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CANDU REACTOR EXPERIENCE: FUEL PERFORMANCE

Fonctionnement des réacteurs CANDU: performance du combustible

P.T. TRUANT and I.J. HASTINGS

Paper presented at the Sixth Annual Conference of the Canadian Nuclear Society,
Ottawa, Ontario, 1985 June 3-4

Chalk River Nuclear Laboratories
Laboratoires nucléaires de Chalk River

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Résumé

Ontario Hydro a une expérience de plus de 126 années-réacteurs en ce qui concerne le fonctionnement des réacteurs CANDU. La performance du combustible s'est avérée excellente alors que 47 000 opérations de chargement de combustible ont été effectuées avec succès et que 99,9% de plus de 380 000 grappes irradiées ont fonctionné comme prévu. Les limitations de performance du combustible et les défauts de ces derniers ont eu un effet négligeable sur la fiabilité des centrales en matière de sécurité, sur l'environnement et sur le coût. Les défaillances attribuables au combustible sont inférieures à 0,1% au cours de la vie entière des centrales et récemment, elles ont été nulles.

Rapport présenté au Sixième Congrès
annuel de la Société nucléaire canadienne
tenu à Ottawa (Ontario)
du 3 au 4 juin 1985

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ABSTRACT

Ontario Hydro has more than 126 reactor-years experience in operating CANDU reactors. Fuel performance has been excellent with 47 000 channel fuelling operations successfully completed and 99.9% of the more than 380 000 bundles irradiated operating as designed. Fuel performance limits and fuel defects have had a negligible effect on station safety, reliability, the environment and cost. The actual incapability charged to fuel is less than 0.1% over the stations' lifetimes, and more recently has been zero.

INTRODUCTION

CANDU-PHW reactors are the basis of the Canadian nuclear-electric generation program. Ontario Hydro has more than 126 reactor-years experience in operating CANDU reactors. The 1984 in-service nuclear capacity is 12 units generating 6869 MWe. Nine more units generating 6941 MWe will be in-service in the period 1985 to 1992. Both Quebec and New Brunswick have one 600 MWe unit giving total committed Canadian CANDU capacity of 15010 MWe. Argentina and Korea also operate one 600 MWe unit each.

In this paper we outline Ontario Hydro's reactor experience with respect to fuel, including fuel management strategy and associated date base, defect behaviour, fuel performance, and fuel usage as of 1984 December 31.

FUEL MANAGEMENT

Ontario Hydro's fuel management encompasses all fuel cycle activities, including the commercial and technical activities associated with material purchases, inspection, transportation, use and storage.

The once-through natural uranium fuel cycle used in CANDU-PHW reactors has been developed and improved with an integrated "team" approach involving AECL, Ontario Hydro, the fuel manufacturers (Canadian General Electric Limited, Westinghouse Canada Inc. and Combustion Engineering-Superheater Limited) and the UO_2 powder producer Eldorado Resources Limited. Much of the early part of this work was provided by AECL's research and development laboratories. As the program has grown, Ontario Hydro has expanded its capability in these areas and is fully conversant with all aspects of fuel management as defined above. Close liaison (1) continues between all members of the team, and is a key ingredient in achieving economical, high performance fuel.

The fuel for commercial CANDU-PHW reactors consists of 500 mm long bundles of natural uranium dioxide with CANLUB-coated Zircaloy-4 sheathing approximately 0.4 mm thick. Each Pickering fuel bundle is made up of 28 elements, of 15.2 mm O.D. Bruce fuel is similar, with 37 elements of 13.1 mm O.D. Each horizontal fuel channel contains the equivalent of twelve bundles in-core. Most reactors use 4/8 bundle refueling, with the central channels being refueled in four-bundle increments and the outer channels having eight-bundles added and discharged during each refueling. The four-bundle shifting in the central core region results in higher burnup and less channel power variation than is obtained with eight-bundle shifts. The fuelling zones are shown schematically in Figure 1 for the Bruce A reactor core.

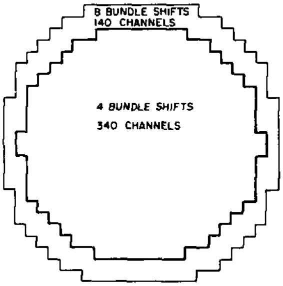

FIGURE 1: BRUCE NGS-A FUEL SHIFTING MAP OF REACTOR CORE FACE.

Fueling performance has been excellent, with more than 47 000 channel fueling operations successfully completed and 99.9% of more than 380 000 fuel bundles operating as designed. Table 1 summarizes the fuel handling experience for each station. The outer elements of a CANDU fuel bundle experience the highest powers and burnups. Figure 2 shows the outer element linear powers and burnups of 6240 fuel bundles in Bruce Unit 1 taken at one instant in time (a "snapshot") in March 1983. To interpret the graph in terms of outer element performance statistics, multiply each point shown by 18 giving 112 320 data points. The

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*Member, CNS

TABLE 1 FUEL HANDLING EXPERIENCE LIFETIME TO 1984 DECEMBER 31

	Pickering NGS-A	Pickering NGS-B	Bruce NGS-A	Bruce NGS-B
Number of Channel Fueling Operations	17 812	1 679	27 423	219
Number of Bundles Replaced	169 294	7 464	150 393	876
Bundles still in Reactors	9 360	13 680	24 960	12 480

effects of bundle radial flux depression can be incorporated giving a total of 230 880 fuel element data points. All elements at significant power experience a constant well-defined axial neutron flux. These data are extracted from reactor physics and refueling calculations routinely performed at least once per week for every reactor and more often if requested by the station fueling engineers. This information is stored on computer files for every fuel bundle irradiated by Ontario Hydro.

These data can be processed to define an individual element history. Figure 3 shows a typical outer element power history for a bundle from a Bruce-A high power channel (four-bundle shift region). The three distinct power levels in its history result from its residence in channel positions 3, 7 and 11 respectively. We expect to operate Bruce fuel at a power level 8% above this.

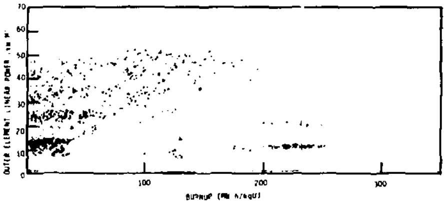

FIGURE 2: OUTER ELEMENT LINEAR POWER VERSUS BURNUP FOR ALL FUEL BUNDLES IN BRUCE NGA-A, UNIT 1 (1983 MARCH 31). ONE POINT REPRESENTS 18 OUTER ELEMENTS.

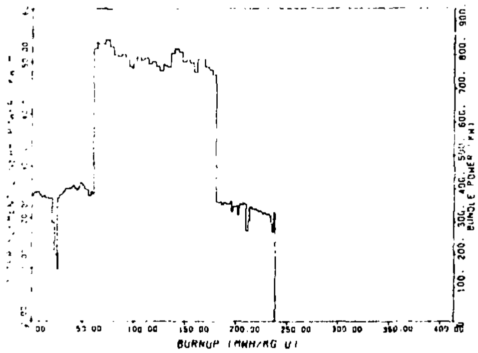

FIGURE 3 OUTER ELEMENT POWER HISTORY FOR BRUCE NGS-A FUEL (FOUR BUNDLE SHIFT REGION, POSITIONS 3/7/11). AVERAGE POWER.

For Bruce NGS-A, Figure 4 shows the percentage of outer elements discharged as a function of discharge burnup. The peak at approximately 135 MW.h/kg U is from lower burnup fuel discharged from the eight-bundle shift region. These are currently being assessed as candidates for recycle into the four-bundle shift channels. Based on the same data, Figure 5 shows the percentage of outer elements experiencing the maximum power shown at some time during their irradiation, as a function of linear power . Figure 6 gives the distribution of times spent in the primary heat transport system. This information is used to quantify our fuel scheduling experience, develop improved operating guidelines and interpret fuel defect information.

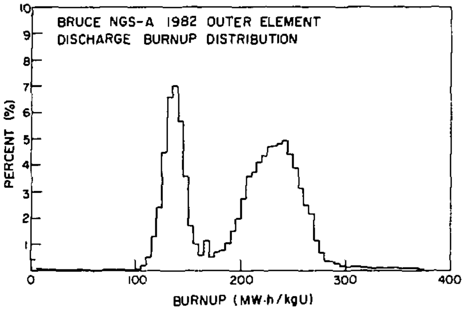

FIGURE 4 BRUCE NGS-A, OUTER ELEMENT DISCHARGE BURNUP (1982).

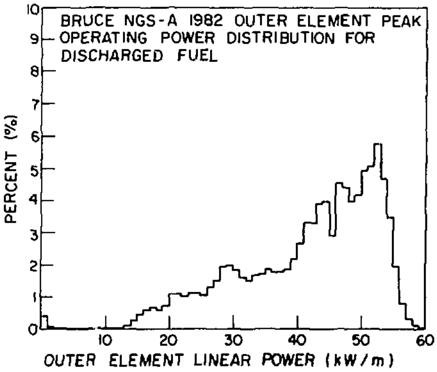

FIGURE 5 BRUCE NGS-A, OUTER ELEMENT PEAK OPERATING POWER DISTRIBUTION FOR DISCHARGED FUEL (1982).

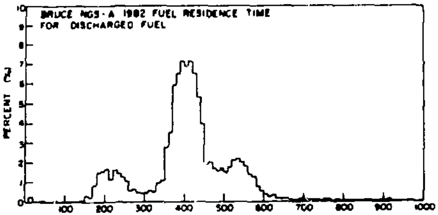

FIGURE 6: BRUCE NGS-A, FUEL RESIDENCE TIME DISTRIBUTION FOR DISCHARGED FUEL (1982).

In addition to the operating data, hot-cell examinations are essential to confirm defect causes so that appropriate follow-up action can be taken. Ontario Hydro nuclear operations owns and maintains a shipping flask for irradiated fuel. The maximum capacity is two CANDU fuel bundles or 30 individual elements in holders. Since its purchase in 1969 this flask capacity has been adequate for all our fuel performance needs. During the period from purchase to the end of 1984, 89 shipments have been completed to CRNL and WNRE for fuel test programs and defective fuel examinations. The total distance travelled by the flask without incident has been approximately 95 000 kilometers.

To ensure that shipments of defected fuel arrive at the AECL hot-cells in a state undamaged by additional oxidation, a program has been performed at CRNL to define the time/temperature oxidation behaviour of defected irradiated fuel (2). We have used such information to define flask heat load limits for fuel shipments, and to determine if inert covering gas should be used to minimize oxidation.

DEFECT EXPERIENCE

In Ontario Hydro power reactors, we have experienced fuel defects resulting from four primary causes:

- stress corrosion cracking (SCC) of the Zircaloy sheathing as a result of high stresses experienced during refueling power ramps,
- fabrication flaws such as a small "piping" pathway in the fuel sheath to end-cap weld or in the end-cap itself, which allows ingress of primary heat transport fluid into the fuel element,
- delayed hydride cracking (DHC) in the sheath to end-cap weld area, driven by high stresses experienced during refueling power ramps, and
- sheath penetrations caused by fretting by a small amount of debris in the heat transport circuit.

Table 2 shows the number of fuel bundles irradiated in Pickering NGS-A, Pickering NGS-B, Bruce NGS-A, and Bruce NGS-B, the numbers found or suspected to be defective and the defect rates. Suspect fuel defects are those discharged because of monitoring system signals but not confirmed visually.

TABLE 2: FUEL DEFECT EXPERIENCE LIFETIME TO 1984 DECEMBER 31

	Pickering NGS-A	Pickering NGS-B	Bruce NGS-A	Bruce NGS-B
Bundles Irradiated	178 400	16 300	175 100	13 300
Bundles Defective	113	20	223	0
Defect Rate (%)	0.063	0.123	0.127	0.0
Station Incapability (%)	0.1	0.0	0.0	0.0

At Pickering NGS-A, the identified defective fuel bundles have been only 0.063% of the total, with 90% of the defects occurring in the first 2 years of operation due to SCC following power increases during irradiation. Simple changes in control rod sequencing and fueling schemes to reduce transient local power increases have virtually eliminated this type of defect (1). More recently, less effort has been devoted to identifying defects at Pickering NGS-A. However, fission product levels in the heat transport system indicate that the defect rate is approximately 0.05%.

During the first year in service of Units 1 and 2 at Bruce NGS-A (1977-78), defective fuel bundles were detected by the DN system and subsequently discharged from the reactors. Visual inspections in the station's irradiated fuel bay confirmed the presence of defective fuel. Analyses of the bundle operating power histories indicated that the defects had a low probability of occurring as a result of power increases. Selected bundles were examined by AECL in hot cell facilities at CRNL and Whiteshell Nuclear Research Establishment (WNRE) to determine the defect cause. Through detailed visual examinations, neutron radiography, gas puncture analysis, leak testing and metallography, the primary defects were shown to be fabrication flaws. Of the defective elements examined, 80% were shown to have defects due to incomplete sheath to end-cap closure welds. The majority of flaws were very small oxide-filled stringers in the weld area which allowed ingress of the primary heat transport fluid into the fuel element. Figure 7 shows a typical leak path. Another 10% of the fuel examined was shown to be defective due to stringers through the end-cap itself. The balance of defects were caused by debris fretting. The

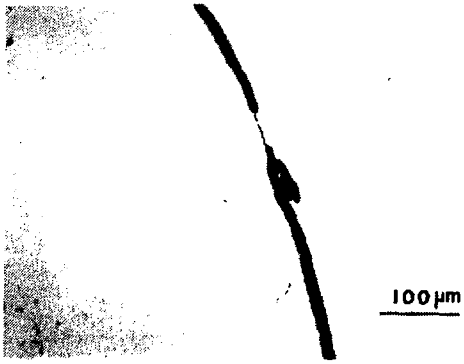

FIGURE 7 TYPICAL LEAK PATH DUE TO INCOMPLETE SHEATH TO END-CAP CLOSURE WELD. MICROGRAPH OF WELD INTERFACE.

sheathing damage observed in the irradiated fuel bays was secondary damage which occurred during fuel irradiation.

Early in 1984, high heat transport iodine levels indicated fuel defects in Unit 3 of Bruce NGS-A. Fuel inspections localized the problem to fuel bundles that had recently been shifted from low to high powered positions. A fuel management scheme was instituted to remove suspect fuel and to prevent further defects. During the first 5 months of 1984, 36 defective bundles were removed from Unit 3, and iodine levels returned to normal. Hot cell examinations have tentatively identified the primary cause as DHC in the sheath weld heat affected zone. Design changes have already been implemented. Bruce NGS-A experienced a 0.36% defect rate during 1984 with a lifetime defect rate of 0.13%.

At Pickering NGS-B the lifetime fuel defect rate is 0.12%. The 1984 defect rate (0.28%) was unusually high due to debris-fretting defects which probably were caused by debris from primary heat transport system strainers that failed during commissioning tests. Typical fretting wear is shown in Figure 8. The fuel defect rate at Bruce NGS-B remained at less than 0.05% during 1984.

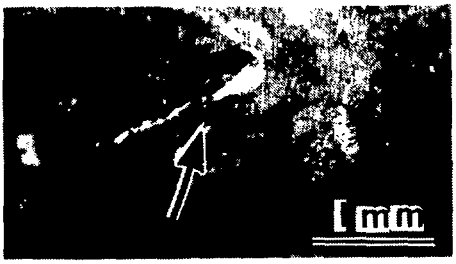

FIGURE 8: DEBRIS FRETTING DEFECT

FUEL PERFORMANCE

Fuel utilization experience continues to be excellent with current average discharge burnups of 205 MW.h/kg U at Pickering NGS-A and 200 MW.h/kg U at Bruce NGS-A. Fuel bundles routinely operate at burnups up to 280 MW.h/kg U.

Since 1980, Ontario Hydro has achieved a burnup increase of approximately 25 MW.h/kg U at Pickering NGS-A and Bruce NGS-A. This is a result of:

- The moderator heavy-water isotopic content has been upgraded by more than 0.1% (+13 MW.h/kg U).
- Expanding the four-bundle shift zone and improved guidelines for the selection of channels to be refueled have been implemented. Previously the priority had been given to channels which had high burnup fuel in the discharge positions. Now we focus on the burnup distribution of bundles which currently reside in high flux positions in the channel. These channels are selected to ensure that fuel will have high burnup when they are shifted into lower flux positions prior to discharge (+9 MW.h/kg U).
- The average uranium content per bundle has been increased by more than 1%. The fuel manufacturers achieved this by using existing allowed fabrication tolerances to maximize UO_2 content and by increasing the average UO_2 pellet density (+3 MW.h/kg U).

Pickering NGS-B and Bruce NGS-B are not yet operating with equilibrium cores, so discharge burnups at the end of 1984 were low. Discharge burnups will increase as these stations reach equilibrium. This is illustrated in Figure 9, which shows the evolution of discharge burnup from Bruce Unit 3. The dashed curve shows the discharge burnup distribution of the first 6 100 bundles discharged. The dotted line gives the burnup distribution obtained in 1980 with equilibrium fueling under the old guidelines. The solid line is the current discharge burnup distribution achieved under the new fueling guidelines. As fueling matures, the distributions shift their weight toward higher burnups.

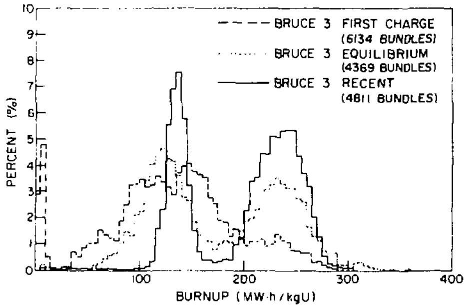

FIGURE 9: EVOLUTION OF DISCHARGE BURNUP, BRUCE NGS-A, UNIT 3.

Occasionally fuel handling system abnormalities will preclude discharging fuel from a particular channel for an extended period of time. In this event, the fuel burnups increase beyond the nominal range. About 3 000 bundles have experienced average burnups in excess of 280 MW.h/kg U with the maximum value of approximately 630 MW.h/kg U. This maximum value corresponds to an outer element burnup of 700 MW.h/kg U (30 000 MW.d/TeU). All these bundles were discharged within the normal fuel handling groundrules and no problems were encountered which could be attributed to high burnup mechanical behaviour.

To expand our detailed knowledge of CANDU fuel behaviour at high burnup, we have established a fuel hot cell examination program at CRNL. Initial results of this program have been presented (3), where a Bruce NGS-A fuel bundle irradiated to 500 MW.h/kg U was determined to be in excellent mechanical condition. The next phase will be to complete shipment and examinations of fuel bundles with outer elements experiencing burnups of approximately 700 MW.h/kg U.

Fuel From Ruptured Pressure Tube, Pickering NGS-A, G16

On 1983 August 1 a leak of heavy water was detected at Pickering NGS-A, Unit 2. The reactor was cooled and depressurized in the normal manner. The leak was identified as resulting from a pressure tube rupture in channel G-16. The channel was defueled and irradiated fuel bay inspections determined that a fuel element was missing from both the position 10 and 11 bundles. Subsequent investigation revealed that the two elements were jammed in the pressure tube split, as shown diagramatically in Figure 10. These elements were later removed using special tooling.

Six bundles and the two separated elements were shipped to CRNL for detailed hot-cell examinations in four separate shipments. An inert cover gas was used to prevent oxidation of the exposed UO_2. Examination of fuel from the channel showed bundle damage to be purely mechanical, with the majority resulting from the defueling sequence. Figures 11(a) and 11(b) show the typical ductile deformation observed and the mechanical twinning of the Zircaloy. However, some of the damage such as the detachment of one element from both bundle 10 and 11 occurred with the first shock of the pressure-tube break. Analysis of the physical markings shows that the elements were drawn into the pressure tube crack and did not force it open.

Sampling and analysis of internal gases revealed very low fission gas release (less than 0.07%) which implies that the bundles did not experience significantly increased temperatures before being discharged into the spent fuel bays. Further confirmation comes from the lack of thick oxide films on the sheathing, and no thermal restructuring of the UO_2, as shown in Figures 12(a) and (b). Adequate channel cooling was thus available at all times. Release and fuel structure were consistent with the recorded operating linear powers of less than 30 kW/m. We concluded that the fuel had no role in initiating the pressure tube rupture. This was confirmed by subsequent pressure tube hot-cell examinations.

Demonstration Irradiations

Two irradiations to demonstrate improved CANLUB coating are committed at Bruce NGS-A: 1000 Bruce fuel bundles with a water-based graphite coating on the inside of the fuel sheathing have been produced. This coating shows potential for improved performance and economics over present alcohol-based CANLUB coatings. More than 140 bundles have been irradiated as normal fuel. One hundred and twenty four bundles have been discharged from high power positions with no indication of performance problems.

Two hundred Bruce fuel bundles have been produced with Siloxane coating on the inside of the fuel sheathing. Up to the end of 1984, 72 bundles have been irradiated in-core, then successfully discharged as normal intact fuel. The current incentive is to provide evidence for good siloxane performance at high burnups for the AECL advanced fuel cycle program.

CONCLUSIONS

Fueling performance has been excellent with 47 000 channel fueling operations successfully completed and 99.9% of the more than 380 000 bundles irradiated operating as designed. Fuel performance limits and fuel defects have had a negligible effect on station safety, reliability, the environment and cost. The actual incapability charged to fuel is less than 0.1% over the station's lifetimes and more recently has been zero.

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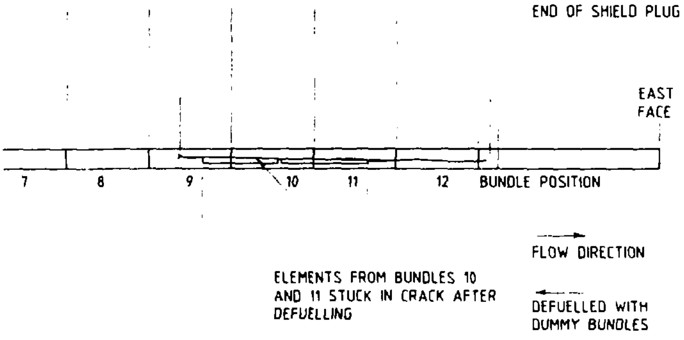
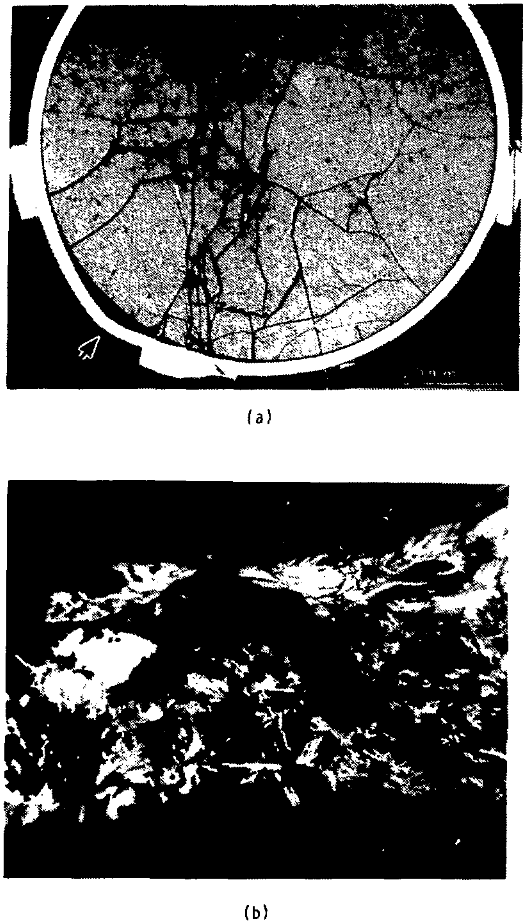


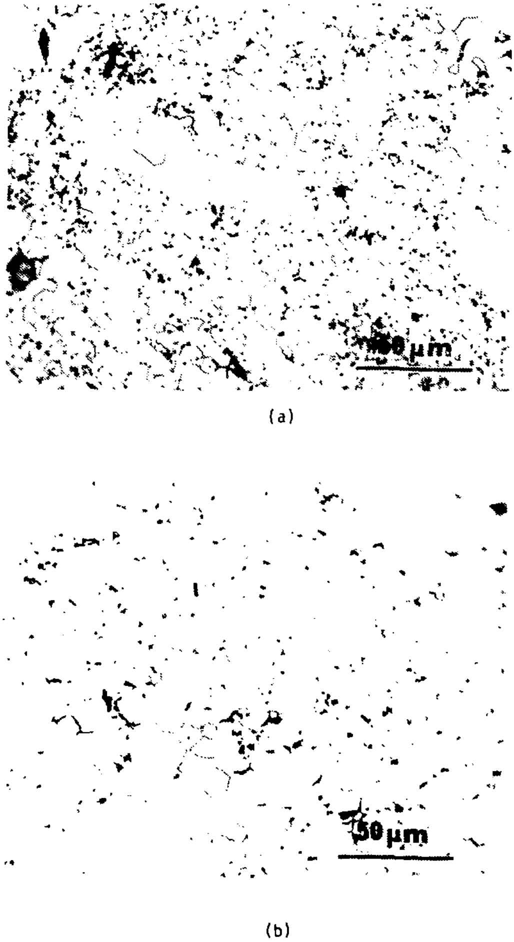
FIGURE 10:

DISPOSITION OF TWO JAMMED ELEMENTS, PICKERING NGS-A, CHANNEL G-16.


(a)

(b)

FIGURE 11 BUNDLE FROM PICKERING G-16, (a) BULGED AND WRINKLED REGION NEAR SPACER PAD. (b) SHOWS THE FLOWED AND MECHANICALLY WORKED GRAINS IN THE ZIRCALOY AT THE PAD.



(a)

(b)

FIGURE 12 CERAMOGRAPHS OF FUEL FROM (a) THE PERIPH AND (b) CENTRE OF ELEMENT. NO GRAIN GROWTH HAS OCCURRED. "CLEAN" APPEARANCE OF (b) REFLECTS FISSION-INDUCED REMOVAL OF SINTERING POROSITY (4).

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