FUEL RE-ORDERING IN THE BRUCE A REACTOR CORES

E. KOHN AND J. NOVAK
Ontario Power Generation
700 University Avenue, H11
Toronto, Ontario, Canada, M5G 1X6

H. BROMFIELD, AND R. DAY
Ontario Power Generation
Bruce A Nuclear Division
Tiverton, Ontario, Canada

ABSTRACT

In the spring of 1993, physicists discovered that the power pulse due to a large inlet header break in the primary coolant system of the reactors could be higher than previously calculated and could potentially invalidate the safety analysis and licensing basis of the reactors. The higher power pulse was due to the fuel string relocation towards the channel coolant inlet. The amount of relocation had been increasing with operating time due to irradiation growth of the pressure tube. The safety assessments of the physics implications of the movement had not been considered in the analysis. The reactors were then de-rated to 60% of full power until the power pulse issue was resolved. Bruce A considered two design alternatives: reduce the fuel string axial gap, and reverse the fuelling direction.

A reduction in the axial gap would reduce the size of the power increase. This solution was partially implemented by inserting the flow straightening inlet shield plugs (FSISPs) into the centre channels of the core. This had the immediate effect of decreasing the amount of relocation within the core during the postulated accident because the flow straightening shield plug is longer than the shield plug it replaced. This allowed a slight increase in operating power. A further gap reduction method was considered: the introduction of the long fuel bundle design, which was implemented at Bruce B. At Bruce A, the amount of benefit, and the foreseen difficulties in implementation led to the choice of reversing the fuelling direction, fuelling with the flow (FWF). This paper presents an overview of the steps in reversing the core and the problems encountered.

The immediate concern with FWF was how to change the fuelling direction quickly and economically, and without causing the fuel to defect. A fuel shift scheme was devised in which 12 fuel bundles from one channel would be discharged into the fuelling machine in the normal direction, and then re-inserted into a neighbouring channel with the opposite flow direction. This would then place the high burnup fuel on the latches and the low burnup fuel at the coolant inlet. The fuel rearrangement would take place at power and only the lower burnup fuel would experience significant power increases.

The next concern was whether the fuel could tolerate the reversal of the flow direction and the load applied to the irradiated bundle due to the latch. Test bundle irradiations showed that the fuel bundles would fail by delayed hydride cracking if also subjected to a thermal cooldown transient. Destructive inspections of the fuel in hot cells revealed cracks. New in-bay inspection tooling was devised which could examine the end plates using ultrasound technology and detect incipient cracks. The loads on the end plates were sufficiently high (this was confirmed by analysis) that a new design was necessary to accommodate fuelling with flow. A new fuel supporting outlet shield plug, F3SP, was designed to fully support the end plate through the latch and prevent cracking of the end plates. The shield plug was qualified in out-reactor loop tests. Test strings were re-ordered and the performance of the fuel was monitored by in-bay inspection. The core reversal of Bruce A units was in progress when the units were laid up in 1998.

1. Introduction

This paper describes some of the history, investigations, and implementation of solutions to the Bruce A power pulse problem. Ontario Power Generation Bruce A and Bruce B reactors were derated from full to 60% power in March 1993 in order to maintain adequate safety margins. This measure was a result of safety assessments that had predicted a problem with the effectiveness of the shutdown systems. The analysis used newly considered information about the possibility of fuel string location in Loss of Coolant Accidents (LOCAs). Solutions were proposed and investigated: problems with the proposed solutions were found and resolved; new designs tested, and finally implemented. The implemented changes resulted in new requirements being placed on the fuel and this paper concentrates on the changes that influenced the fuel behaviour.

2. Background

2.1 Problem discovery:

In the process of investigating solutions to inlet rolled joint fretting in some channels caused by fuel vibration and the axial channel expansion of the pressure tubes due to irradiation creep, the potential consequences of removing one fuel bundle from the fuel string was investigated. The axial expansion was causing the coolant inlet fuel bundle rest its in-board bearing pads on the rolled-joint burnish mark of the pressure tube. Since this is a very stress sensitive area of the tube, it would be an advantage to relocate the fuel string so that the fuel bearing pads would not rest on the burnish mark. One solution that had good potential was the removal of one bundle to give a 12 bundle fuel channel. This would shorten the fuel string, and the inlet bundle would be well away from the critical region of the channel. A much larger inlet channel axial gap would then exist.

Assessments were made regarding the possibility of fuel string relocating upstream in Loss of Coolant Accidents (LOCAs) in the 12 bundle string configuration. The assessments considered the consequences of the fuel movements which would result in inlet header breaks. In a large break LOCA on the coolant inlet side of the core, the rapid depressurization causes the pressure drop in the channels to reverse, while the coolant begins to flash to steam. The fuel is forced towards the coolant inlet side, first by the depressurizing pressure wave which results from rapid depressurization, and then by the pressure drop across the fuel string. The fuel string would be driven from its normal support position, resting on the latch at the coolant outlet end of the channel, towards the shield plug at the channel inlet. This movement is very rapid, and occurs in about 200 ms and causes fresh fuel to move towards the centre of the core and the high burnup fuel from the core. This occurs in the fuelling against flow reactors because the fresh fuel is inserted at the latch end, while the high burnup fuel is discharged at the coolant inlet end of the channel. Physics assessments considered a large number of channels moving simultaneously in the reverse direction by a distance equal to the axial gap plus the equivalent length of the fuel bundle that had been removed. These studies indicated a large power pulse could occur as a result of the fuel movement. Neither the reactor regulating system, nor the safety shutdown systems would react quickly enough to compensate for the reactivity insertion, before a significant amount of heat is added to the fuel, which would invalidate previous safety analysis.

The discovery of the reactivity insertion with the 12 bundle string channel was sufficient to immediately raise questions about the fuel string relocation in the normal 13 bundle channels. Since reactor operation had been elongating the channels, this was leading to an increased gap, as compared to the initial design, by about 5 mm per year of operation. The amount of possible fuel string relocation increased as a result of channel axial creep from the initial design values of about 10 cm to about 15 cm. The subsequent assessments showed that a significant derating was required to maintain the safety assessments in a previously accepted state. The calculated fuel movement added reactivity and caused a significant increase in the calculated power pulse that was already large due to coolant voiding one primary heat transport loop design at Bruce A. As a temporary measure, the core powers were reduced so that the energy deposition was within the previously analysed values.

2.2 Solutions

Solutions to the power pulse problem in Ontario Power Generation's reactors were divided into two approaches:

1) the reduction of the axial gap to maintain the power pulse at acceptable levels, and

2) the reversal of the core fuelling direction.

The Darlington and Bruce B reactors followed the first approach and qualified the long fuel bundle design to maintain a small axial gap. At Bruce B, flow straightening inlet shield plugs were also installed to minimize the axial gap and raise power.

Bruce A followed the second approach. However, it also adopted the flow straightening inlet shield plugs in order to immediately reduce the axial gap and raise the core powers to 70%. This step was necessary to prevent the possibility of hydride blisters forming on the pressure tube at contact points with the calandria tube. The higher temperature of operation would prevent the formation of blisters.

2.3 Evolution of Options

Initially, all stations that fuelled against the flow were impacted, and reduced power to a safe level. The relative impact of power pulse on the three stations was due mainly to the following factor:

> **Channel elongation**: the older the station, the greater the channel elongation, and therefore, the greater the fuel string movement, and subsequent relocation reactivity.

The channel elongation effect dominated the overall relocation reactivity and resulted in the reduction of the Bruce A safe operating power to 60% FP, compared with significantly higher power at the other, newer, adjusted core stations.

2.3.1 Bruce A's Preference

Bruce A's initial preference to resolve the power pulse problem was to employ a form of Gap Management involving the use of Flow Straightening Inlet Shield Plugs (FSISPs, Figure 1) in combination with a Creep Compensator (CC), which was to be inserted in front of the outlet shield plug. The gap would be controlled by the use of Creep Compensators which would be available in lengths of 1/2 inch increments. They would function by protruding through the fuel channel latch, and fully support the fuel string while reducing the gap at the flow inlet end by an amount equal to their length.

In the course of developing and testing the CCs, the coolant pressure drop incurred during the insertion process as the CC was passing through the latch, was higher than was desired from an operational standpoint. The pressure drop measurements are used to provide indication of channel flow reduction or blockage and the insertion process would result in an unacceptably high number of what would, in effect, be spurious alarms. The development of the CCs was terminated at this point. However, the FSISPs were installed and resulted in a real gap reduction of 2 inches, which, in conjunction with further analysis, resulted in a power increase to 75% FP.

At this point Bruce A had to decide between the Gap Management scheme using the 1/2 inch longer fuel bundle which was then under development and the Fuelling With the Flow (FWF) method. The factors inherent to this decision were as follows:

<u>Gap Management with Long Fuel Bundles (LFB):</u>

1. This method would require fuelling specific channels in a known sequence such that the required combination of normal and long fuel bundles could be loaded in the fuelling machines. Bruce A was not comfortable with this as predicting how the unadjusted cores will respond to a sequence of fuelling operations is very difficult.

There was no software tool available at the time to satisfactorily perform this type of operation, even though a trial was conducted with limited success.
2. Bruce A was uncomfortable from an operational perspective with the entire process of inventory management and fuelling with bundles of two different lengths. This is based on current and past experience where there were incidents of visiting the wrong channel, inserting an incorrect number of bundles, or even, on one occasion, visiting the wrong unit.
3. The gap management system was felt to be unable to completely compensate for the reactivity insertion in Bruce A and a permanent derating would have had to be imposed.

Fuelling With the Flow (FWF)

Conversely, Bruce A had significant experience with flow defuelling operations, as well as limited experience with a cascade FWF operation undertaken in 1988 to recover some of the fuel associated with the multitude of fuel channel inspection programs undertaken at Bruce A over the years.

Fuel Handling operational and technical personnel thoroughly investigated all of the physical and software aspects of the FWF operation and were satisfied that there would be no concerns that would hinder its implementation. A subsequent investigation determined that the Bruce A F/H system had originally been designed to perform flow assisted defuelling operations.

An additional investigation was undertaken with regard to the inlet rolled-joint fretting concern which was of some significance to Bruce B, but was significantly less at Bruce A. It was decided that, should this concern become significant at Bruce A in the future, a 12 bundle core configuration could be implemented in the FWF mode with minimal operational and physics impact.

Since the burnup profile in the channels would be reversed with FWF, a postulated inlet header failure would result in higher burnup fuel with lower reactivity moving into the higher flux region. Thus the power pulse would be reduced with FWF, once the change over had been implemented. Hence, there would be no imposed power penalty to operation.

2.3.2 Bruce B's Preference

Bruce B, on the other hand, felt comfortable with the sequential fuelling required as the adjusted cores lend themselves more readily to this type of operation as there is less reactivity - and power - change with a similar fuelling operation. They normally employ sequential fuelling for fuelling operations.

They were less comfortable with FWF operations as they had less operational experience with it. In addition, the use of gap management permitted them to ensure that the rolled joint wear caused by the outboard bearing pad of the bundle at the flow inlet end could be eliminated by controlling the length of the fuel string.

2.3.3 Divergence

While Bruce B committed its resources to the Long Fuel Bundle(LFB)/Gap management solution, Bruce A initially pursued both paths, but was to have implemented a solution with the retube project. When that project was cancelled, and the demands on resources forced a selection of one option, Bruce A decided on FWF as the preferred option having seen the delays being incurred as a result of the fuel compressibility in LOCA issues intrinsic to the gap management process.

In March 1994 Bruce A made a presentation to the OPG Management Team explaining its selection of the FWF option. Initially the selection was challenged by the team, but during the meeting there were some questions raised as to why the LFB had been accepted as the official solution. It was finally agreed that it was probably beneficial to OPG to be pursuing two totally different solutions in the event that one or the other proved to be unworkable.

3. Fuelling with Flow

Assessments were conducted to review the fuelling with flow (FWF) option. Fuel and physics conducted a number of analytical studies on the re-order process. The objective was to avoid significantly perturbing the core physics and hence fuel power ramps as a result. This was a significant problem. The time to effect the re-order should be acceptable. A simple reversal of the fuelling process was not possible because the high burnup fuel would have had to go through the core, leading to power ramp failures. Because all of the newer fuel would be removed from the core by subsequent FWF, the loss of reactivity of the core would have prevented operation (lack of fuelling capability).

The solution to the problem is the re-order cascade process shown in Figure 2. As shown, the fuelling process starts with one channel with 12 fresh bundles. Some of these bundles could be depleted to control the reactivity. The fuelling is the normal fuelling against flow method and removes all the fuel except for bundle 1 which is moved to position 13. The 12 bundles removed are re-inserted into another channel which has the opposite flow direction, in the same axial core positions. Thus bundle 13 from the first channel (high burnup) is placed on the latch. The fuel has little power change if the channel is about the same power, and the process does not result in high burnup fuel having to pass through the core. The fuel from the second channel is then inserted into another channel in the opposite flow direction to its operation. This process is repeated. The process was estimated to re-order the inner coolant zone (280 channels) of the core in approximately 1 week. Numbering of bundles was intended to be in the fuelling direction, after total re-order. However, to avoid any confusion, the bundles in the core will be numbered from the latch end until all units and channels have completed their re-order.

Some of the considerations about the effects on the fuel were:

3.1 Reversal of Bundle Doming

Bundle doming occurs in CANDU fuel when it is supported by fuel latches and the hydraulic loads result in a small amount of deformation of the end plate in the direction of flow, Figure 3. Recycling from one channel to the next (part of the change-over of an existing core to FWF) causes the flow direction on a bundle to be reversed, so a bundle with a domed endplate may find itself against the latch subjected to a flow direction which reverses the doming, thereby increasing the strain cycle and increasing the possibility of failure. It should be noted that once the changeover is completed and equilibrium fuelling is proceeding, this condition (doming reversal) ceases to exist.

Several hundred bundles have been recycled in Ontario Power Generation reactors and have resided against the latch for significant periods. These have experienced normal operation including reactor shutdowns with the occasional associated period of lower-temperature operation (Figure 4); they were hydrided and many of them had been subjected to flow reversal during recycling. There were no instances of abnormal fuel behaviour, but the bundles had not been examined closely enough to determine if there was an incipient performance problem or not. Ten of these high burnup bundles were examined in the fuel bays and no endplate cracking was observed.

In order to qualify the changeover to FWF, twelve bundles were selected for recycling, with flow reversal. These had been irradiated in BNGS-A Unit 2. These bundles were fuelled such that they placed onto the latches in a channel such that the rest of the fuel string (normal doming in flow direction) applied a larger load to the latch bundle, (see Figure 5). Consequently, this was a very severe test. In addition, the bundles were placed in channels that had been identified as acoustic in the Bruce B reactors. The bundles and channels were:

Donor Channel	Burnup (MWh/kg U)	New Channel
P17E	280	S03W
N10W	347	S22E
L12W	320	C15E
E11E	244	U13W
U13W	235	K14E
K14E	251	K05W
K05W	220	S14E
S14E	246	M21W
M21W	226	Q06E
Q06E	241	D17W
D17W	212	G15E
G15E	269	K01W

Visual examination of the bundles in the fuel bays revealed no cracks.

3.2 Hydride (deuteride) concentrations

The initial evaluation of the potential of hydride (deuteride) concentration and redistribution did not result in a concern. The hydride concentration will increase in the endplate/endplug weld region during operation and high burnup fuel will have high hydride concentration in the bundles placed on the latch. Increased concentrations near the weld notch might have a deleterious effect as far as crack propagation is concerned if the solubility limit was exceeded, particularly during low-temperature (zero power) operation. The CRL laboratory fatigue tests on irradiated endwelds (1) have shown a negligible dependence on test temperature (573 or 373 K), indicating that hydriding should not be a major concern.

This initial evaluation was later proven to be mistaken. The reactors have a requirement to be able to run in the hot shutdown condition at a coolant temperature of about 265°C. This was pointed out by the workers on pressure tubes (M.Leger, and G.Shek of Ontario Power Technologies (OPT), who also had to contend with this problem. Thus the fuel might be subjected to a decrease in fuel temperature from about 300°C, while highly stressed on the latch, promoting delayed hydride cracking. Delayed hydride cracking (DHC) can occur when the hydogen concentration is above solid solubility and is particularly fast when the temperature is decreased. This leads to a super saturated condition in the Zircaloy which causes hydrogen to diffuse and migrate in the stress gradient to a notch or crack tip. Hydrides precipitate and then crack in the stress field. The process then repeats causing a measurable propagation rate. Since the end plates were highly stressed, could contain high concentrations of hydrogen, and contained stress raising notches at the end cap to end plate welds, there was a strong potential for this failure mechanism to occur.

In order to examine whether there really was a practical problem, the fuel bundles that had been tested in the reverse dome condition, a very severe test, were examined for delayed hydride cracking, since it was determined that this fuel had also experience a hot shutdown transient. The fuel was examined at Atomic Energy of Canada Limited –Chalk River Laboratories (AECL-CRL), and DHC was found, Figure 6 (2).

This immediately led to a re-evaluation of the FWF program. Although, it was possible that the severe stress condition of the end plate in the test bundles might have been avoided with the cascade fuelling scheme, management opted for a fuel supporting shield plug, F3SP. This concept, championed by GEC, was a normal Mk3 shield plug, but at the core end was machined to allow an additional nose piece Figure 7. The nose piece was held in the channel lugs to prevent rotation on fuelling and protruded into the channel in front of the latches so that the shield plug would support the three rings of the fuel. This was felt to be an assured option but required the development and installation of the F3SP's before the core re-ordering could start. The F3SP was evaluated for its effect on the fuel behaviour. Qualification testing of the F3SP revealed that no deleterious vibrational effects existed. The F3SP underwent a full design review that considered all operational and safety factors. It was accepted and implemented.

The F3SP solution also considered the fact that the doming of the end plates would be reversed by the change in fuelling direction during the transition phase and that this might stress the end plates and cause cracks to develop. In order to examine whether the end plates developed cracks with the F3SP, OPT developed an in-bay fuel end plate inspection tool. This tool was a high resolution ultrasonic scanning tool which scanned the end plate in a raster mode to detect whether there were any end plate cracks at the root weld notch. This is a very difficult problem since the end plates were not flat in the region of interest, and the welds themselves from fuel manufacture, not identical. Thus the set up conditions were critical in developing this technique. The skills of the staff allowed this technique to move into production mode.

The in-bay inspection of test channels and of the trial cascade fuelled channels resulted in no cracks detected. The bundle configuration is shown in Figure 8. The program could proceed with full implementation.

AECB gave approval to operate Unit 3 at 94% on Feb 10, 1997. The 94% power was now limited by issues related to trip margin on fuel dryout, unrelated to the power pulse issue.

4. Acknowledgements:

This overall program involved nearly a thousand individuals who deserve credit for parts of this work from safety analysis to implementation tests. At Bruce A station, many were involved with the direct application of the technology. At other Ontario Power Generation sites and Ontario Power Technologies, efforts assisted in developing and reviewing the engineered solutions, and in developing special equipment (e.g., the EPIC fuel examination tool developed at OPT). Much of the work was also supported by the development efforts of staff at General Electric Canada (GEC) (F3SP and Fuel Handling), Atomic Energy of Canada Limited – Sheridan Park AECL-SP ((design reviews) and AECL-Chalk River Laboratories (AECL-CRL) (Fuel post irradiation examinations), and Stern Laboratories (F3SP Qualification tests). T.Daniels helped in putting the report together.

5. References:

1. R.R.Hosbons and B.L.Wotton, "The Effect of Irradiation on the Fatigue Life of CANDU Fuel Endcap to Endplate Welds", AECL-RC report RC-1102, (1993)

2. J.Montin, S.Sagat, R.Day, J.Novak, and H.Bromfield, “The Post Irradiation Examination of Fuel in Support of Bruce A Nuclear Division Fueling With Flow Program” 4th International CANDU Fuel Conference, Oct 1-4, 1995 Pembroke Canada. Also as Atomic Energy of Canada Limited report AECL-11464

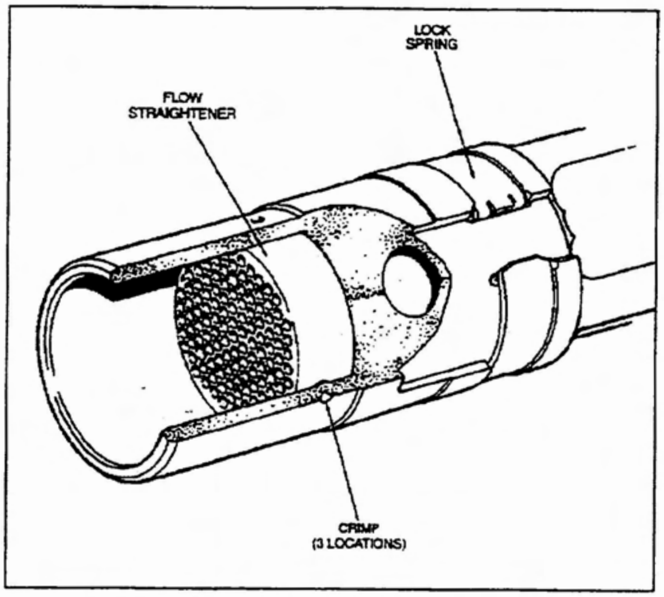


Figure 1 **Flow straightening inlet shield plug.**

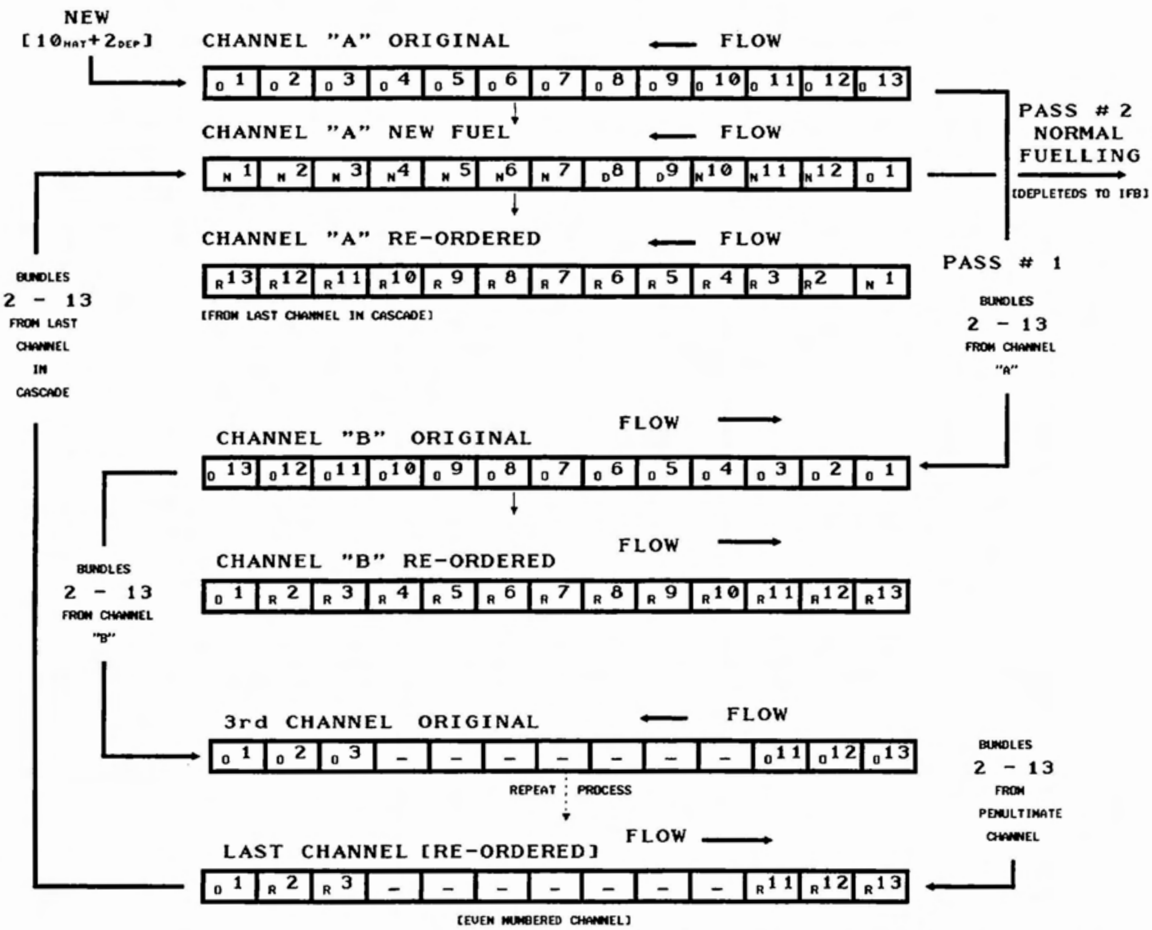


Figure 2 Fuel re-order process - during transition from Fuelling Against Flow to Fuelling With Flow

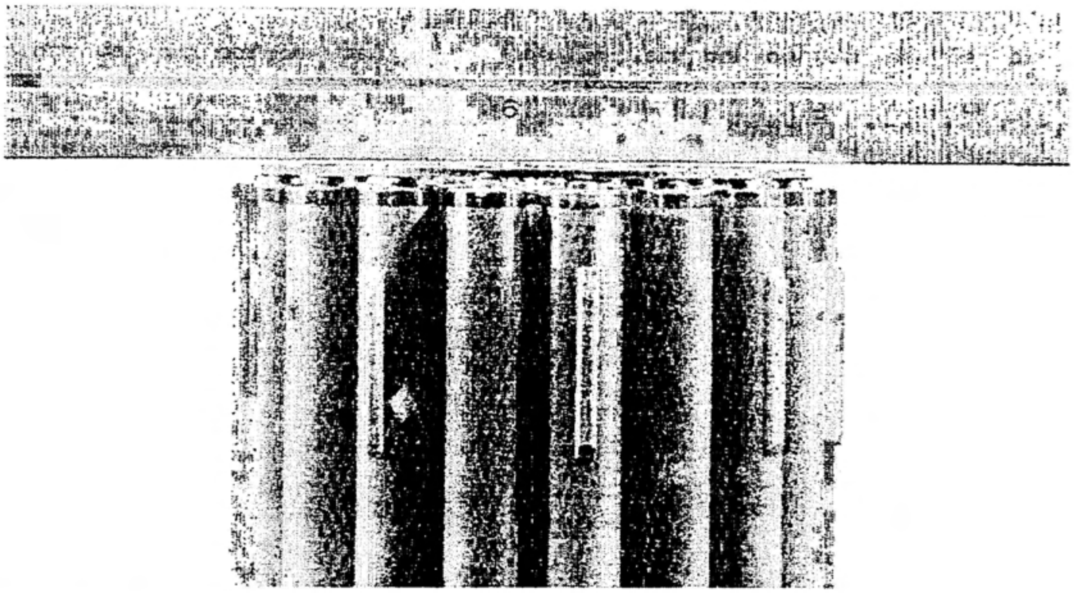


Figure 3 Side profile of a bundle showing end plate doming, a small gap against the straight edge at the outer elements of the bundle

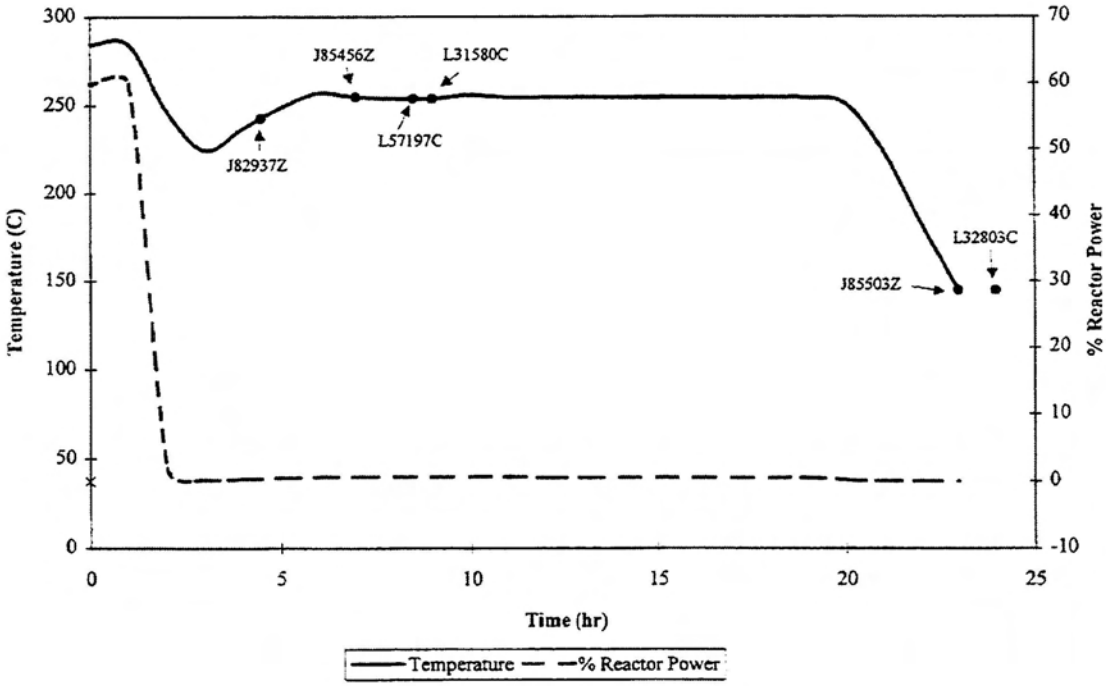


Figure 4 Thermal cycle of the fuel placed on the latches in the reversed direction

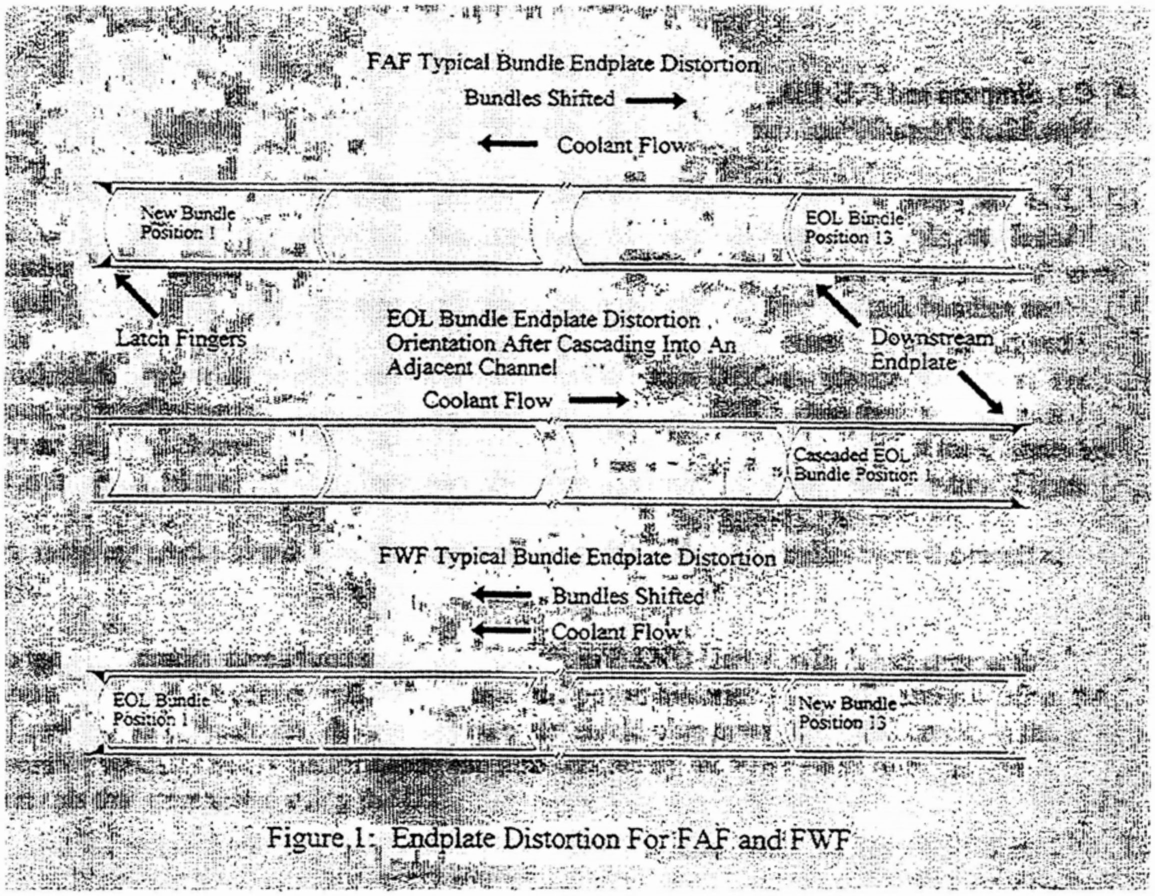


Figure 5 Schematic of fuel doming of test fuel on the latches

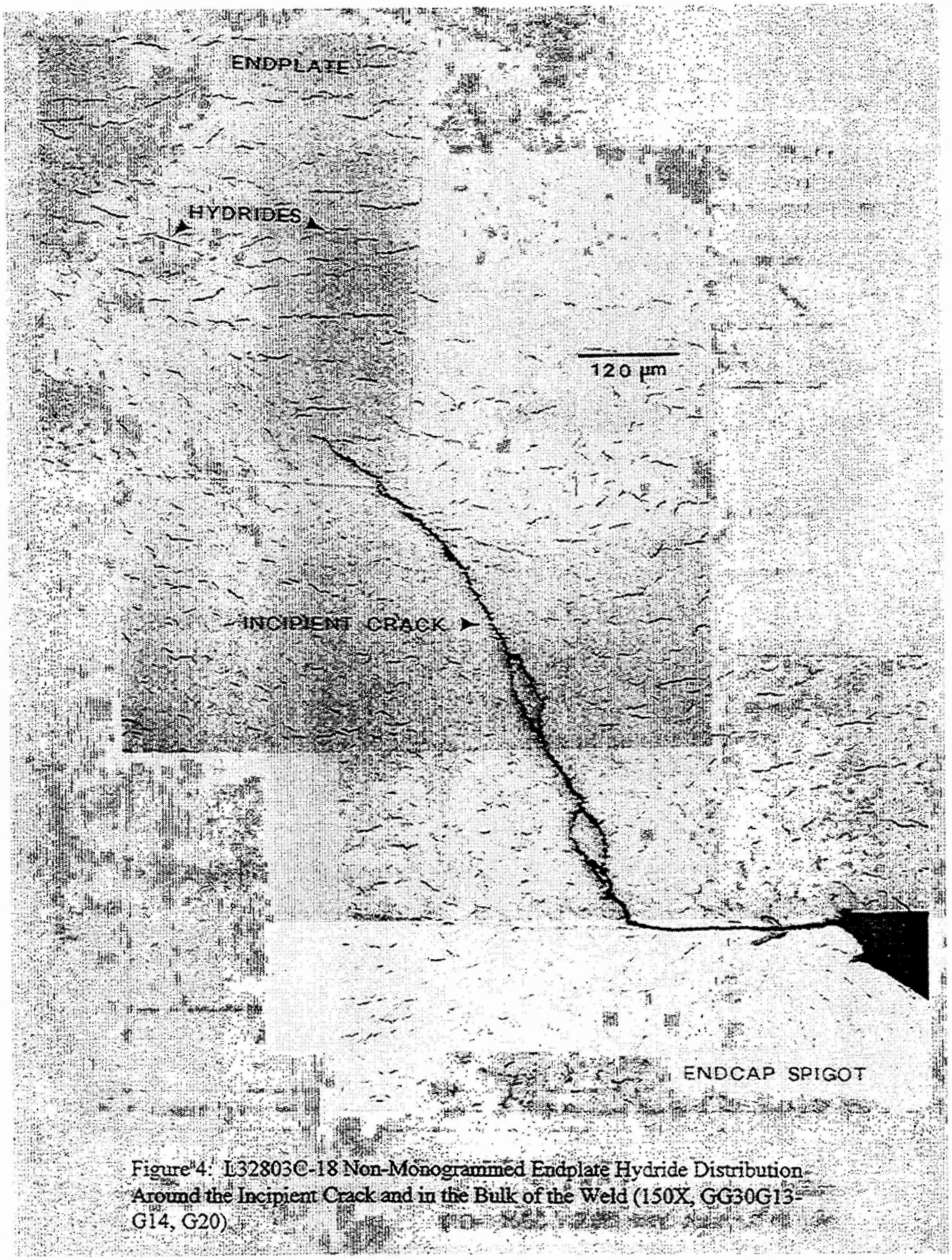
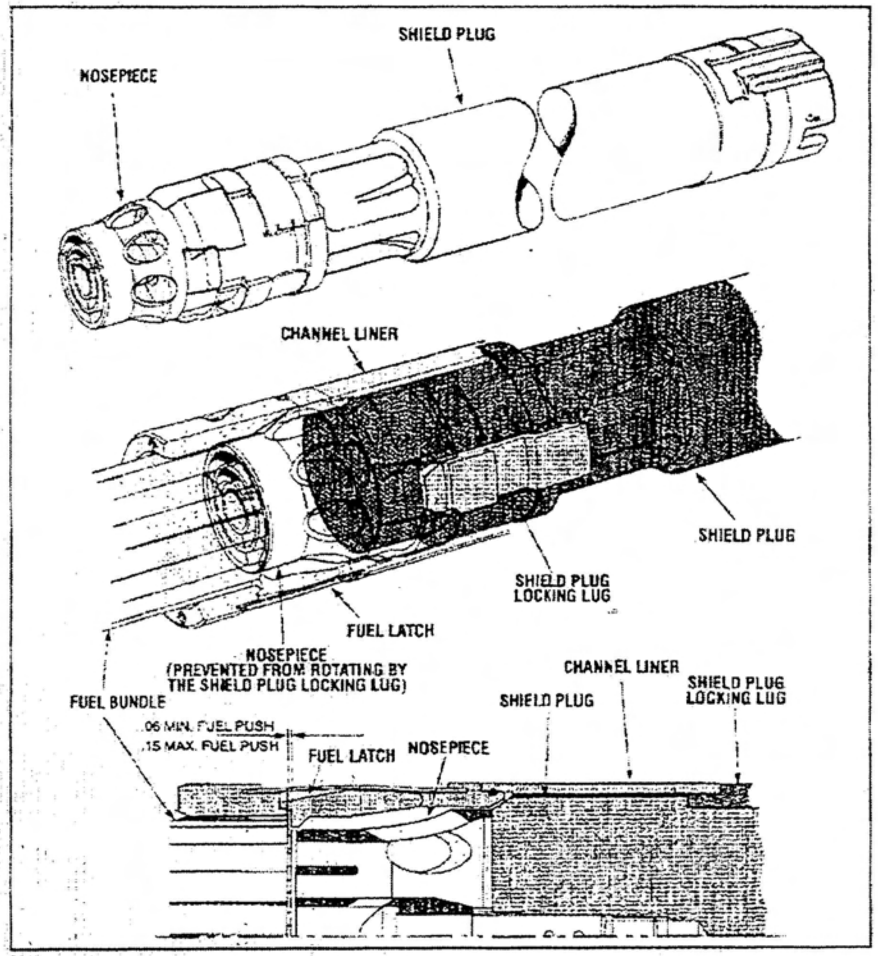


Figure 6 Delayed hydride Cracking of end plate (From Reference 2)



Section F3SP.

Figure 7 Fuel supporting shield plug which supports three rings of fuel elements

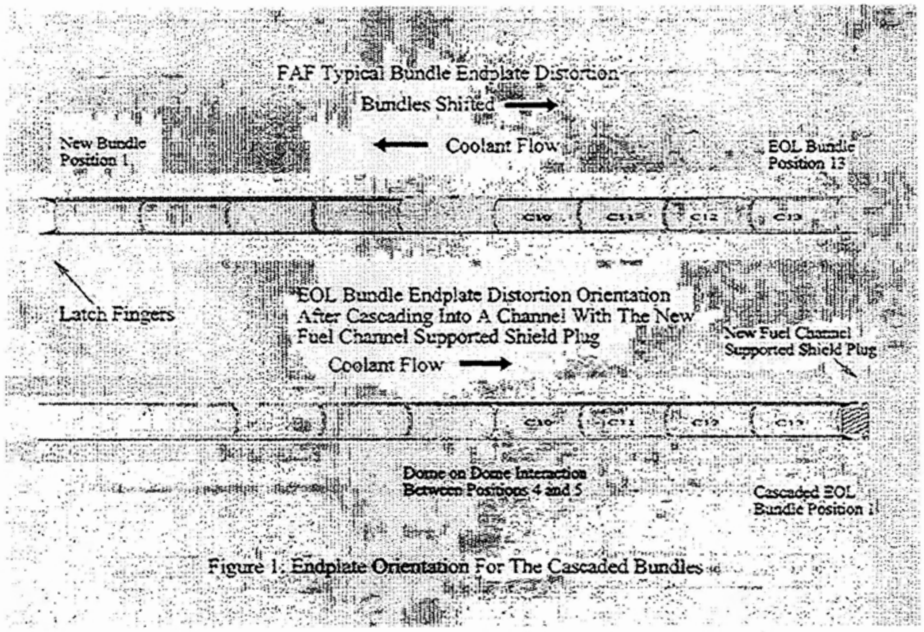


Figure 8 Cascade 4 bundle shift re-order