POST-DEFECT DETERIORATION OF CANDU FUEL: WHAT HAVE WE LEARNED?

by

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ABSTRACT

Post-defect deterioration is an important consideration for CANDU users who need to decide when to remove fuel defects from the core. Previous work on this subject showed that defective fuel is sufficiently stable while operating within the high power envelopes of current CANDUs and will not pose risk to refuelling operations. For defective elements operating below about 1000 kW/m^2, secondary hydride damage of the Zircaloy cladding occurs at burnups above 40 MWh/kgU. At higher heat fluxes, hydriding can be present at lower burnups. The primary hole size also influences deterioration rates; fuel elements with small holes hydride earlier than ones with large holes.

INTRODUCTION

Most large CANDU reactors are equipped with failed fuel detection and location systems that can pinpoint the channel location of defective fuel. The on-power refuelling capability enables fuel failures to be removed without any operating restrictions. However, a premature refuelling of a suspect channel leads to an increase in fuelling machine demand, loss in fuel burnup, and perturbations to fuel management. This creates an incentive to leave defective fuel in the reactor until they achieve their design burnups. This approach leads to certain risks associated with: loss of structural integrity of the defective fuel element or bundle due to post-defect deterioration, and UO_2 release from the defective fuel element that can deposit on heat transport system components.

Loss of fuel element integrity can potentially cause jamming in the fuel channel or fuel handling systems leading to forced reactor shutdowns and expensive cleanup operations. UO_2 release is also undesirable because it tends to increase occupational exposures at the station, as discussed elsewhere [1,2,3].

This paper summarizes previous work on understanding the post-defect deterioration of CANDU fuel. The main intent was to identify any operating restrictions or precautions that can be taken to reduce the above risks.

THEORY

It is well known that Zircaloy clad UO_2 fuel undergoes some degradation when hydrogen is present within the fuel element. This condition occurs when a breach in the cladding permits coolant ingress, or when the fuel element initially contains excess hydrogen. The post-defect deterioration refers to the secondary hydride (or deuteride) damage to the cladding that occurs after the formation of the primary hole. As the amount of secondary damage increases, so does the amount of uranium exposed to the coolant.

There are at least three steps of deterioration due to secondary damage:

1) *incubation*: This is the period when the hydrogen dissociates from the source and finds a point of entry on the inside surface of the cladding.

2) *sunburst formation*: This is the period when the hydrogen within the cladding forms hemispherical regions (referred to as "sunbursts") of solid hydride located on the inside (hot) surface of the Zircaloy cladding.

3) *clad cracking*: The volumetric expansion associated with the buildup of zirconium hydride eventually causes cracking of the cladding.

REVIEW OF WORK DONE PRIOR TO THE 1980s

The behaviour of defective Zircaloy clad UO_2 fuel elements was summarized in 1969 by Locke of the UKAEA[4,5,6]. He plotted "days-to-failure after defection" against the surface heat flux (SHF) of the defective element for several in-reactor tests. The database included Canadian defects, specifically ones irradiated in the NRX experimental loop and in the Nuclear Power Demonstration (NPD) reactor. Locke was able to show a threshold delineating "successful" defect operation versus "unsuccessful" operation on the basis of failure of the fuel element due to extensive hydride damage (see Figure 1). Some secondary hydriding can be present for successful operation, whereas, fuel breakup or loss in structural integrity is associated with unsuccessful operation. Locke concluded that the post-defect deterioration rate is very dependent on the SHF and the post-defect residence time (Δt).

Locke's graph of Δt versus SHF provides an excellent method for comparing the post-defect degradation of fuel elements of different geometries. Here are some of the reasons:

1) These parameters can be easily calculated from available power histories of defects.

2) The surface heat flux for Zircaloy sheaths, is essentially a measure of the temperature gradient across the sheath for a range of element diameters and sheath thicknesses. This gradient is an important parameter because it controls the hydrogen diffusion rate in the cladding.

3) The time-to-failure parameter is particularly useful to the CANDU station operator in deciding when to remove defective fuel.

Locke's papers express the "time-to-failure" in both "effective full power days" and in "calendar days" without discrimination. The former is a measure of the amount of energy produced by the reactor in one day operating at full power, whereas, the latter is independent of reactor power. In view of this discrepancy, we reviewed the reference for the one Canadian defect used to help position the left end of the upper bound of Locke's curve in Figure 1. According to Locke, a defective bundle was discharged from NPD with a "time-to-failure" of about 900 days. The original AECL report[7] reveals that this bundle was mechanically damaged during a non-standard reverse fuelling operation and had remained in the reactor for an additional 28 months, or about 850 calendar days. However, subtracting the time that NPD was shut down, the time at power after becoming defective was only 604 days. Since NPD was not likely operating at full power during this period, the amount of energy produced was likely less than 604 effective full power days. Consequently, AECL has always used Locke's curve with caution.

Evidence obtained from the Canadian reactors indicated that some fuel elements with relatively large holes had post-defect deterioration rates that were essentially reduced to zero while operating at high SHFs and for long Δt's, as briefly mentioned below:

1) In the 1960s, AECL embarked on several in-reactor tests to investigate post-defect deterioration and fission product release behaviour of fuel elements with pre-drilled holes to simulate defective fuel[8]. These tests which lasted only a few weeks, did not provoke any secondary hydride damage, even when irradiated at high linear powers (or high SHFs). Whereas, fuel elements that operated at similar powers and that became defective via the more conventional ways like overpower, stress corrosion cracking, porous endcaps, etc. did display secondary damage.

2) In the early 1970s, both Douglas Point and Pickering reactors experienced several power ramp fuel defects[9] that had a range of post-defect residence times. The fuel inspections in the bay showed that fuel defects with *similar* power histories but with *different* post-defect residence times displayed *similar* hydride damage with large holes.

1982 SURVEY OF POST DEFECT BEHAVIOUR OF CANDU FUEL

To improve our understanding of post-defect deterioration, AECL began collecting information on defective fuel elements irradiated in the experimental loops of NRX and NRU, and in the CANDU power reactors. By 1982, the information was consolidated into one database and the results were assessed, as described below.

Database

Until about 1976, General Electric Canada (under AECL contract) collected a considerable amount of information on fuel defects discharged from NPD, Douglas Point and Pickering reactors, representing about 33 reactor years of experience. The information came from the fuel inspections done at the stations and from the Post-Irradiation Examinations (PIE) done in the hot cells at AECL. A similar database was also created for the fuel defects from the NRU and NRX loops using information primarily available from the PIE reports.

The database included the following information:

- bundle serial number,
- number of defective elements,
- channel and bundle positions,
- loading, shifting and discharge dates,
- power ramp date (if the cause was due to SCC),
- days at power for each position,
- total days at power,
- burnups at the end of each position dwell and at the time of defecting,
- best estimate of defect categories based on PIE and/or other evidence, and
- hydriding damage classification.

The three defect categories included:

- *manufacturing flaws* due to incomplete welds or porous endcaps,
- *power ramping* due to SCC or centreline melting, and
- *mechanical damage* due to gouging on fuel channel components, fretting by debris, pre-drilled holes or machined slits.

In a few cases where neutron radiography and metallographic sections were available from the PIE, we could provide a hydriding damage classification, as follows:

- *no hydriding,*
- *incipient hydriding* where internal hydriding was present but no through the wall cracks, and
- *visible hydriding* as observed in the bays or in the visual inspection cells.

In cases where fuel elements were only inspected in the fuel bays and confirmed as being defective, the classification was listed as "visible hydriding". Very few of the power reactor fuel defects received PIE. Any bundles that were not visually confirmed as defective were excluded from the database.

By 1982, the database included about 137 defective bundles discharged from NPD, Douglas Point, Pickering and Bruce power reactors; and about 133 defective fuel elements irradiated in the experimental loops in the NRX and NRU research reactors in Chalk River.

With the above information, it was possible to calculate the average SHF after the onset of failure, and the post-defect residence time in units of "days at power". The onset of failure corresponds to: the time of initial loading for a manufacturing defect because the primary hole is present during the total time at power; the time of the power ramp for a power ramp defect; and to the time of the incident that led to the initial damage for a mechanically damaged defect. The post-defect residence time is equal to the time period from the initial onset to discharge.

Survey Results

Figures 2, 3, and 4 show the post-defect residence times versus the average surface heat flux for defects caused by manufacturing flaws, power ramping, and mechanical damage, respectively. The operating boundaries for CANDU reactors shown on these figures were derived for 37-element fuel bundles. All data from the power reactors should have SHFs and ∆ts below this boundary. The upper portion of this curve represents the maximum residence time of a fuel element having a burnup of about 400 MWh/kgU. Most defective fuel elements in the power reactors are discharged before achieving this burnup. The far right portion of the curve represents the maximum surface heat fluxes of outer elements of a CANDU 6 fuel bundle operating along its high power envelope that peaks at 900 kW. This envelope is also representative of the maximum powers of bundles loaded into the Bruce and Darlington reactors. The maximum SHFs for Pickering size fuel elements with its larger diameter would be positioned to the left of the operating boundary.

a) Fuel Elements with Manufacturing Flaws

Figure 2 shows a secondary hydriding threshold which is drawn below the post-defect residence times calculated for hydrided fuel elements having manufacturing flaws. Below SHFs of about 1000 kW/m^2, the threshold is drawn to coincide with a burnup of 48 MWh/kgU for 37-element size fuel elements and of 58 MWh/kgU for 28-element size fuel. Above 1000 kW/m^2, the threshold drops off due to the presence of hydride damage found among NRX elements that had lower burnups of about 32 MWh/kgU. Very few defective elements displayed hydride damage below this threshold. The exceptions are:

1) One fuel element from a NPD bundle that had resided at essentially zero power for 762 days displayed a cracked hydride at one end. Half the bundle resided outside the core while the other half remained at very low flux. It is unknown if the hydrided end was in the flux, but if it were, the discharge burnup could have easily exceeded 58 MWh/kgU.

2) Two NRU fuel elements were internally contaminated with sodium silicate during fabrication, which is believed to have been the source of hydrogen that led to hydriding damage.

3) One NRU fuel element was clad with Zr-2.5 wt% Nb which is believed to have different corrosion behaviour than the standard Zircaloy cladding.

b) Power Ramp Defects

Almost all power ramp defects from the power reactors displayed hydride damage as shown in Figure 3. The one exception was a slightly enriched experimental bundle in Douglas Point that displayed incipient hydriding after operating for only two hours after the power ramp. Power ramp experiments in the research reactors were normally terminated within hours of the power ramp if there was an indication of a defect. Consequently, the absence of hydride damage among the defects from the experimental loops enabled us to draw a secondary hydriding threshold for power ramp defects. This curve which decreases from about one day to about two hours as the SHF increases suggests that the post-defect deterioration rates for power ramp fuel are initially very high.

The inspection sheets for the power reactor defects indicated that bundles discharged a few days after the power ramp had similar hydride damage as those discharged months later. These observations suggest that beyond certain hole size, the deterioration rates are low and independent of the post-defect residence time.

c) Mechanically Damaged Defects

The 19 points on Figure 4 represent 22 mechanically damaged fuel elements from the NRU, NRX and NPD as briefly described below:

- 4 were NPD bundles each with one defective element gouged by the fuel latch during abnormal refuelling[7],
- 3 were NRU loop bundles, with five defective elements among two bundles damaged by fretting against a fuel carriage device, and with one element on the third bundle gouged by fuel handling between irradiations, and
- 12 were NRX loop elements that were purposely defective: having either small holes drilled through the sheaths, or slits machined along the sheath before or during their irradiation[8].

Only 3 of the 22 defective elements displayed some hydriding damage. Two of these had unusual features: one contained thoria fuel, and the other had a sheath diameter of 20 mm and a length equal to about half the standard CANDU fuel element. The third one came from the NRU loop and had a discharge burnup of 43 MWh/kgU which is consistent with the secondary hydriding threshold for elements having manufacturing flaws.

There are 4 Bruce fuel defects in the database that were caused by fretting by debris. These were excluded from Figure 4, because the time of failure in each case was unknown which would have led to a large uncertainty in calculating the post defect residence times. Nevertheless, three of the four defective elements displayed hydride damage and had discharge burnups between 164 and 266 MWh/kgU. The fourth which was not hydrided, had the lowest burnup of 93 MWh/kgU.

Survey Findings

The 1982 survey findings are summarized below:

1) Below 1000 kW/m^2, secondary hydriding has only been observed on defective elements with discharge burnups greater than about 40 MWh/kgU. This generally holds true for the three defect categories.

2) Above 1000 kW/m^2, secondary hydriding has been present on defective elements with discharge burnups as low as 10 MWh/kgU. This trend is particularly apparent among the NRX defects (manufacturing flaws and power ramp) that operated at high powers.

3) The post-defect deterioration rate is relatively high for defective elements with small holes that permit water ingress. Elements with small holes (manufacturing flaws) display more secondary damage than those with large holes (mechanically damaged).

4) The post-defect deterioration rate is further enhanced for defective elements with small holes and high fission product concentrations within the pellet-to-sheath gap. This is most likely the case for power ramp defects within a couple of hours after a large power ramp. After holes develop via the secondary hydriding, the deterioration rate diminishes to negligible levels, as indicated by the Pickering defects that have resided in the core for hundreds of days at power.

FEEDBACK ON POST-DEFECT DETERIORATION SINCE 1982

Since 1982, 16 large scale CANDUs came on line: 4 CANDU 6 units, 4 units each at Bruce B, Pickering B and Darlington. Each station has specific procedures for routinely monitoring and collecting information for the fuel defects as they occur. There is no periodic formal overview to assess the post-defect behaviour of the fuel. However, experts within the Canadian nuclear industry participate in detailed investigations that take place whenever there are systematic fuel failures or defect excursions. Although the main purpose is to identify the defect cause, the investigations generally shed some light on the post-defect behaviour of CANDU fuel. Some examples of defect excursions in recent years include:

- excess hydrogen defects at Bruce 3 in 1984[(10)],
- debris fretting defects at Pickering 5 in 1985,
- power ramp defects at Pickering 1 in 1988[(11)], and
- excess hydrogen defects at Point Lepreau in 1992[(12)].

The post-defect behaviour of fuel during these events is consistent with trends observed in 1982. The excess hydrogen defects at Bruce 3 and Point Lepreau generally displayed secondary hydriding damage at power and burnup conditions that are consistent with those for fuel elements having manufacturing flaws[(13)]. The power ramp defects at Pickering 1 in 1988 appeared to deteriorate almost immediately after the power ramp, as indicated by the radioiodine levels in the coolant. The debris fretting defects at Pickering 5 in 1985 were not assessed from the standpoint of post-defect behaviour.

DISCUSSION

The incubation period when the hydrogen becomes available for pickup by the cladding tends to be short (hours) for power ramp defects and long (weeks) for elements with manfacturing flaws, and extremely long (months) for elements with large holes created by mechanical damage, as schematically shown in Figure 5. This large variation in incubation periods may not be entirely explained by factors like hydrogen liberation due to oxidation of the UO_2 pellet and cladding in a high temperature steam environment, nor by the degradation of the corrosive properties of the cladding due to irradiation embrittlement.

Another contributing factor may be due to the presence of the corrosive fission products that accumulate within the pellet-to-sheath gap. They may play some role in assisting the hydrogen to dissociate from the coolant and to enter the fuel cladding. Fuel elements with manufacturing flaws contain hydrogen at burnups below 40 MWh/kgU. The cladding does not become hydrided because there are no significant concentrations of fission products in the gap. Hydriding at low burnup only occurs at high SHFs (or at element linear powers above 40 kW/m for 37 element fuel). At these high ratings, fission product release to the gap is enhanced, even at the low burnup.

Defective elements with relatively large holes (like the mechanical defects) do not generally become hydrided, because the large holes allow the coolant better access to the gap. This process tends to flush out the fission products which prevents hydrogen pickup by the cladding.

Power ramp defects tend to occur at burnups greater than about 40 MWh/kgU due to the characteristics of stress corrosion cracking. Almost immediately after a power ramp, the fission products that are normally trapped within the pellets are released directly into the gap at the time when the sheath is stressed. The initial hole created by SCC is likely to be small, but large enough to permit water ingress before the fission products have time to escape from the gap. Under these conditons, hydrogen pickup and subsequent cracking of the sheath occur very rapidly, as demonstrated by the secondary hydriding threshold on Figure 3.

CONCLUSIONS

1) There is no evidence to suggest that a time limit is needed for post-defect residence times from the standpoint of fuel element integrity. All fuel defects that occur at power, have been successfully discharged without incident, even after hundreds of days at power.

2) There appears to be a burnup dependent threshold for secondary hydriding corresponding to about 40 MWh/kgU. Hydriding can occur at lower burnups, but only at surface heat fluxes higher than about 1000 kW/m^2 (or about 40 kW/m for 37-element fuel).

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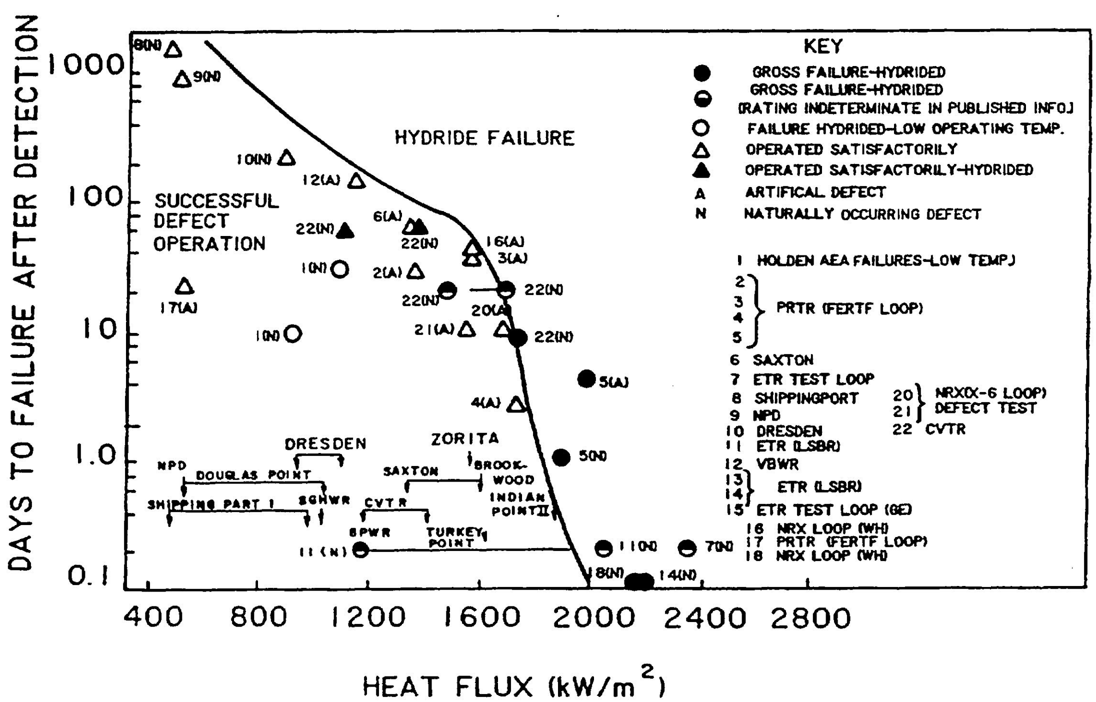

FIGURE 1: LOCKE'S DEFECT PERFORMANCE CURVE OF ZIRCALOY CLAD FUEL (1,2,3)

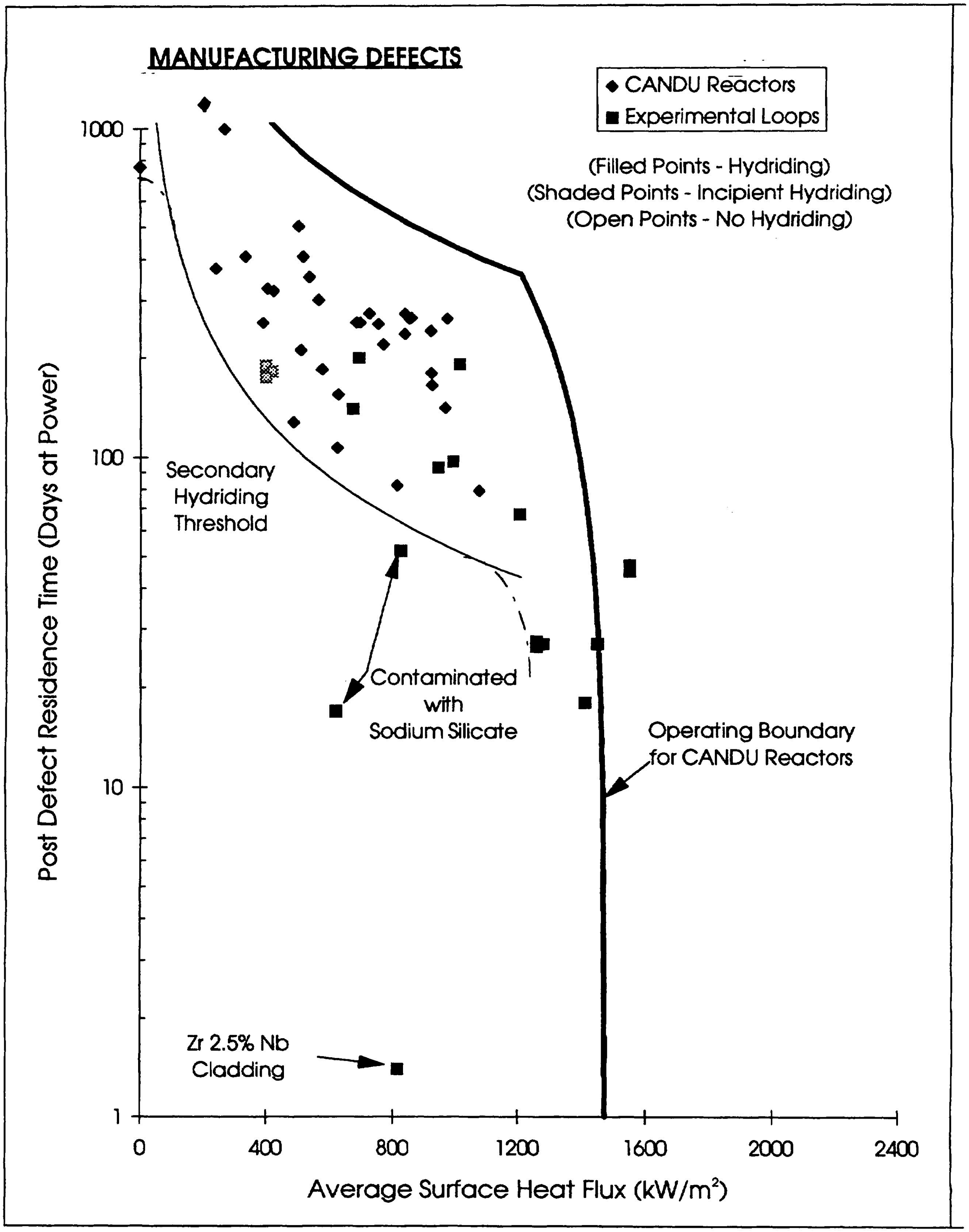

FIGURE 2: POST-DEFECT PERFORMANCE OF CANDU FUEL MANUFACTURING DEFECTS

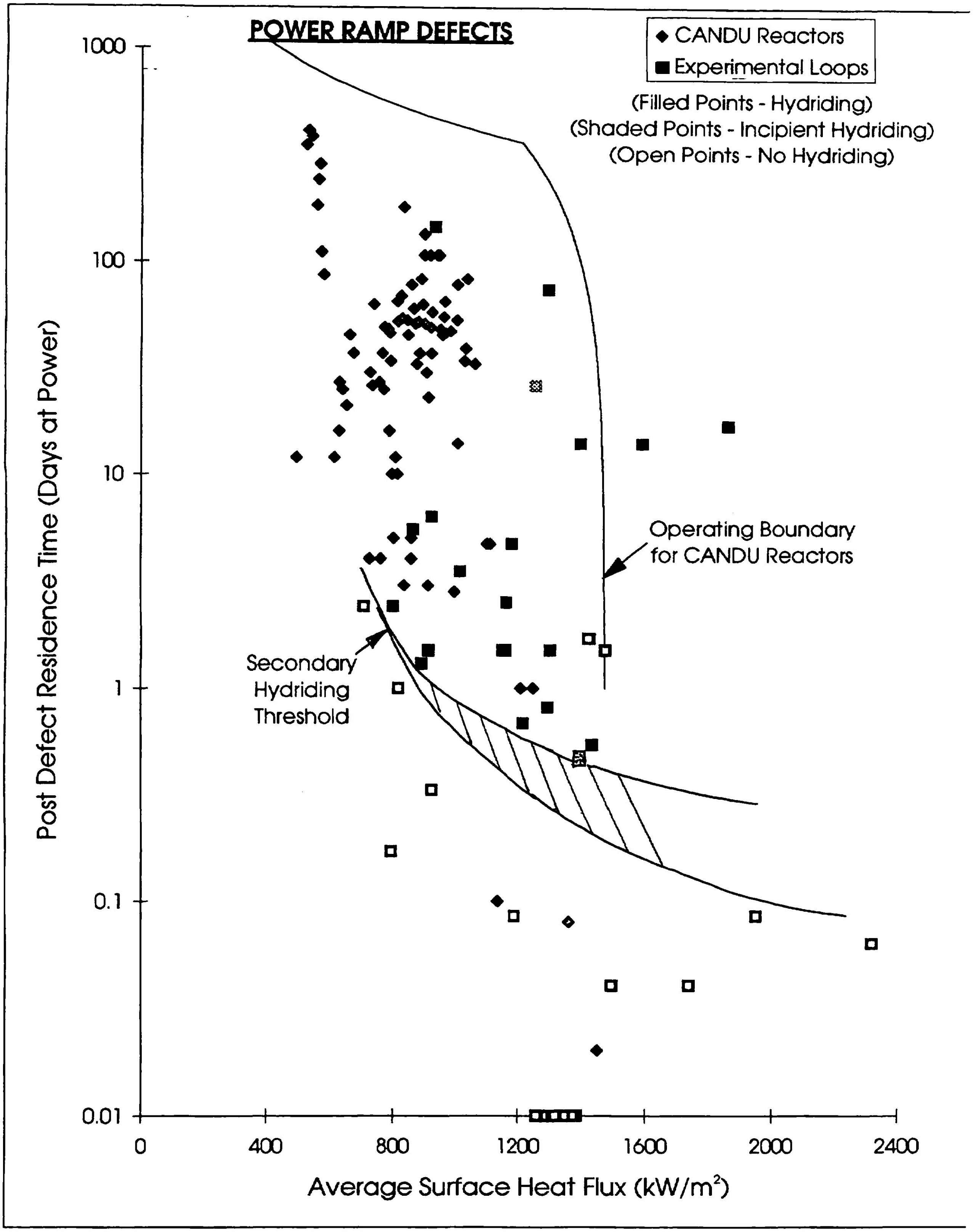

FIGURE 3: POST-DEFECT PERFORMANCE OF CANDU FUEL POWER RAMP DEFECTS

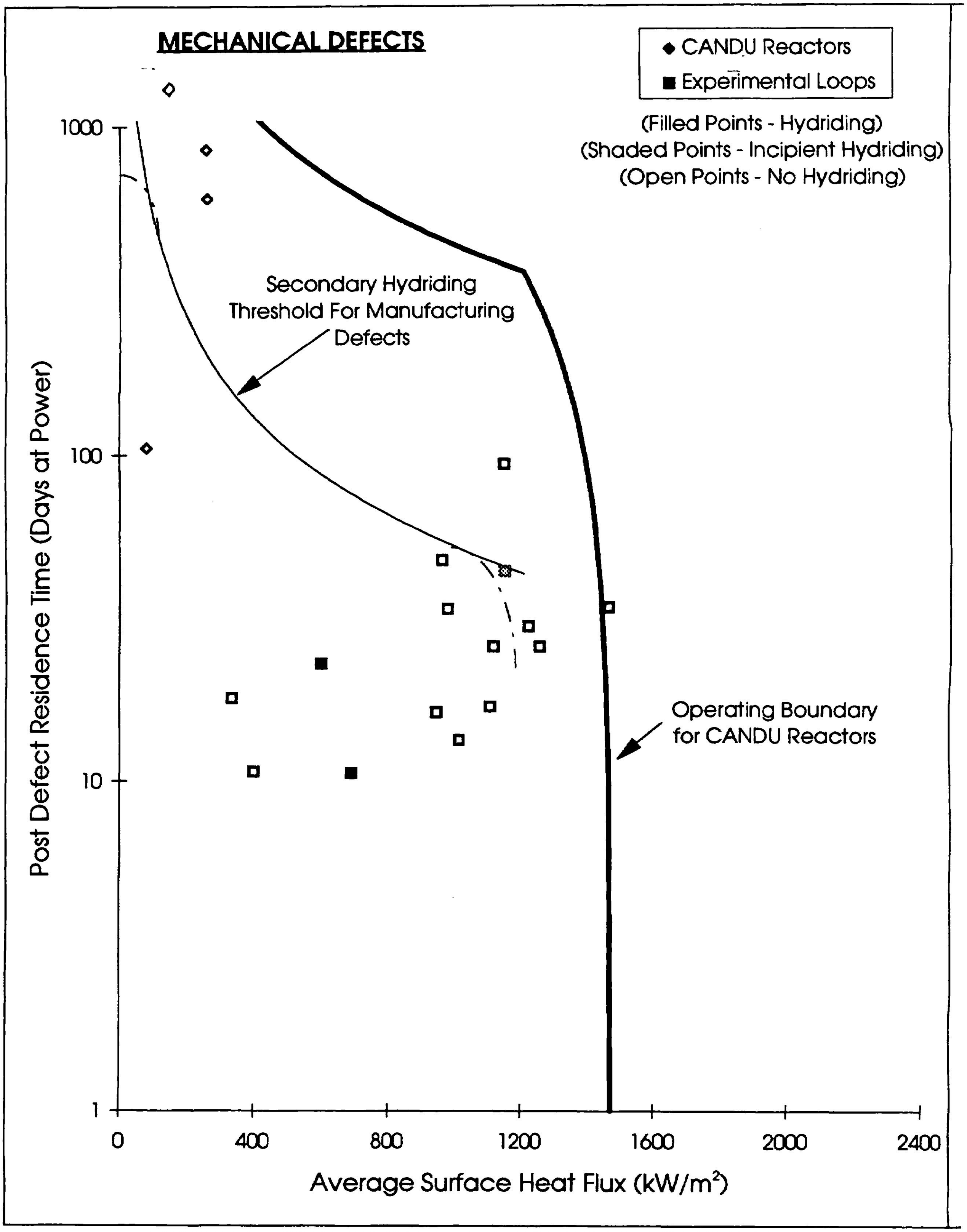

FIGURE 4: POST-DEFECT PERFORMANCE OF CANDU FUEL MECHANICAL DEFECTS

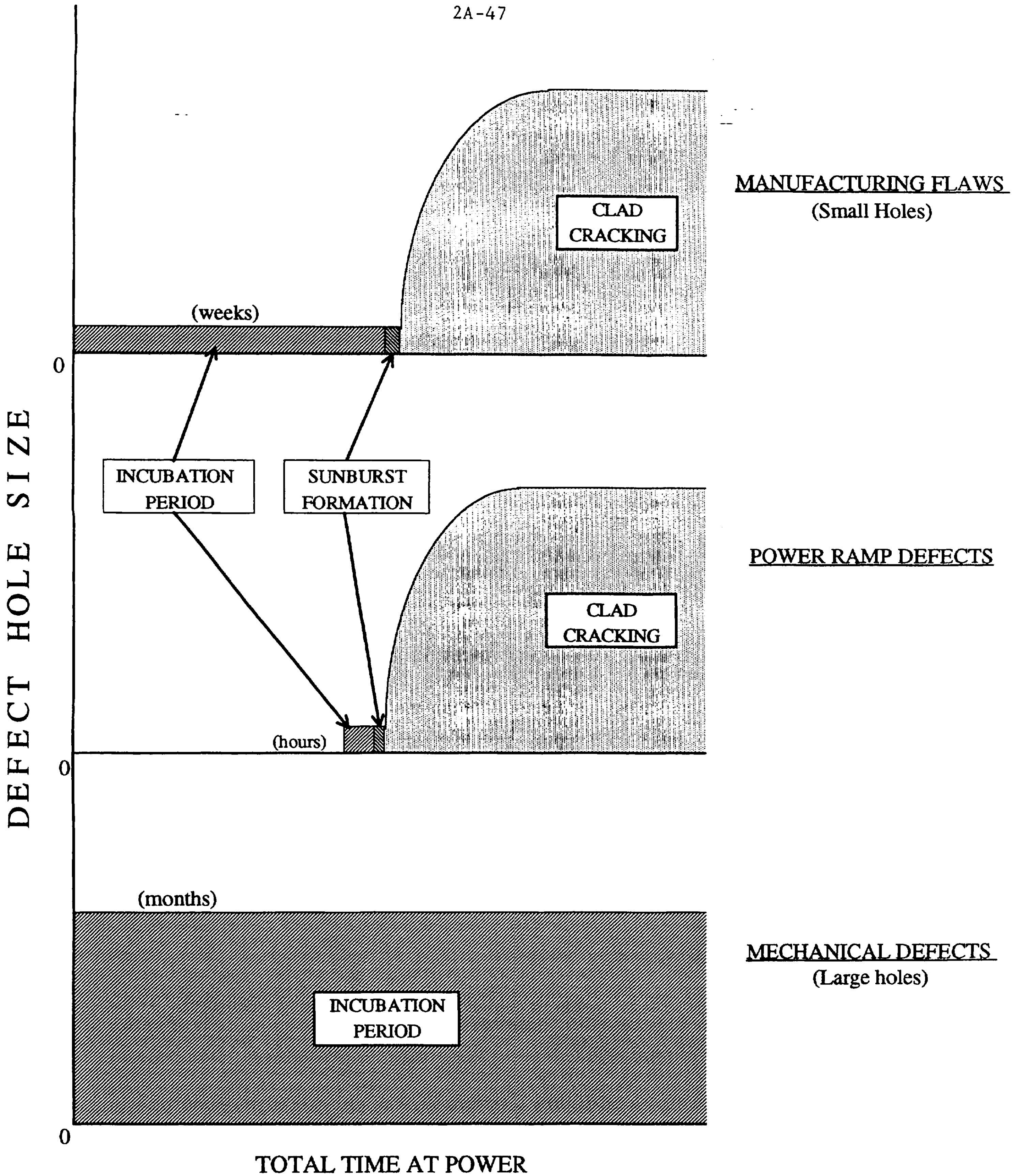

FIGURE 5: POST-DEFECT DETERIORATION BEHAVIOUR FOR THE VARIOUS FUEL DEFECT TYPES