Nuclear Generation Division

Central Nuclear Services

CANDU Fuel Performance:

Nineteen Years of Power Reactor Experience

CNS-73

January 1982

N.V. Ivanoff, E.G. Bazeley and I.J. Hastings*

*AECL Research Company, Chalk River Nuclear Laboratories

Summary*

CANDU fuel has operated successfully in Ontario Hydro's power reactors since 1962. In the 19 years of experience, about 99.9% of all fuel bundles have performed as designed.

Most of the defects occurred before 1979 and subsequent changes in fuel design, fuel management, reactor control, and manufacturing quality control have reduced the current defect rate to near zero.

Loss of power production due to defective fuel has been negligible. This outstanding performance continues while maintaining a low unit energy cost for fuel.

---

*Presented at Canada/Mexico Nuclear Symposium on CANDU Fuel, Mexico City, November 4 and 5, 1981.

1.0 FUEL PERFORMANCE SUMMARY

CANDU fuel has operated successfully in Ontario Hydro's power reactors since 1962 (Table 1 summarizes station electrical output and in-service dates). At the end of August 1981, more than 303 000 fuel bundles had been fabricated. Of these, more than 268 000 had been irradiated. In the 19 years of experience, about 99.9% of all fuel bundles have performed as designed. The cumulative defect rate over that period is 0.13%, or 359 bundles. In terms of individual elements, the defect rate is only about one-tenth of the above figure.

Most of the defects occurred before 1979 and were primarily due either to:

(a) Interaction between pellets and cladding during rapid power changes (power ramping).

or

(b) Manufacturing flaws.

Changes in fuel design, fuel management, reactor control, and manufacturing quality assurance have reduced the number of defects, and loss of power production due to defective fuel has been negligible. This outstanding performance continues while maintaining a low unit energy cost for fuel.

2.0 FUEL DESIGN

There are only 7 basic components in the 37-element CANDU fuel bundle, as shown in Figure 1. Each Zircaloy-4 sheath contains high density natural UO_2 pellets with Zircaloy end caps resistance welded in position. Elements are assembled into bundles by resistance welding them to end plates. Induction brazed appendages are used to maintain inter-element and bundle-to-pressure tube spacing. The bundle is approximately 0.50 m long, containing 18.8 kg of uranium (U) and 2.3 kg of Zircaloy. Further details of fuel characteristics and design are reported elsewhere.(1)(2)(3)(4)(5)

The sheathing is collapsible under coolant pressure and is supported by the fuel pellets during operation. The short bundle, horizontal orientation, and high density fuel have eliminated concerns such as pellet stack slumping, fuel densification, and longitudinal ratchetting.

3.0 FUEL DEVELOPMENT PROGRAM

Successful development of CANDU fuel has resulted from a cooperative approach involving Ontario Hydro, AECL, and the manufacturers. The program began with single element loop irradiations and was extended to full-sized bundle irradiations in AECL's test reactors at Chalk River Nuclear Laboratories (CRNL). Well characterized irradiation data have been obtained (6) and these have been incorporated into fuel performance codes used in reactor operation.[7][8][9][10]

4.0 POWER REACTOR FUEL PERFORMANCE

4.1 Pickering NGS (PNGS)

More than 142 000 bundles have been irradiated with an overall defect rate of 0.08%. Over 90% of the failures occurred during the first two years of station operation (1971 to 1972) and were attributed to sharp power increases during irradiation, termed power ramping. Typically, the defects were cracks of about 1 cm in length in the sheathing of several outer elements per bundle.

Towards the end of the first year of operating Unit 1 (1971), a substantial increase in the heat transport radioiodine concentration indicated the presence of fuel defects. The detailed investigation which followed was greatly facilitated by the characteristic of the CANDU Reactor, which allows removal and analysis of defective fuel bundles during operation. After a combined effort by Ontario Hydro and AECL, the cause of these failures was determined to be fission-product-induced stress corrosion cracking.[11][12] This resulted from the interaction between pellets and cladding during power ramping which accompanied the movement of control rods, and by fuel shifting while replacing defective fuel bundles with new ones. Because new fuel was loaded into channels which previously contained defects, there were several channels with unusually high powers, and fueling near these channels resulted in power increases of sufficient magnitude to fail some bundles.

The fueling data obtained for these investigations were statistically analyzed, and criteria were developed which correlated the probability of a defect occurring with fuel burnup, maximum power, and power increase. This correlation was used successfully to remove fuel defects and to assist fuel scheduling. As a result of the investigation, revisions were made to the fuel management scheme and the sequence of control rod movement. All defective bundles were subsequently removed from the core. The problem of fuel bundle susceptibility to large power increases was overcome by a development program which effectively utilized the combined efforts of AECL, Ontario Hydro and the nuclear fuel manufacturers. This work resulted in an improved fuel design having greater resistance to power increases. The new design was arrived at after extensive testing of various alternatives in the research reactors of AECL at CRNL.(3) The key modification was the introduction of a graphite interlayer (designated CANLUB) on the inner surfaces of the sheaths of the outer elements.(13)(14)

As a result of these measures, current fuel performance at PNGS is excellent. Low concentrations of iodine in the heat transport system indicate that the defect rate is negligible.

4.2 Bruce NGS (BNGS)

More than 101 000 bundles have been irradiated to date, with an overall defect rate of 0.11%. This rate peaked at 0.26% in 1979 because of early manufacturing flaws. Changes in bundle production techniques and quality assurance procedures have reduced the rate to a level of 0.03% in 1981.

During the last quarter of 1977 (first year in service of Units 1 and 2), a number of defective fuel bundles were detected, discharged from the reactor, and confirmed by inspection in the irradiated fuel bay of the station. (The total number suspected was only 114 out of the 101 000 bundles irradiated. The visible damage observed in the irradiated fuel bay was the result of deterioration during irradiation.) Analysis of the bundle power histories and inspection results indicated that these bundles had a low probability of having failed as a result of power increases. Some bundles were examined by AECL in hot cell facilities at CRNL to determine the cause of failure. Examination showed that defects in these bundles were associated with fabrication. The flaws identified were either incomplete end closure welds or porous end plugs. The information was made available to the fuel manufacturers who took corrective action to reduce the number of manufacturing defects by increased quality assurance measures and improved production parameters.

5.0 OTHER DEFECT TYPES

Most fuel defects have been due to power ramping or manufacturing flaws, as discussed in Section 4. The balance of defects (less than 10 bundles) failed due to factors external to the bundle. These included handling damage and fretting by debris in the coolant.

6.0 URANIUM UTILIZATION AND FUELING COSTS

Average fuel burnups at BNGS of 189 MW.h/kg U and at PNGS of 186 MW.h/kg U indicate the high uranium utilization of CANDU reactors. Figure 2 shows the BNGS example, with discharge burnup plotted versus cumulative reactor heat. This high uranium utilization, combined with an efficient, competitive manufacturing industry, has resulted in actual fueling costs in 1980 of $2.33/MW.h at PNGS and $2.67/MW.h at BNGS.

7.0 CONCLUSIONS

With the introduction of the new fuel design (CANLUB), modified fuel management schemes, and revisions to the sequence of control rod movements, failures due to power ramping have been eliminated. Failures due to manufacturing flaws have been reduced to a very low level (0.03%) by effective quality assurance measures in manufacturing. The basic fuel design is considered proven and it remains, therefore, a matter of ensuring continuing production quality assurance to keep manufacturing flaws to these levels. Figure 3 summarizes CANDU fuel production and performance to August 1981, emphasizing the excellent record of CANLUB fuel.

Nineteen years of power-reactor experience has shown the value of a team approach to design evaluation and problem solving. It has demonstrated the importance of communication and collective contribution to a common objective by those involved in research and development, design, manufacturing, and station operation.

References

(1) M. Gacesa, J.C. Wood, and I.J. Hastings, "CANDU Fuel Design Requirements and Features", Presented at Canada/Mexico Nuclear Symposium on CANDU Fuel, Mexico City, November 4 and 5, 1981. Atomic Energy of Canada Limited, report AECL-7520 (1981).

(2) A.S. Bain, et al., "CANDU Fuel - The Influence of Design on Fuel Performance", IAEA Conference on "Fabrication of Water Reactor Elements", Vienna 1979. Atomic Energy of Canada Limited, reprint AECL-6697 (1979).

(3) D.G. Hardy, J.C. Wood, and A.S. Bain, "CANDU Fuel Performance and Development", Atomic Energy of Canada Limited, report AECL-6213 (1978).

(4) A.S. Bain, et al., "The Performance and Evolutionary Development of CANDU Fuel", Proc European Nuclear Conference on "Nuclear Energy Maturity", Paris 1975. Atomic Energy of Canada Limited, reprint AECL-5091 (1976).

(5) I.J. Hastings and G.C. Hatton, "Microstructures in UO_2 Fuel From Canadian Reactors", Fuel Performance Summary, Atomic Energy of Canada Limited, report PP-35/1 (1980).

(6) Summarized by J.R. MacEwan in "Research and Development for CANDU Fuel Channels and Fuel", Atomic Energy of Canada Limited, report AECL-6953 (1980).

(7) M.J.F. Notley, "ELESIM: A Computer Program for Predicting the Performance of Nuclear Fuel Elements", Atomic Energy of Canada Limited, report AECL-6522 (1979).

(8) M.J.F. Notley and I.J. Hastings, "A Microstructure-Dependent Model for Fission Product Gas Release and Swelling in UO_2", Nuc Eng and Design 56 (1980) 163. Atomic Energy of Canada Limited, reprint AECL-5838 (1979).

(9) I.J. Hastings and M.J.F. Notley, "Prediction of Fission Gas Release From High Burnup Oxide Fuel", Trans 5th Int Conf SMIRT, Vol C, Paper C1/3 (1979). Atomic Energy of Canada Limited, reprint AECL-6682 (1979).

(10) I.J. Hastings, M.J.F. Notley, and D.H. Rose, "Irradiation-Induced Volume Changes in Commercial UO_2 Fuel: Comparison with Model Prediction", J Nucl Mater 7 (1978) 301. Atomic Energy of Canada Limited, reprint AECL-6224 (1978).

(11) J.C. Wood, "Interactions Between Stressed Zirconium Alloys and Iodine at 300°C", Nuc Tech 23 (1974) 63. Atomic Energy of Canada Limited, reprint AECL-4774 (1974).

(12) J.C. Wood and J.R. Kelm, "Effects of Irradiation on the Iodine-Induced Stress Corrosion Cracking of CANDU Zircaloy Fuel Cladding", IAEA Specialists' Meeting, Riso, Demark, September, 1980.

(13) J.A.L. Robertson, "Improved Performance for UO_2 Fuel", Engineering Journal, November and December, 1973. Atomic Energy of Canada Limited, reprint AECL-4366 (1973).

(14) A.S. Bain, J.C. Wood, and C.E. Coleman, "Fuel Designs to Eliminate Fuel Defects on Power Increases", Proceedings of the International Conference on Nuclear Fuel Performance, London, England, October 1973, British Nuclear Energy Society, p.56.1-56.6. Atomic Energy of Canada Limited, reprint AECL-4518 (1973).

TABLE 1

In-service Dates for Ontario Hydro Power Reactors

Stations	Net Electrical Output (MW)	Unit 1	Unit 2	Unit 3	Unit 4
NPD NGS	1 x 22	Oct 1962			
Douglas Point NGS	1 x 206	Sep 1968			
Pickering NGS-A	4 x 515	Jul 1971	Dec 1971	Jun 1972	Jun 1973
Bruce NGS-A	4 x 740	Sep 1977	Sep 1977	Feb 1978	Jan 1979

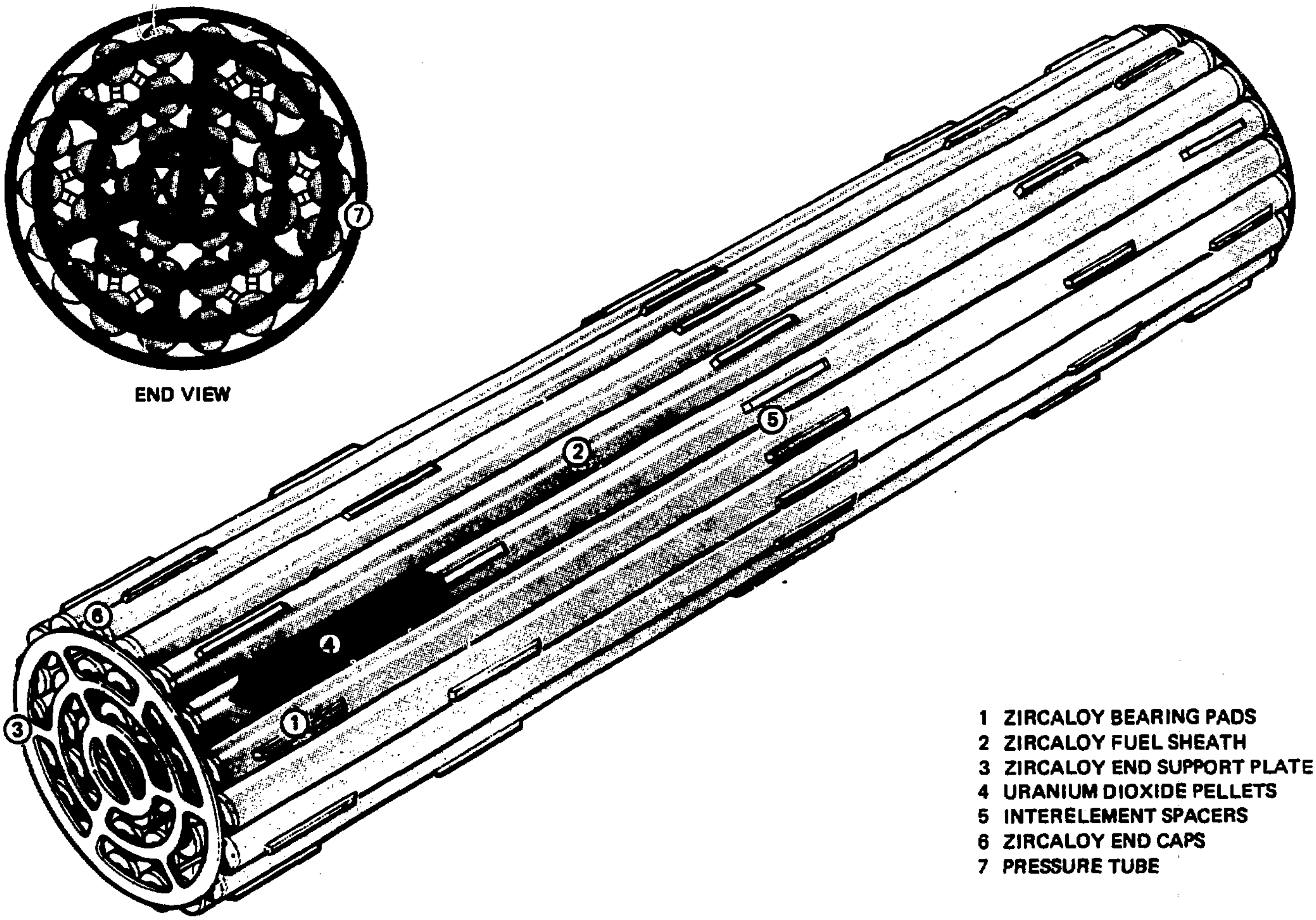

*Figure 1 37-element CANDU fuel bundle - Bruce NGS design.

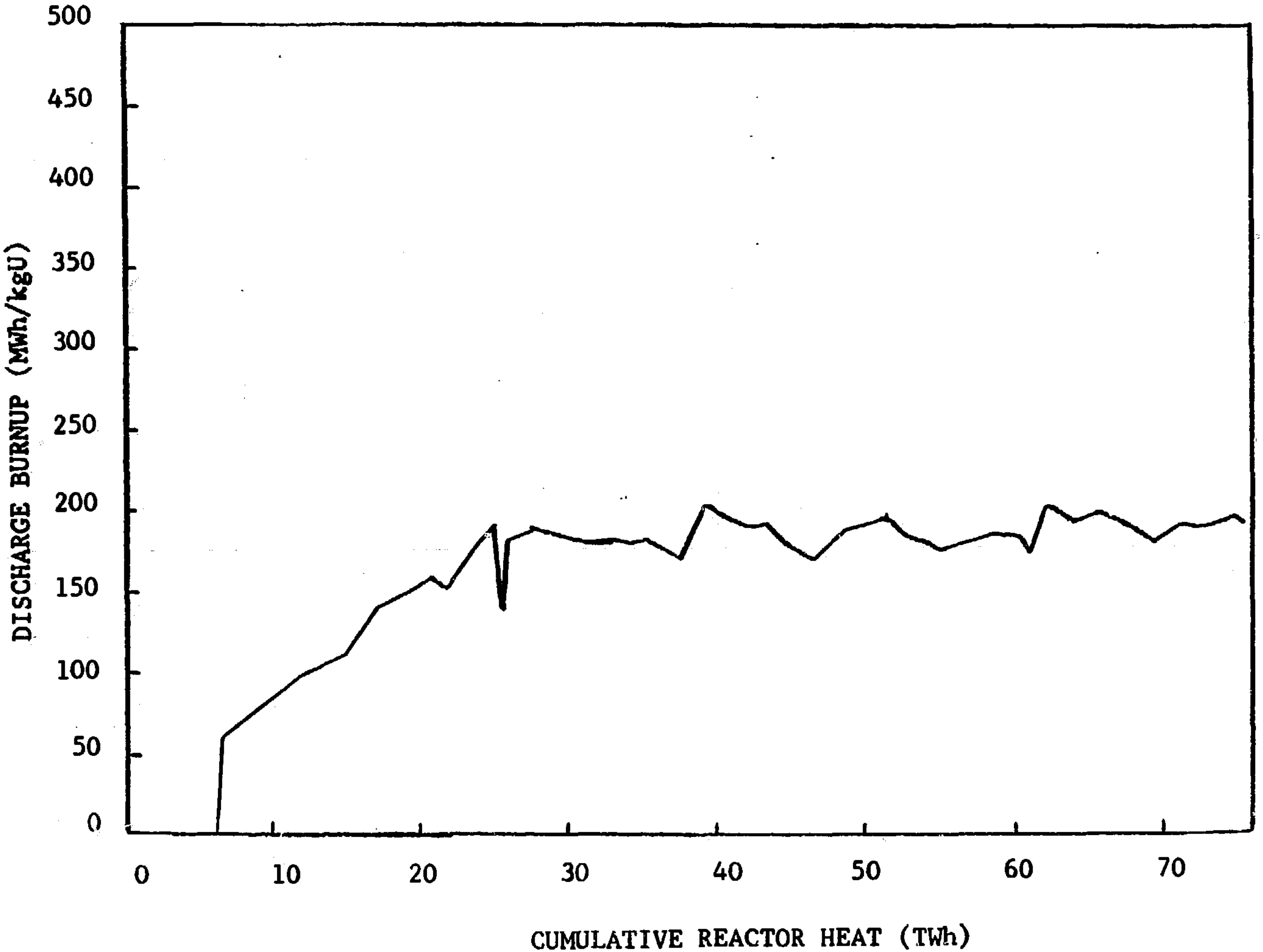

Figure 2 Bruce N.G.S. Unit 1 fuel performance to 1981 June.

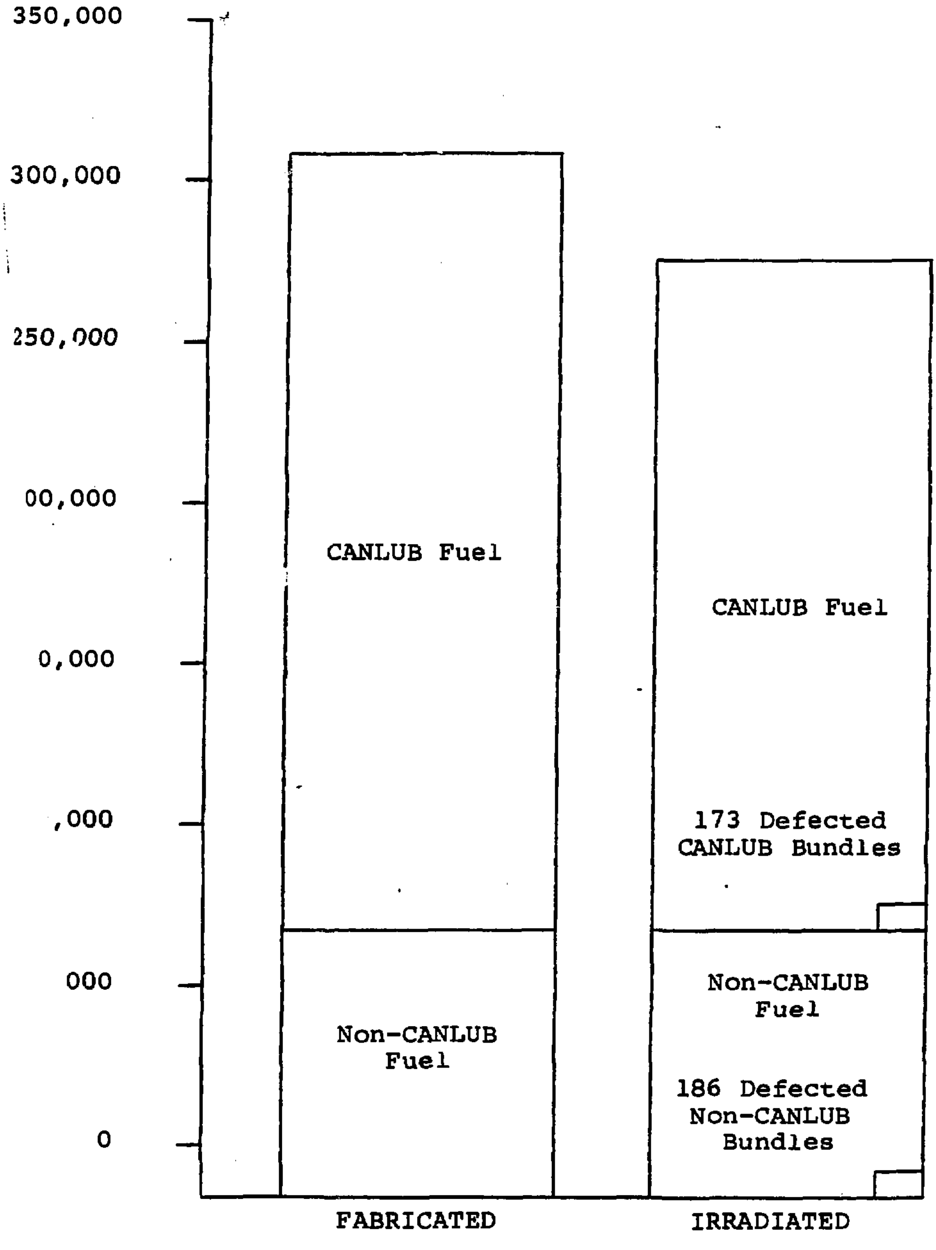

Figure 3

Summary of CANDU fuel production and performance to August 1981.