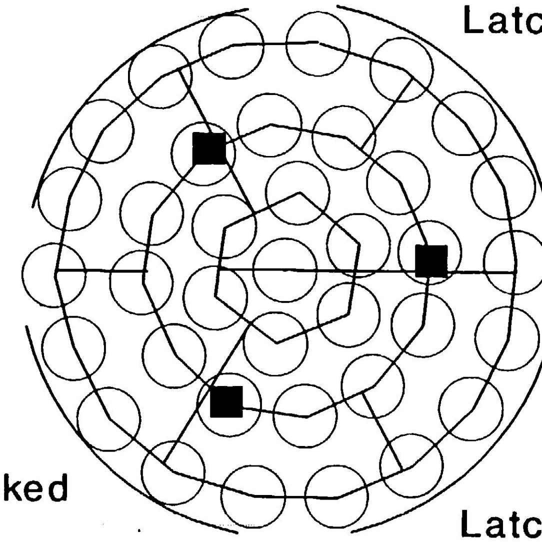
B = UNDERWATER INSPECTION IN THE IRRADIATED FUEL BAY

E = HOT-CELL EXAMINATION AT CRL OR WRE

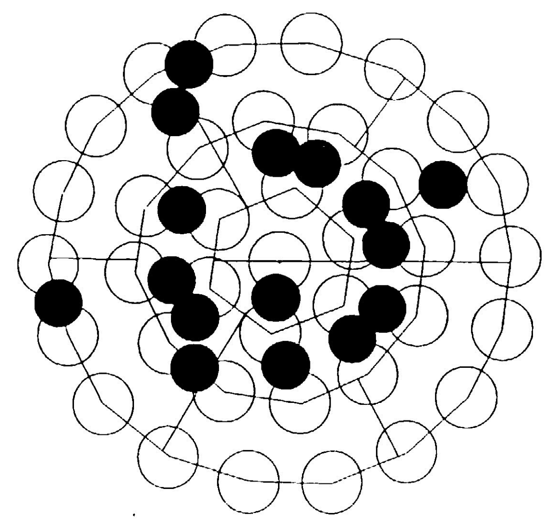
(shaded) = CHANNELS CONTAINING FUEL BUNDLES WITH CRACKS ARE SHADED (INCIPIENT AND COMPLETED)

FIGURE 3: D2Q12/01 (L23406)





FLOW →



NOTES: Bay + CRL

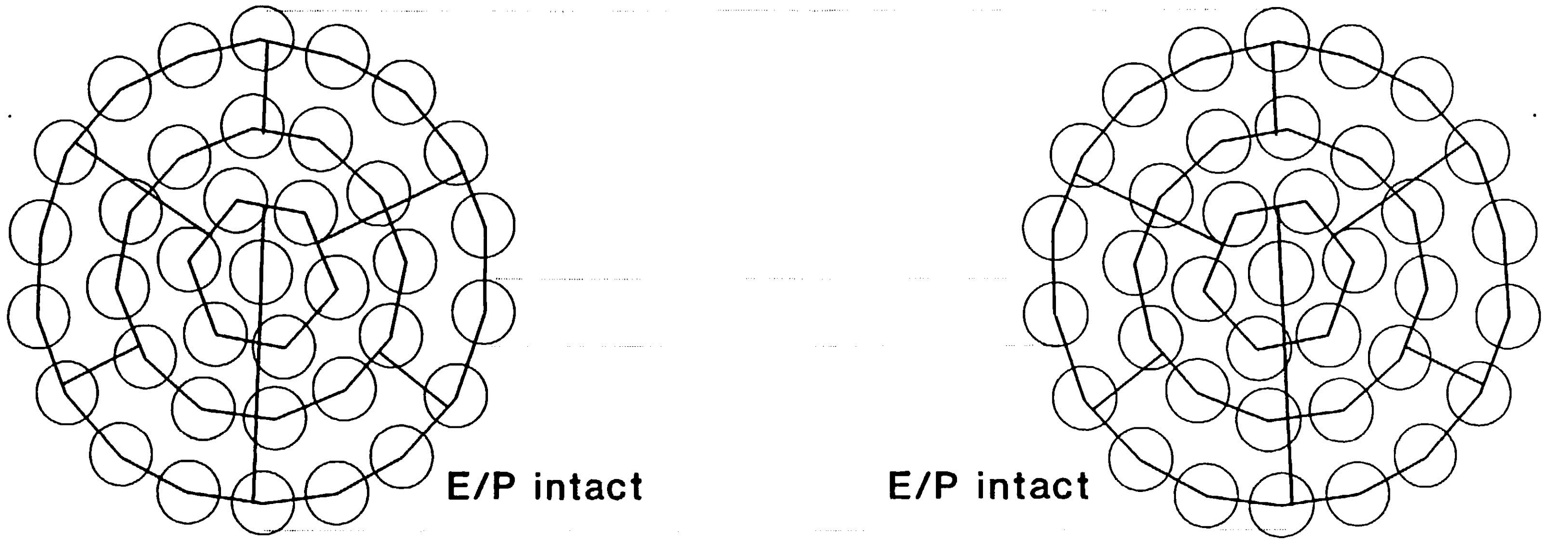
- DNGS Unit2, first charge, position 1 only
- orientation by channel video

■ - 5 endplate cracks (1 complete + 4 partial)

● - is spacer pad wear of type 6 or greater (complete mating surface contact)

FIGURE 4: D2Q12/13 (L23251)

REFERENCE END



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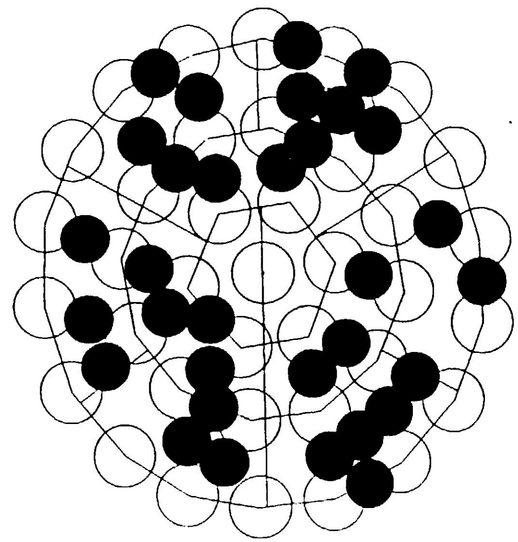

NOTES: Bay + CRL

- DNGS Unit2, first charge, position 13 only
- orientation by bearing pad wear (bottom)
- no endplate cracks
- is spacer pad wear of type 6 or greater (complete mating surface contact)