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FUEL FOR CANDU PRESSURIZED HEAVY WATER REACTORS

by

R.D. PAGE and G.R. FANJOY

Technical paper 6/10 presented at NUCLEX 75, International Nuclear Industries Fair and Technical Meetings, 7 to 11 October 1975, Basel, Switzerland.

Chalk River Nuclear Laboratories
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BRENNSTOFF FUER DIE CANDU-SCHWERWASSER-DRUCKREACTOREN

COMBUSTIBLE DES REACTEURS CANDU A EAU LOURDE PRESSURISEE

by
par

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The unique characteristics of CANDU fuel and its design and development are described. The production requirements, uranium consumption, and fuel costs are discussed. The in-service performance of the fuel has been excellent and defect mechanisms and operating criterion are described. The evolutionary improvements in CANDU fuel and new fuel cycles such as plutonium and thorium are being explored to insure that the CANDU reactor remains competitive in the future.

Die einzigartigen Eigenschaften des CANDU-Brennstoffs seine Ausführung und seine Entwicklung sind hier beschrieben. Die Herstellungsbedingungen, der Uraniumverbrauch und die Brennstoffkosten werden erörtert. Die "in Betrieb" Brennstoffleistung ist hervorragend. Die Fehlermechanik und die Betriebskriterien werden beschrieben. Laufende Verbesserungen des CANDU-Brennstoffs und neue Brennstoffzyklen wie der Plutonium und Thoriumzyklus werden untersucht, damit die CANDU-Reactoren in Zukunft Konkurrenzfähig bleiben.

Cet exposé décrit les caractéristiques uniques du combustible CANDU, sa conception et sa mise au point. Il aborde les exigences de la manufacture, la consommation d'uranium et les coûts du combustible. Il décrit l'excellent rendement du combustible, la mécanique des ruptures et les critères de fonctionnement. Il explore les progrès du développement du combustible CANDU et des cycles du nouveau combustible tel que le plutonium et le thorium pour s'assurer que le réacteur CANDU demeurera concurrentiel à l'avenir.

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INTRODUCTION

CANDU Power Reactor Fuel is different in many ways when compared to the fuels of the other two commercially operating nuclear generating systems - Light Water LWR and Gas Cooled Reactors MAGNOX. The only features it has in common with the LWR type fuel are Zircaloy sheathing and UO_2 pellets, and in the case of MAGNOX reactors - the use of natural uranium.

Evolving as an integral part of the CANDU system the fuel has a number of unique characteristics. Some are due to the use of natural uranium dioxide fuel as opposed to enriched fuel and some are the result of deliberate engineering decisions, such as the short fuel bundle in the horizontal pressure tubes with on-power fuelling. The drive to conserve neutrons led to the development of a simple fuel design with thin wall collapsible sheathing. The net result is that the fuelling cost for the CANDU system is the lowest of the present day nuclear generating systems.

From the beginning, the objective has been to develop power-reactor fuels that are both reliable and inexpensive. To achieve this, the fuel has been kept as simple as possible. The bundle consists of only the fuel and a minimum of structural materials; all related but non-consumable components - such as channels, orifices, control and monitoring equipment, and fuel handling hardware - are kept as part of the reactor capital equipment. Fabrication techniques are also simple and, whenever possible, are adapted from normal industrial practice. These techniques are susceptible to standardization and automation.

FUEL DESIGN

The Pickering fuel bundle shown in Figure 1 is the fuel designer's response to the objective. There are only seven different types of components and all the 51,000 bundles that have been used to date in the 2,160 MW(e) Pickering Generating Station are externally identical. It is a bundle of 28 closely packed elements, each containing high-density natural UO_2 in a thin (0.4 mm) Zircaloy sheath. Plates welded to the end of the elements hold them together; spacers brazed to the sheaths keep the desired separations. The bundle is approximately 500 mm long and 100 mm in diameter. The Pickering fuel bundle is 92 wt% UO_2, the 8 wt% Zircaloy is made up of the sheaths, end-caps, structural end-plates, and spacers. The structural material accounts for only 0.7% of the thermal neutron cross-section of the bundle, to give a fuel assembly that is highly efficient in its use of neutrons. The same design will be used in the four units of Pickering 'B' now under construction. This will raise the total electrical power of the overall nuclear station to 4,320 MW(e).

DEVELOPMENT HISTORY

In Canada, the development of power reactor fuels began some 18 years ago with the design and manufacture of the first charge for the demonstration power reactor, NPD. The design and development of fuel for the CANDU type reactors has been well documented(1,2,3,4,5) therefore it is necessary only to outline briefly the salient points.

The original fuel charge for NPD contained wire-wrapped 7-element bundles in the outer zone and 19-element wire-wrap bundles in the centre. The 7-element bundle has not been developed further and is being phased out of the reactor. The 19-element bundle design was modified for Douglas Point. Because of the concern of possible sheath fretting by the wire wrap which spaces the elements apart, the replacement fuel for this reactor is designed with the element spacers and bearing pads brazed to the sheath. This method of fabrication is now standard for all CANDU power reactor fuels.

The fuel for the Pickering reactors, as described previously, uses the same length and diameter of element (495 mm and 15.3 mm). The number of elements has been increased to 28 to fill the 103.4 mm diameter pressure tube, as compared to the 82.5 mm diameter pressure tube for NPD and Douglas Point.

For the Bruce 750 MW(e), Gentilly-2 600 MW(e) and future 1200 MW(e) type reactors, we have developed a 37-element bundle shown in Figure 2. 35,000 of these bundles are under construction at Canadian General Electric for the four units of the Bruce Generating Station (3,000 MW(e)). First unit will go on power in early 1976.

The various cross-sections of fuel bundle designs described above are shown in Figure 3, including the fuel for Gentilly-1 which is a CANDU boiling light water reactor. The nominal design and operating conditions for the various CANDU reactor fuels are listed in Table 1.

FABRICATION AND FUEL COSTS

CANDU fuel fabrication utilizes unique features compared to other fuel designs. They are:

(1) The short fuel bundle lends itself to easy handling in mass production.

(2) Induction brazing of the bearing pads and inter-element spacers to the sheathing with a zirconium-beryllium alloy.

(3) The use of thin wall collapsible (0.40 mm) Zircaloy cladding, which is designed to be supported by the UO_2. As high-density fuel was specified when the concept was introduced years ago, the problems associated with densification were avoided.

(4) The use of resistance welding to seal the end caps to the sheath, compared to the normal Tungsten Inert Gas weld used by the majority of designs.

The use of short, natural uranium bundles and concentration on a single reactor type has resulted in a very significant fabrication experience of mass producing fuel. Table 2 shows the total number of fuel assemblies completed and irradiated as of April 1, 1975. Greater than 100,000 CANDU bundles have already been completed, representing more than 2,500,000 elements and 5,000,000 closure welds. This numerical volume of Zircaloy-UO_2 fuel production experience may be the largest in the world.

The maturity of the Canadian fuel industry was celebrated recently by presenting the 100,000th fuel bundle to the Prime Minister of Canada, at the Canadian Nuclear Association conference in Ottawa, June 1975.

It is well to remember that this amount of nuclear fuel has the capability of producing energy in CANDU reactors equal to that produced by 45 million tons of coal, 205 million barrels of oil or 1,188 billion cubic feet of natural gas.

Ontario Hydro has 13,320 MW(e) operating or under construction and is planning to have 50,000 MW(e) committed in Ontario by 1990(6). Other Canadian utilities and exports to other countries have 3,181 MW(e) operating or under construction with a further 3,600 MW(e) to be committed in the next decade.

This growth in nuclear power station construction will require a rapid expansion of fuel production as shown in Figure 4, where the Canadian annual uranium requirement is projected to the end of the century (2000). It indicates an expansion from approximately 383 MgU or 25,000 bundles a year capacity in 1975 to over 1,000 MgU by 1980 and with an approximate doubling of consumption every five years during the next decade. The cumulative uranium requirements during the next 25 years will be approximately 10 GgU.

Although the CANDU fuel development program is directed and largely financed by ATOMIC ENERGY OF CANADA LIMITED (AECL), and ONTARIO HYDRO, the development of production and fabrication methods is carried out by private industry. Westinghouse Canada Limited (WCL) and Canadian General Electric (CGE) are the two fully qualified fuel fabricating companies in Canada. A third, Combustion Engineering-Superheater is planning to enter the market between now and 1980. AECL fuel teams at Sheridan Park, Chalk River and the Whiteshell Nuclear Research Establishment complement the program by designing, executing irradiation experiments and directing the fuel development programs. Exceptional loop facilities in the NRX, NRU and WR-1 research reactors provide the fundamental data on which detailed fuel design is based.

The procurement policy of all fuels for CANDU reactors has been based on a competitive fixed price bidding system. This has resulted in a decreasing fuel price as the program matured. The total fuel costs in $ per kg/U (including uranium) in dollars of the year, are shown in Figure 5. In the period, 1967 to 1973; decreasing fabrication costs countered inflation, achieving constant fuelling costs in this period.

The value of spent fuel is given no credit for potentially saleable isotopes. The CANDU reactor fuel cycle is a simple once-through cycle, with the long term underwater storage of spent fuel at the reactor sites. Further expansion of this concept of fuel storage is being planned(7).

Todays replacement fuel prices for Pickering G.S. are approximately $60/kgU (1975 $ Canadian). This increase is due to the combined effect of the world price of the uranium and inflation. As the uranium component is more than half the total, its effect is the strongest.

It may be noted, also from Figure 5, that in addition to a "hold the line" price performance, the bundle thermal performance has also improved. Thus in real terms, the cost relative to thermal performance has decreased substantially.

These total fuel costs are the lowest in the world and result in a fuelling cost for Pickering Generating Station of approximately 1.0 m $/kwh.

Even with the rising world price of uranium the CANDU reactor fuelling costs will remain lower than its nuclear and fossil competitors by a significant margin.

IN-SERVICE PERFORMANCE

The in-service performance of CANDU fuel has been excellent. Of the 72,382 fuel bundles irradiated up to December 1974, in nine CANDU reactors (totalling 2,840 MW(e), 99.7% have performed as designed$^{(8,9)}$. It should be noted that these statistics are based on bundles, not defective pins, elements or rods, which, if used, would improve the statistics by an order of magnitude i.e. 0.03% defective. As of April 1, 1975 the number of bundles irradiated has increased to 76,665. Of the relatively few defects that have occurred in CANDU reactor fuel, most could be attributed to a single cause - sheath rupture due to a substantial power increase following a prolonged period of low power. These power increases can be caused by the movement of fuel during fuelling or by changes in flux due to nearby reactivity mechanisms. The description of the power changes causing power ramp defects both in Douglas Point and Pickering are described in detail in Reference 9 and therefore will not be repeated. It is suggested that this behaviour will also apply to other reactors where the fuel is exposed to power changes caused by fuelling, movement of control rods and gross reactor power changes after periods at low power. This behaviour was originally indicated by analyses of the operating records from the Douglas Point reactor and later, from the records of Pickering Unit 1.

Laboratory and in-reactor experiments have identified two mechanisms which can cause cracking of fuel cladding during power ramps. The primary mechanism is stress corrosion cracking associated with the fission product iodine at specific combinations of stress and iodine concentrations$^{(10,11,12)}$. Similar experiences have been reported in Europe$^{(13,14,15)}$. The other mechanism is mechanical interaction of the pellet with the sheath causing tensile failure of the fuel cladding without the assistance of iodine stress corrosion cracking. It has been found that the necessary concentration of both stress and strain can be produced by the radial cracks during thermal expansion of the UO_2 and at interfaces between pellets, i.e circumferential ridges. Also over small chips of UO_2 that become wedged between the fuel and sheath in the diametral gap.

After identifying the cause of the fuel defects the immediate remedy at the stations was to modify the fuel management schedules to avoid power increases that led to the original defects. Since 1972 this has resulted in a marked drop in the defect rate equal to or less than the design target of 0.1%(9) (a "zero defect" target appears to be an unwarranted expense in view of the fact that defects can be removed from CANDU plants without shutting down).

From a reactor operators point of view, any restrictions to fuel management or reactor power maneuvering is undesirable. A program has therefore been instituted in the test reactors to prove a fuel design more tolerant to power increases. A preferred solution is designated Canlub(16,17,18) which incorporates a thin graphite layer between the UO_2 and the sheath. The graphite acts as a lubricant between the UO_2 and the sheath, reducing stress concentrations and possibly acts also as a barrier to the chemical attack of the Zircaloy by the iodine under these stress conditions. Loop tests have shown a significant improvement in the performance and modifications have been introduced into all CANDU fuel production with minimal cost penalties.

Analysis of fuel performance data has produced a reliable fuel performance criterion(19). This criterion has been successfully employed to avoid defects which can be induced by fuel management, reactivity mechanism movement, and gross reactor power increases. The four important parameters affecting the defect behaviour are:

(1) Maximum element power per unit length during power change

(2) Power increase

(3) Fuel burnup

(4) Time at maximum power

This criterion is based on a statistically significant number of operating fuel bundles and maybe applicable to other reactors using Zircaloy and UO_2 to prevent power ramp defects$^{(20)}$.

The speed of response to any unforeseen problem is determined by two factors: the time taken to identify the problem and the time to find and implement a solution. The identification of the defects and their causes was greatly facilitated by CANDU reactor design. The capability of monitoring activity release from individual fuel channels allowed the incidence of failures to be correlated with reactor parameters. It was also possible to identify the defected bundle in the channel. The capability of on-power fuelling meant that fuel could be discharged immediately and examined before any evidence was destroyed by secondary damage. The use of heavy water coolant permitted the distinction between sheath hydride due to in-service corrosion and that due to internal contaminants. In fact little hydrogen (as opposed to deuterium) was observed in the sheaths of failed elements so we were not misled into attributing the failures to hydrogenous contaminants.

CANDU reactors are designed as base load stations with continuous on-power fuelling. The heavy swing to nuclear power in the utilities' systems will require increasing emphasis on the reactors to follow daily loads. Considerable experience has been obtained with daily power cycles with the CANDU KANUPP reactor in Karachi where it has been following the daily grid demands and accumulated hundreds of power cycles without any performance change in fuel. We have been informed that the RAPP-1 reactor in India is also successfully load following to meet the grid demands.

During the commissioning of the CANDU-BLW reactor Gentilly-1, it was found to be beneficial to raise the reactor to full power in small power increments with an overshoot and a hold at each step. This prevented the fuel experiencing a large power increase which could have caused a significant number of defects predicted by the defect criterion. The procedure was necessary due to the prolonged period of low power during commissioning.

POTENTIAL FOR FUTURE DEVELOPMENT

There are still opportunities for evolutionary improvements in CANDU fuel and these are being explored. However, one of the attractive features of the CANDU system is its versatility. The same general design of heavy water moderated pressure tube reactor can exploit many varied fuel cycles with changes in fuel design.

The development of plutonium fuels for future applications in present and planned reactors has started with initial bundles in NPD exceeding burnups of 400 MWh/kgU, compared to the average uranium discharge burnup of less than 200 MWh/kgU(21). The overall program, when completed, will allow the utilities to recycle plutonium, when the economic environment changes to warrant its use. Also the thorium fuel cycle associated with plutonium is being investigated for application in the late 90's and early years of the twenty-first century to conserve fertile material and counter the rising costs of uranium and other energy sources(22).

The capability of on-power fuelling of the CANDU reactor allows the simple and gradual introduction of new fuel materials such as plutonium and thorium when the economics of future fuel cycles warrants their use. Such versatility makes the CANDU reactor unique among its contemporaries. This provides protection against escalating costs of uranium enrichment and independence from foreign fuel supply, assuring Canadians of adequate resources for centuries, without developing major new reactor concepts.

SUMMARY

Three criteria govern present CANDU fuel designs and the direction of future development; neutron economy, simple design, on-power fuelling.

Fuel performance has been excellent, greater than 99.7% of all the bundles irradiated have performed as designed. This high performance has not carried a premium price, e.g. for Pickering, the present total fuel cost is approximately $60/kgU, including uranium. This is the lowest fuel supply cost of any operating nuclear generating system in the world.

Even with the rising world price of uranium, the CANDU reactor fuelling costs will remain lower than its nuclear and fossil competitors by a significant margin.

Also new fuel cycles are being investigated and developed such as plutonium and thorium for future application to ensure that the CANDU reactor remains competitive with other reactor concepts.

REFERENCES

(1) R.D. Page et al: "Engineering and Performance of UO_2 Fuel Assemblies", Proc. Inter. Conf., Peaceful Uses of Atomic Energy, Geneva, 10, 65, CRNL Report AECL-2018, Atomic Energy of Canada Limited (1964).

(2) R.D. Page: "Engineering and Performance of Canada's UO_2 Fuel Assemblies for Heavy Water Power Reactors", CRNL Report AECL-2949, SM-99/48, IAEA Symposium on Heavy Water Power Reactors, (September 1967).

(3) R.D. Page, A.D. Lane: "The Performance of Zirconium Alloy Clad UO_2 Fuel for Canadian Pressurized and Boiling Water Power Reactors", joint ANS/CNA Conference, Toronto, AECL-3068, Atomic Energy of Canada Limited (June 1968).

(4) L.R. Haywood et al: "Fuel for Canadian Power Reactors", Proc. Intern. Conf. Peaceful Uses of Atomic Energy, Geneva, A/Conf.49/A/156, CRNL Report AECL-3979, Atomic Energy of Canada Limited (1971).

(5) J.R. MacEwan et al: "Irradiation Experience with Fuel for Power Reactors", Proc. Intern. Conf., Peaceful Uses of Atomic Energy, Geneva, A/Conf.49/A/158, CRNL Report AECL-3981, Atomic Energy of Canada Limited (1971).

(6) W.G. Morison: "CANDU Nuclear Power in Ontario", Nuclear Engineering International (Vol. 19, No. 217, June 1974).

(7) R.W. Barns, S.A. Mayman:"The Canadian Program for Management of Spent Fuel and High Level Wastes", ANS/CNA Topical Meeting on Commercial Nuclear Fuel Technology, Toronto (April 1975).

(8) A.S. Bain et al: "Performance and Evolutionary Development of CANDU Fuel", ENS/ANS Paris Conference (April 1975).

(9) G.R. Fanjoy et al: "Canadian Nuclear Fuel Operating Experience", ANS/CNA Topical Meeting on Commercial Nuclear Fuel Technology, Toronto (April 1975).

REFERENCES (Continued)

(10) J.C. Wood, Nuclear Technology 26, 63, (1974).

(11) B. Cox, J.C. Wood: "Corrosion Problems in Energy Conversion and Generation", Pub. The Electrical Chemical Society, ED.C.S. Tedman Jr. (October 1974).

(12) J.A.L. Robertson: "Nuclear Fuel Failures, Their Causes and Remedies", ANS/CNA Topical Meeting on Commercial Nuclear Fuel Technology, Toronto (April 1975).

(13) E. Rolstand and K.D. Knudsen, Proceedings of 4th International Conference on Peaceful Uses of Atomic Energy", Geneva, 10, 257, IAEA Vienna (1971).

(14) S. Aas, K.D. Oshausen: "Fuel Failures Caused by Overpower Ramp", British Nuclear Engineering Society, London (October 1973).

(15) A.S. Bain, J.C. Wood, C.E. Coleman: "Fuel Designs to Eliminate Defects on Power Increases", British Nuclear Engineering Society, London (October 1973).

(16) J.A.L. Robertson: "Improved Performance for UO_2 Fuel", CRNL AECL-4366, Atomic Energy of Canada Limited (January 1973).

(17) J.A.L. Robertson, R.D. Page, L.L. Bodie: "Canadian Fuel Performance", ANS, Chicago, Illinois, AECL-4520, Atomic Energy of Canada Limited (June 1973).

(18) J.A.L. Robertson: "The Physical Metallurgy of CANDU Fuel", International Conference on Physical Metallurgy of Reactor Fuel Elements, Berkley Nuclear Laboratories, (September 1973).

(19) W.J. Penn, R.K. Lo, J.C. Wood: "CANDU Fuel - Power Ramp Performance Criteria", ANS, San Francisco, to be published, (1975).

(20) P. Knudsen: "Cladding Failure in BWR and PWR Overpower Tests", ANS/CNA Topical Meeting on Commercial Nuclear Fuel Technology, Toronto (April 1975).

REFERENCES (Continued)

(21) J.R. MacEwan, A.J. Jeffs: "Development Program for Plutonium Fuelled CANDU Reactors", presented at IAEA Symposium, Atomic Energy of Canada Limited, CRNL-1226 (November 1974).

(22) A.J. Mooradian, O.J.C. Runnalls: "CANDU - Economic Alternative to Fast Breeders", presented at 9th World Energy Conference, Detroit, Atomic Energy of Canada Limited AECL-4916 (September 1974).

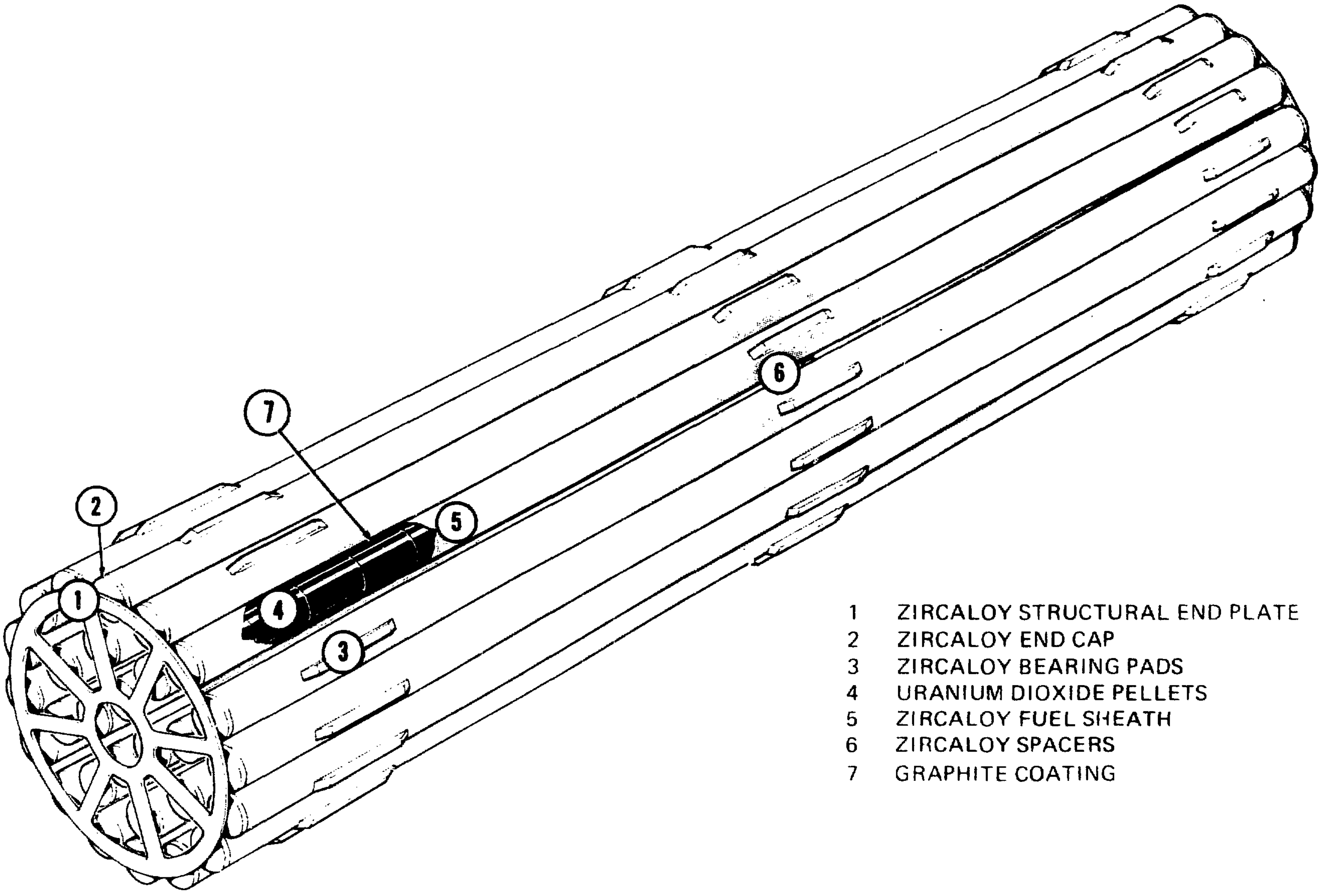
REACTOR		NPD	NPD	DOUGLAS POINT	GENTILLY 1 BLW	PICKERING A	BRUCE A	600 MW
NUMBER OF ELEMENTS PER BUNDLE		7	19	19	18	28	37	37
ELEMENTS								
MATERIAL		ZIRC-2	ZIRC-4	ZIRC-4	ZIRC-4	ZIRC 4	ZIRC-4	ZIRC 4
OUTSIDE DIAMETER	mm	25.4	15.25	15.22	19 74	15.19	13.08	13 08
MIN. CLADDING THICKNESS	mm	0.64	0 38	0.38	0 49	0.38	0 38	0 38
BUNDLES								
LENGTH	mm	495.3	495.3	495.3	500 0	495 3	495 3	495 3
MAXIMUM DIAMETER	mm	82.04	82.04	81.74	102.41	102 49	102 49	102 49
NUMBER PER CHANNEL		9	9	12	10	12	13	12
PRESSURE TUBE								
MINIMUM INSIDE DIAMETER	mm	82.55	82 55	82.55	103 56	103.38	103 38	103 38
OPERATING CONDITIONS								
COOLANT		D_2O	D_2O	D_2O	H_2O	D_2O	D_2O	D_2O
NOMINAL INLET PRESSURE	MPa	7.9	7.9	10.16	6 32	9 6	10 2	11 09
NOM.MAX.CHANNEL POWER	MW	0.985	0 985	2.752	3 18	5 43	6 64	6.51
EXIT STEAM QUALITY	%	–			16.5		0.8/4 0	~ 2 55
MAX. MASS FLOW/CHANNEL	kg/sec	6.6	6.6	12.6	11 2	23 88	23 81	23.94
NOM. MAX HEAT RATING $\int \lambda d\theta$	kW/m	3.45	2 08	4.0	4 8	4 2	4 43	4 3
MAXIMUM LINEAR ELEMENT POWER	kW/m	43.4	24.9	50.3	61 2	52.8	55 67	54 08
MAX.SURFACE HEAT FLUX	kW/m2	560.7	514.1	1070	986 5	1120.	1354 7	1315 5
NOM.MAX. BUNDLE POWER	kW	221.	221.	420	484.	636.	873	830.
AVG. DISCHARGE BUNDLE BURNUP	MWh/kgU	156.	156.	190.	168	170/185	196	180

TABLE I CANADIAN POWER REACTOR FUEL – DESIGN AND OPERATING DATA

STATION	BUNDLES COMPLETED	BUNDLES IRRADIATED	BUNDLES DISCHARGED
NPD	4,005	3,622	2,434
DOUGLAS POINT G.S.	12,272	11,061	7,429
GENTILLY 1	5,870	3,214	134
PICKERING G.S.	60,707	50,478	32,302
BRUCE G.S.	9,693	0	0
RAPP	4,420[e]	4,420[e]	740[e]
KANUPP	4,738	3,870	1,582
TOTALS	101,705	76,665	44,621

[e] ESTIMATED

TABLE 2: CANDU FUEL PRODUCTION AND IRRADIATION DATA
(AS OF APRIL 1, 1975)



1	ZIRCALOY STRUCTURAL END PLATE
2	ZIRCALOY END CAP
3	ZIRCALOY BEARING PADS
4	URANIUM DIOXIDE PELLETS
5	ZIRCALOY FUEL SHEATH
6	ZIRCALOY SPACERS
7	GRAPHITE COATING

FIGURE 1 FUEL BUNDLE FOR PICKERING REACTOR

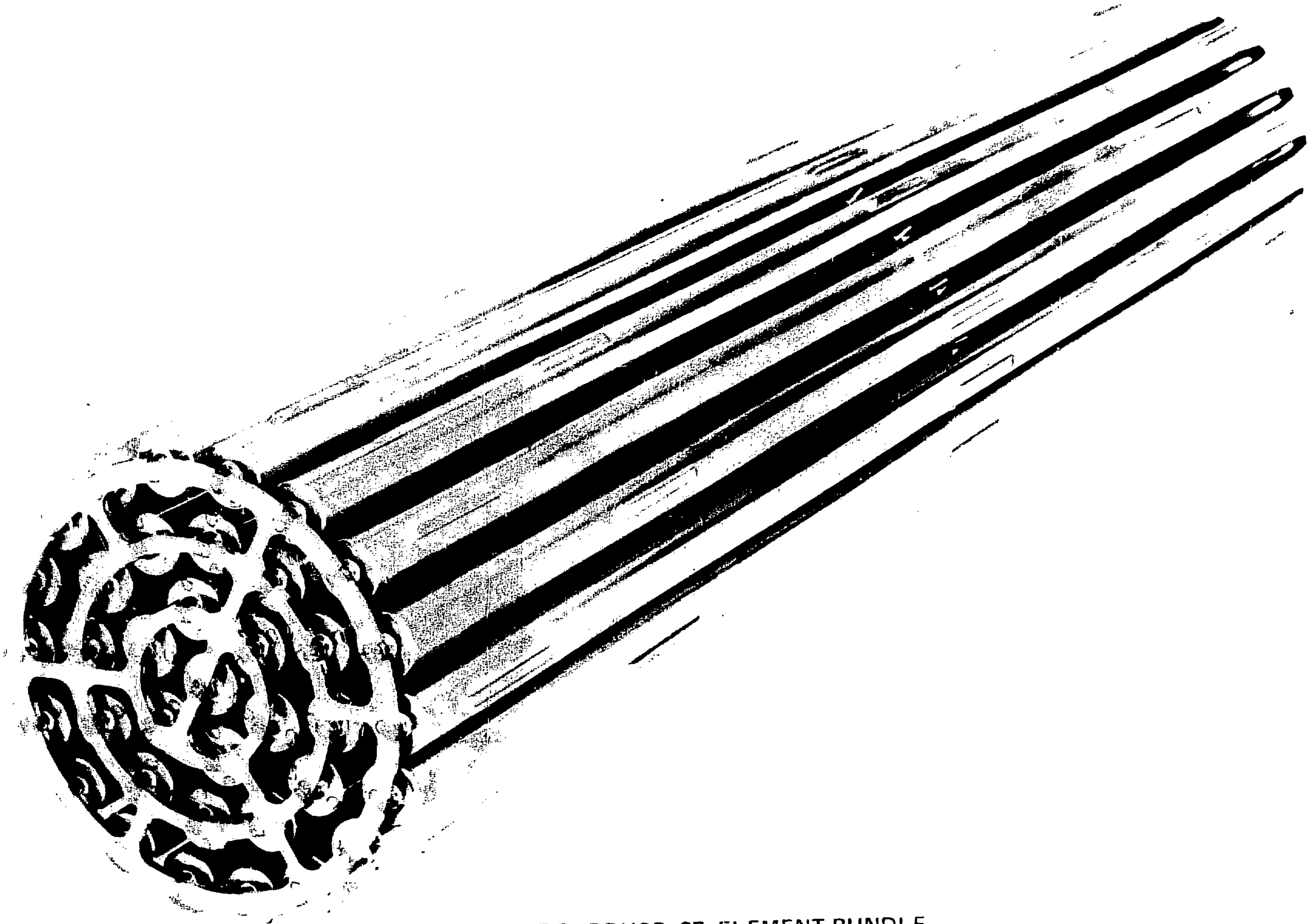


FIGURE 2 BRUCE 37 ELEMENT BUNDLE

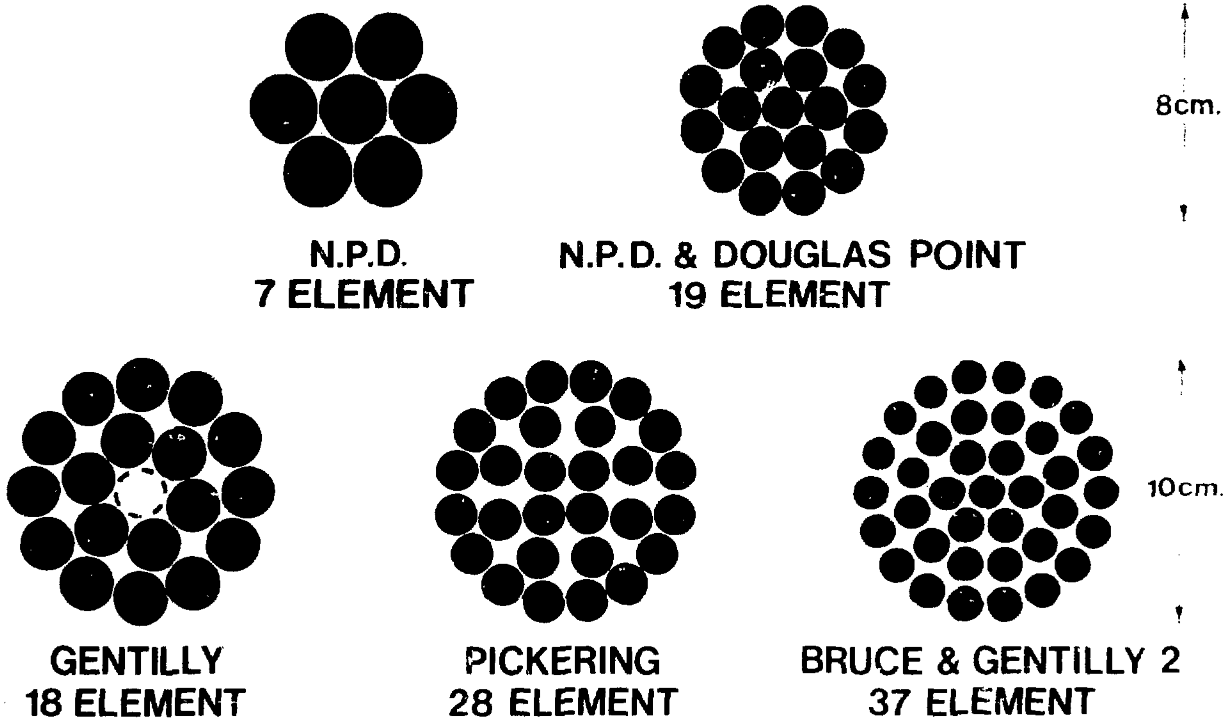


FIGURE 3 FUEL BUNDLE CROSS SECTIONS

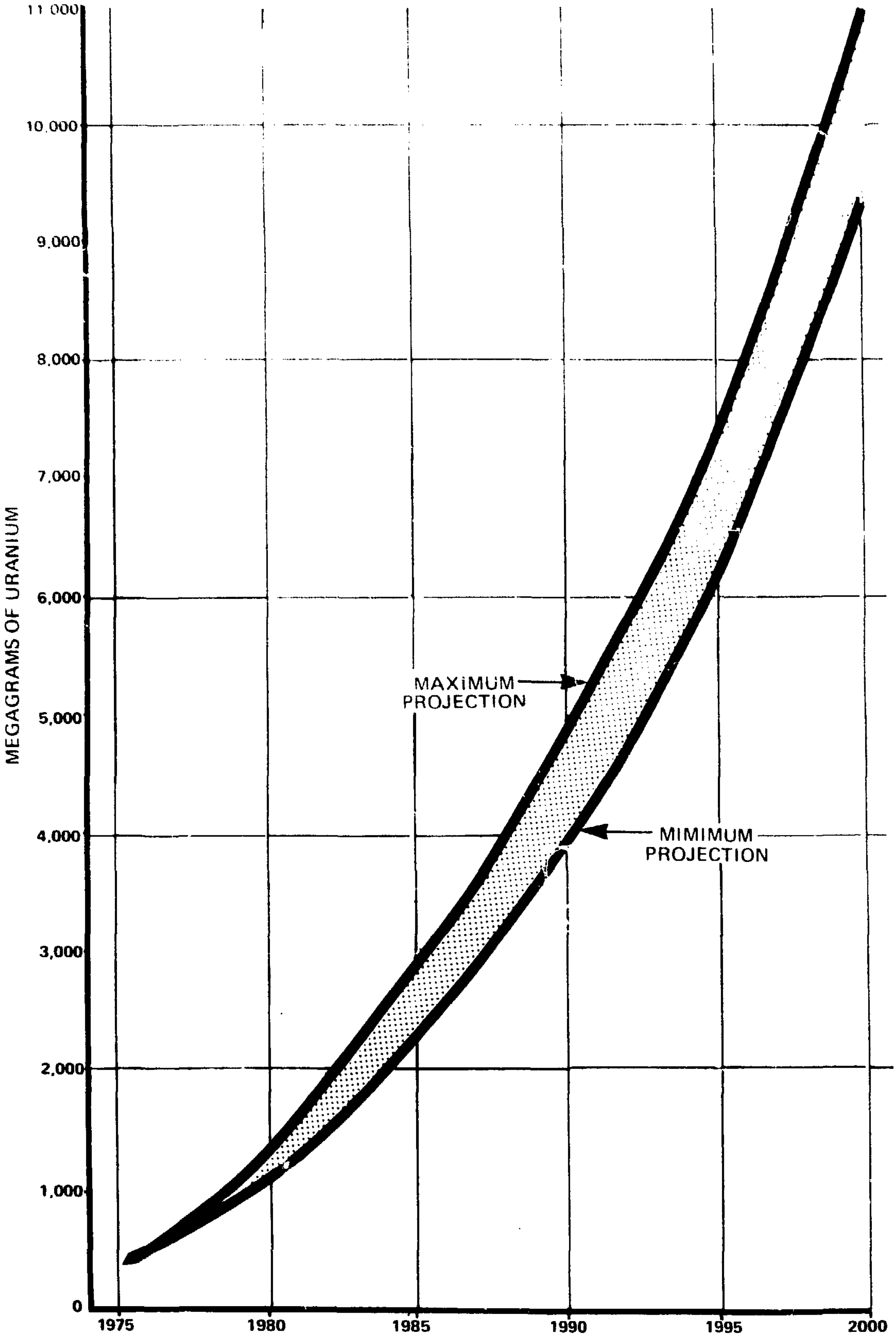


FIGURE 4 PROJECTED ANNUAL CANDU URANIUM CONSUMPTION

01.37000 - 224

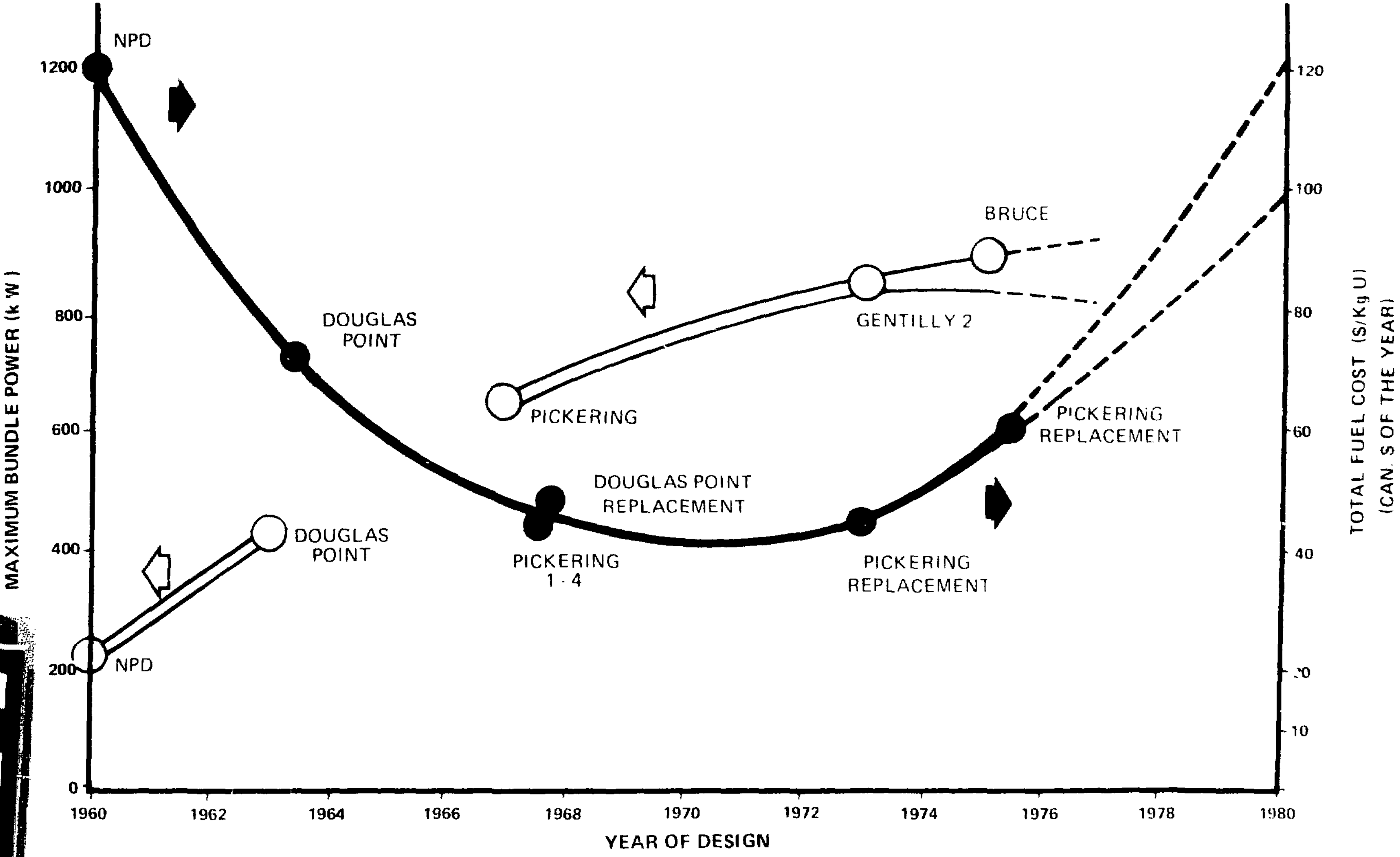


FIGURE 5 VARIATION OF BUNDLE POWER AND FUEL COSTS SHOWING EVOLUTION WITH TIME

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