AECL-9255

ATOMIC ENERGY
OF CANADA LIMITED

L'ÉNERGIE ATOMIQUE
DU CANADA LIMITÉE

ADVANCES IN URANIUM ENRICHMENT PROCESSES
A CHALLENGE TO INNOVATION

H.K. RAE, J.G. MELVIN and J.B. SLATER

Presented by H.K Rae to the Canadian Nuclear Association International Nuclear Conference
Royal York Hotel, Toronto, Canada, 1986 June 8 – 11

Chalk River Nuclear Laboratories   Laboratoires nucléaires de Chalk River

Chalk River, Ontario

May 1986 mai

AECL-9255

ATOMIC ENERGY OF CANADA LIMITED

ADVANCES IN URANIUM ENRICHMENT PROCESSES - A CHALLENGE TO INNOVATION

by

H.K. Rae, J.G. Melvin, J.B. Slater

Presented by H.K. Rae to the
Canadian Nuclear Association
International Nuclear Conference
Royal York Hotel, Toronto, Canada
1986 June 8 - 11

Research Company
Chalk River Nuclear Laboratories
Chalk River, Ontario, KOJ 1J0
1986 May

ATOMIC ENERGY OF CANADA LIMITED

ADVANCES IN URANIUM ENRICHMENT PROCESSES - A CHALLENGE TO INNOVATION

H.K. Rae, J.G. Melvin and J.B. Slater

ABSTRACT

Advances in gas centrifuges and development of the atomic vapour laser isotope separation process promise substantial reductions in the cost of enriched uranium. The resulting reduction in LWR fuel costs could seriously erode the economic advantage of CANDU, and in combination with LWR design improvements, shortened construction times and increased operational reliability could allow the LWR to overtake CANDU. CANDU's traditional advantages of neutron economy and high reliability may no longer be sufficient - this is the challenge.

The responses include:

- combining neutron economy and dollar economy by optimizing CANDU for slightly enriched uranium fuel;
- developing cost-reducing improvements in design, manufacture and construction; and
- reducing the cost of heavy water.

Technology is a renewable resource which must be continually applied to a product for it to remain competitive in the decades to come. Such innovation is a prerequisite to Canada increasing her share of the international market for nuclear power stations.

The higher burn-up achievable with enriched fuel in CANDU can reduce the fuel cycle costs by 20 to 40 per cent for a likely range of costs for yellowcake and separative work. Alternatively, some of the benefits of a higher fissile content can take the form of a cheaper reactor core containing fewer fuel channels and less heavy water, and needing only a single fuelling machine.

An opportunity that is linked to this need to introduce an enriched uranium fuel cycle into CANDU is to build an enrichment business in Canada. This could offer greater value added to our uranium exports, security of supply for enriched CANDUs, technological growth in Canada and new employment opportunities. AECL has a study in progress to define this opportunity.

Research Company
Chalk River Nuclear Laboratories
Chalk River, Ontario, K0J 1J0
1986 May

TABLE OF CONTENTS

1. INTRODUCTION

In the early stages of development of the CANDU concept, it was decided to focus on the use of heavy water as both coolant and moderator and on natural uranium as fuel. The decision to enrich water rather than uranium was in direct contrast to the thrust in the U.S. where the opposite policy was pursued. In both cases, the decision was heavily influenced by prior experience and the industrial capabilities available at the time in the respective countries. The Canadian decision was also influenced by the large energy consumption required to enrich the water, once, for the life of the reactor rather than commit to continual fuel enrichment. However, the use of enriched uranium in CANDU was recognized as a potential future development if the cost and energy investment in the enrichment process were to fall. These changes now appear possible over the next decade or so.

2. TRENDS IN ENRICHMENT MARKETS AND TECHNOLOGY

2.1 Early Canadian Initiatives

The idea of uranium enrichment in Canada is not new. Several projects were proposed in the 1960s and early 1970s and, though they did not come to fruition, interest persisted as evidenced by periodic assessments and status reviews.

The proposals of the 1970s were stimulated by the market outlook at the time. Forecasts of enrichment demand, based on planned and expected rates of nuclear power plant construction, indicated rapid expansion of separative work requirements for several decades to come; there would be room in the market for any and all suppliers.

Moreover, the dominant process was gaseous diffusion, which required large amounts of electric power, several thousand megawatts for a world-scale plant. Canada, with its huge hydro potential at Churchill Falls and James Bay, seemed a natural home for such enterprises.

For better or for worse, the projects did not materialize and the expected market did not develop. Instead, the world fell into economic recession in the wake of the OPEC oil-price shocks. The growth rate of electricity demand fell dramatically from the six to seven percent which had been experienced during the previous decades. Electric utilities, finding themselves with surplus capacity, ceased to commit new plants, nuclear or other, and even cancelled some which were already on order or actually under construction. By the early 1980s the nuclear construction industry had moved from feast to famine and was facing a bleak future.

Meanwhile technology was advancing, with the result that the economics of uranium enrichment were changing.

Given the fluid state of both the market and the technology, any forecast of the future of the uranium enrichment industry is subject to large uncertainty. But opportunity often lurks in uncertainty, so it is worthwhile to take a closer look.

2.2 Market Trends

A ten to fifteen year projection of enriched uranium requirements can be made with some confidence because it takes that long to plan and build a nuclear plant. Thus, only those plants now in operation or committed will require fuel between now and 1995.

On this basis, the separative work demand from now to 1995 is projected in Figure 1, which also shows a projection made in 1980 to illustrate the magnitude of the decline (1,2). The graph shows a 1995 requirement of about 33 MSWU, more than 30 percent below the level projected in 1980.

The graph shows little increase in annual requirements after 1991. At first glance, this relatively flat demand is surprising, but the explanation is straightforward. Demand for enriched uranium has two components, initial inventory for new plants and ongoing consumption by existing plants. As new plants cease to emerge from the planning and construction pipeline, the inventory component dries up. The demand curve for enriched uranium will not begin to rise again until some ten years after the next substantial group of reactor orders.

Annual separative work requirements up to at least 1995 will not exceed 35 MSWU. The enrichment capacity in existence today is greater than 40 MSWU/a. Thus, on the face of it, there is not room for a new supplier such as Canada until some time after 1995. While this is desirable, because it would take at least that long to get into production, it is not necessarily true. Much of the existing capacity is in gaseous diffusion, of which the largest part is in the United States and subject to escalating costs for electricity. In a fiercely competitive market, with prospects for growth in the long term, it is possible that new, low-cost suppliers will seek to displace the older, high-cost producer; there is a technological dimension to the market.

Another statement that can be made with some confidence is that in the longer term, beyond 1995, the demand for separative work will resume its growth as new power plants enter service. There can be little doubt that a new wave of reactor orders is coming, because world-wide consumption of electricity has continued to grow unabated at a rate somewhat greater than that of the economy (3). The global economic recession resulted in substantial over-capacity which is now being rapidly absorbed. At the moment, the need to commit new generating capacity is partially masked by the availability of cheap oil, but this is a transient condition.

There will be early warning of increases in separative work demand because of the time lapse between ordering and operating a nuclear power plant. This lead time might well be shorter than the ten to fifteen years to which we have become accustomed, because of improvements in design and construction methods, but it will still allow sufficient time for construction of the required enrichment capacity by those who possess the technology.

In this sense the glut of enrichment capacity during the next decade can be seen as an opportunity for newcomers, like Canada, to learn the technology and thus prepare themselves to enter the market when expansion resumes.

2.3 Uranium Enrichment Technology

There are two main trends in the technology, both of which offer encouragement to the customer and to the would-be supplier: the cost of separative work is declining and the minimum economic scale of enrichment plant is shrinking.

2.3.1 Declining Costs

The separative-work cost projections in Figure 2 are from a U.S. Department of Energy paper (4) outlining the strategy for gradual displacement of gaseous-diffusion capacity by AVLIS units. The twin advantages claimed for AVLIS are low investment cost relative to other processes and low operating cost, due in part to low energy consumption. Significantly, the "competitive range" on the chart is established by existing processes, the Eurodif diffusion plant with dedicated nuclear electricity supply and the gas centrifuge capacity in the Urenco countries. In effect, the cost trend is downward, whether or not a new process is introduced. The role of AVLIS in the U.S. strategy is to meet the competition by a gradual shift away from gaseous diffusion, thus extending the economic life of these plants rather than undertaking a massive, abrupt changeover to, say, the gas centrifuge.

The evolution, or revolution, of enrichment technology offers opportunity to Canada in the sense that we are not constrained by investment in any existing plant and thus are free to choose the most appropriate technology for entry into the future market. The opportunity is not open-ended, but will exist only until the U.S. has phased out the bulk of its diffusion capacity, or until another country introduces a new, low-cost process.

2.3.2 Shrinking Scale

Gaseous diffusion has set the pace since its start in the 1940s and is still the work-horse of the enrichment industry today. The process is characterized by a low separation factor, which translates into large physical size and high power consumption. Economy of scale therefore dictates huge plants of large capacity, typically about 10 MSWU/a. One such plant would be sufficient to enrich Canada's entire production of uranium to the level required by light-water reactors.

The magnitude of such a project, representing an investment of perhaps $5 billion, has been a barrier to Canadian participation in the enrichment industry, probably explaining the inability of Brinco and Canadif to launch their projects in the 1970s.

The economic scale of operations has been greatly reduced by the gas centrifuge. For example, Urenco claims to be the lowest-cost producer while operating two plants, one in the U.K. and the other in the Netherlands, with a combined capacity of less than 2 MSWU/a.

Other processes, notably AVLIS, promise further reductions in economic scale, so that it is possible to consider projects in the range below 1 MSWU/a.

The shrinking scale is compounded by, or more properly, results from, lower unit investment cost. A diffusion plant requires an investment of about $500/SWU.a and a gas centrifuge plant about the same, but an AVLIS unit is expected to cost about $100/SWU.a.

The net result is a reasonable expectation that the investment required for an economic scale plant would be about $500 million, or one-tenth of the ante needed in the past.

The ten-fold reduction in capital requirement means two things. First, it brings enrichment capability well within the financial means of Canada. Second, it is likely to stimulate other countries to enter the market, or to meet their own separative work needs. Thus, the shrinking scale of economic plant offers opportunity to Canada, but again, the opportunity is not open-ended. There is, as usual, a limited time window.

3. IMPACTS ON CANDU's ECONOMIC POSITION

3.1 Fuelling Costs

Lower enrichment costs will obviously benefit the light water reactors by reducing fuelling costs and, in the case of new reactors, reducing the cost of the initial fuel inventory. If the potential to reduce the cost of separative work by a factor of two over the next two decades is realized, then the fuelling cost of LWRs could be reduced by about 15 percent in real terms. This could seriously erode the economic advantage of the natural uranium fuelled CANDU.

At present CANDU fuelling costs are about half those for LWRs. For example, a recent study by the Nuclear Energy Agency (5) gives the following values for levelized once-through fuel cycle costs in 1984 U.S. funds:

	PWR	CANDU
	mills/kW.h	
Uranium ($83/kg)	3.5	2.6
Conversion	0.2	-
Enrichment ($130/SWU)	2.3	-
Fabrication	0.9	0.7
Spent Fuel Storage/disposal	1.0	0.7
	7.9	4.0

This CANDU advantage derives from its more efficient utilization of uranium and the fact that its fuel is not enriched. These lower fuelling costs are offset to some extent by the charges for heavy water inventory and make-up requirements. However, the low fuel cycle cost of CANDU has always been seen as one of its most attractive features.

3.2 Uranium Utilization

A hallmark of CANDU has been low uranium consumption relative to the LWR, due to the neutron efficiency of the heavy-water moderated, natural uranium fuelled design. While efficiency of resource utilization is a minor consideration at a time when uranium is plentiful and cheap, it will assume increasing significance in the future. The combination of improved fuel cycles and lower separative work costs promises substantial reductions in LWR uranium consumption.

The major feature of improved fuel cycles for LWRs is the extension of discharge burn-up from current levels with an associated reduction in uranium requirements. Typical values for uranium utilization for a PWR and for CANDU are shown in Figure 3 (2).

Under today's economic conditions the optimum enrichment-plant tails concentration is close to 0.25 weight per cent uranium-235. If the ratio of separative work cost to uranium feed cost were to fall by 50 per cent, then the optimum tails concentration would drop to about 0.15 wt.%. Uranium requirements for a PWR would then fall from 216 to 184 $Mg/GW_e.a$.

An extended PWR fuel cycle at the low enrichment tails optimum could further drop the uranium required to 155 $Mg/GW_e.a$, about 10 per cent below the natural uranium fuelled CANDU requirement of 171 $Mg/GW_e.a$. Thus, the potential exists for the PWR to be more uranium-efficient reactor system than CANDU with natural fuel. This, combined with reduced LWR fuelling costs discussed above, would be a dramatic reversal of past perceptions and would seriously undermine a major advantage that customers perceive in the CANDU system. However, CANDU can also benefit from enriched uranium fuelling and this will be discussed in Section 4.

3.3 Other Factors

There are other trends in LWR development and in LWR performance which challenge CANDU's economic position. LWR capacity factors have generally improved in the past few years so that the long-established lead by CANDU is becoming smaller. While the advantage conferred by on-power fuelling will always be available, this is considerably less than the difference in capacity factors observed to date; it will become even smaller as extended fuel cycles are increasingly adopted by LWR operators. Shorter construction schedules are being established for LWRs and developments to reduce capital cost are in progress. All these factors will require significant improvements to CANDU for it to remain an attractive reactor system.

The message is clear: in nuclear power, as in any other technology, success can be sustained only by vigorous, ongoing development. International competitiveness demands continuous effort in research, development and product engineering. CANDU is being challenged by the LWR in terms of cost and performance. By virtue of its neutron economy and other characteristics, CANDU provides scope for response to the challenge. Some responses are described in the following section.

4. ENRICHED CANDUs

Studies over the past decade on the use of enriched uranium in CANDU reactors have concentrated mainly on the potential advantages in fuel cycle costs (6), and on strategies for converting natural fuelled CANDUs to an enriched cycle (7). Only preliminary work has been done on optimizing the reactor design for an enriched core, or optimizing the design to use either enriched or natural fuel.

4.1 Advanced Designs

The additional reactivity provided by an enriched core allows more flexibility in design with potential to reduce capital costs in the next generation of CANDUs. In most cases such changes are not practical with natural fuel because of the large reduction in discharge burn-up that would result.

Examples of potential changes are:

- reduced heavy water inventory through reducing the core reflector thickness and using a smaller interchannel pitch;
- increasing channel power by greater fuel subdivision (smaller element diameter, more elements per bundle) and by using graded enrichment within the fuel bundle;
- improved radial form factor.

Studies now underway at the Chalk River Nuclear Laboratories are investigating these and other capital cost reduction measures to ensure that the flexibility afforded by enrichment is used effectively in optimized reactor designs. A target for these capital cost reductions has been set at twenty percent.

In addition, there are a variety of other initiatives being pursued to reduce CANDU costs. Improvements in fabrication, assembly and installation are being sought to reduce construction schedules as well as simplify design.

Heavy water is an important component of CANDU capital cost. Future costs are difficult to predict given the current large stockpile and several mothballed plants. The GS process is energy intensive and may be unattractive as the production process in the long term. Work is continuing at CRNL on alternative processes which should offer lower costs. The scope and priority of the program will be reviewed during 1986 to determine the optimum strategy for introducing new heavy water production technology around the year 2000.

4.2 Reduced Fuelling Costs

Uranium utilization in CANDUs can be improved substantially with enriched fuel. Figure 3 shows the result for an enrichment of 1.2 weight percent uranium-235, the uranium requirement falling from 171 to 112 $Mg/GW_e.a$.

The use of enriched fuel restores the favourable uranium consumption characteristic of CANDU relative to LWRs.

The major effect of using slightly enriched uranium as a substitute for natural uranium fuel is to increase the reactivity-limited burn-up life of the fuel. Although a greater amount of natural uranium is required to produce unit mass of the fuel, the increase in energy yield more than compensates and the uranium consumption falls for small increases in enrichment. This is illustrated in Figure 4, where both burn-up and uranium consumption are plotted as a function of enrichment level. Comparing natural and 1.2 percent enriched fuel, the major changes are:

- discharge burn-up is increased by a factor of three
- uranium consumption is reduced by approximately thirty percent
- the volume of fuel fabricated and discharged is reduced by a factor of three
- a commitment for enrichment services is incurred by the use of enriched fuel.

The net impact of these changes on fuelling costs (front end of the fuel cycle) is a reducton of twenty percent:

	Natural	Enriched
	mills/kW.h	
Uranium ($100/kg)	1.9	1.3
Fabrication	1.2	0.5
Enrichment ($150/SWU)	-	0.7
	3.1	2.5

The following data were used in this comparison:

Burn-up MWd/kg	7.5	22
Uranium Mg/GW_e.a	168	112
Separative Work MgSWU/GW_e.a	-	40
Fabrication Volume Mg/GW_e.a	168	57
Fabrication cost $/kg	60	80

The enrichment tails concentration assumed was 0.2 wt.% U-235 and the net station efficiency 29 percent.

The effects of varying enrichment and uranium unit costs on this comparison are shown in Figure 5 for 20 GW_e of installed capacity operating at a capacity factor of 80 percent. This is the probable size of the Canadian system early in the next century. The breakeven line represents equal annual operating costs for natural and enriched fuelling. Under today's conditions, enriched fuelling could offer a saving of about 80 million dollars over a total fuelling cost of 430 million dollars for the natural case. If enrichment costs drop substantially more than uranium costs, over the next two decades, then this potential annual saving could exceed 100 million dollars as suggested by the arrow in Figure 5. Thus, there is considerable incentive to introduce enriched uranium into Canadian CANDUs as soon as its feasibility can be demonstrated. The Canadian demand for separative work could be as high as 600,000 SWU/a early in the next century.

In this comparison it is assumed that the back-end costs for both fuel cycles are similar. The advantage of the reduced amount of enriched fuel is compensated by higher storage, transport and ultimate waste management unit costs for enriched fuel because of higher residual radiation and decay heat output per unit mass.

4.3 Feasibility

The feasibility of using enriched fuel in the CANDU-600 reactor, which was designed to use natural fuel, has been the subject of recent in-depth studies both at CRNL and at CANDU Operations, Mississauga. The results of these studies are very positive in that it appears feasible to use enriched fuel with no change to reactor core hardware. Studies are currently underway to define the fuelling strategy by which the reactor can be converted from equilibrium natural fuelling to equilibrium enriched fuelling without shutdown or loss of availability. Solutions to the power-peaking problem identified in earlier studies which could have limited the feasible enrichment level to below 1 wt.% U-235, appear to have been resolved by the development of the "checkerboard" fuel management scheme (7). The remaining major development program is the large-scale demonstration that CANDU fuel can withstand average burn-ups in excess of 20,000 MWd/MgU without failure. Experience to date has been encouraging and confirms that the existing CANDU design is generically capable of high burn-up operation (8).

Canadian fuel fabricators have had considerable experience in the manufacture of low enriched CANDU bundles for loop tests at CRNL and irradiation in NPD. Good performance has routinely been observed.

Hundreds of natural bundles in Ontario Hydro power reactors have reached burn-ups of about 15 MWd/kg with entirely satisfactory performance. A few bundles have reached burn-ups in excess of 20 MWd/kg and have shown signs of undesirable fuel element swelling and higher than normal fuel temperatures. In addition, the majority of our high burn-up experience has been at lower fuel ratings than expected towards the end of life of fuel bundles in an enriched CANDU.

There are obvious gaps in our knowledge of CANDU fuel behaviour at high burn-up and relatively high ratings. More work is required to develop designs which will control swelling, limit fission gas release and allow fuel power cycling at high burn-up during refuelling. In addition, improved end cap welds may be needed. A program has begun at CRNL to develop a high burn-up CANDU bundle.

Together with the utilities, AECL plans to continue studies aimed at bringing the enriched fuelling option for CANDU to the point where a demonstration irradiation in a power reactor could be committed.

5. ENRICHMENT OPPORTUNITY IN CANADA

The combination of trends outlined in previous sections creates the opportunity for Canada, which is already a major supplier of uranium to world markets, to increase the value of these exports by providing enrichment service as well. The trends are, in summary:

a) The emergence of new processes which promise lower production costs than existing plants and require much smaller investment for the minimum economic size.

b) An excess of enrichment capacity for the next 10-15 years, which will allow the necessary time for development of the technology, while discouraging expansion by existing suppliers.

c) The prospect of a domestic market for enriched uranium, of sufficient size to support an economic scale production unit.

d) Eventual resumption of growth in world requirements for enrichment, resulting in a timely opportunity for expansion of an established Canadian operation.

It is because of the apparent convergence of these trends that AECL has undertaken a re-assessment of the technology of uranium enrichment and the potential for such a business in Canada. There are strong indications that such an enterprise, always recognized as desirable, may be on the verge of feasibility.

In addition to the direct possibilities, there are potential subsidiary and spin-off applications involving elements other than uranium.

Requirements for separated isotopes cover a broad spectrum from milligram quantities for pharmaceutical purposes to megagram quantities for industrial uses. The Radiochemical Company of AECL has long been a leading supplier of radioisotopes for medical and industrial purposes. The number of such isotopes is growing and many can be produced most efficiently by neutron irradiation of separated stable isotopes of specific elements. We are currently seeking to apply our ion-source and electromagnetic separation know-how to the economic producton of a range of stable isotopes. We are also looking at chemical separation processes and at the possible scope for centrifugal separation.

At the megagram end of the spectrum, Canada is already the world's major producer of deuterium, in the form of heavy water, for CANDU moderator and coolant. We remain on the alert for new processes which might offer less costly heavy water. AECL and Ontario Hydro are rapidly advancing the technology for separation of the tritium isotope from heavy water, and for the immobilization and safe handling of the separated product.

Further in the future, there are potential needs for isotope separation in the middle of the spectrum, that is, in annual quantities of kilograms or a few megagrams. One example would be zirconium, depleted in the 91 isotope for use in CANDU pressure and calandria tubes. Zirconium-91 has an abundance of 11 percent in the natural element, but accounts for about half of the neutrons absorbed by the material. The use of zirconium depleted in the 91 isotope would produce a significant improvement in neutron economy. While the near-term incentive is not large, especially if slightly enriched fuelling is adopted, the use of depleted zirconium will become increasingly attractive in the future, when uranium is less plentiful.

The supply of materials with altered isotopic compositions to meet special requirements, which may be termed "isotope engineering", may well evolve into a significant industry embracing a variety of isotope separation processes. Canada is already well established on the ground floor, a position which would be strengthened by creation of uranium enrichment capability.

In summary, Canada is and will continue to be one of the world's largest producers of uranium. Canada is also a major developer, user and exporter of nuclear power plants and, in addition, a leader in the volume and diversity of its isotope engineering activities. A uranium enrichment enterprise would fill an obvious gap in our national capability, would be a good fit with our existing mix of nuclear technologies and industries, and would open options for future exploitation. Moreover, the economic and technological events of the past few years have converged to provide the necessary lead time and to reduce the enterprise to a scale appropriate to the Canadian economy.

6. ENRICHMENT TECHNOLOGIES

6.1 Process Outlines

Uranium enrichment processes are in various stages of application or development in several countries, including all those with substantial nuclear-electric programs, except Canada. The variety of processes and technologies is indicated by the following thumb-nail sketches.

Gaseous diffusion depends on the preferential migration of UF_6 molecules containing the lighter isotope of uranium through micropores in a diffusion barrier. This is the original large-scale process and is still the main producer world-wide. Plants in the U.S., France, the U.S.S.R. and China produce more than ninety percent of today's enrichment. As noted earlier, the diffusion plant has high capital and operating costs and demands huge quantities of electric power. It is unlikely that any more such plants will be built, but many of the existing units are expected to continue operation into the next century.

The gas centrifuge is the only other process in commercial operation, notably in the plants of the Urenco consortium - Britain, Germany and the Netherlands; it currently supplies less than ten percent of the world market, but is said to be the lowest-cost producer and is poised for expansion. The separation factor is large relative to that of gaseous diffusion, because the centrifugal effect depends on the mass difference of the isotopes rather than their mass ratio and is amplified by axial counter-flow within the rotor. Only about a dozen centrifuges in series are needed to produce three percent enriched product, but many parallel units are needed for significant throughput. A single plant contains some hundreds of thousands of identical centrifuges, normally produced in a dedicated factory, and can be expanded as desired by the addition of blocks of additional machines. The capital cost is comparable with that of a diffusion plant, but the operating cost is lower because of the much smaller energy consumption.

Two different chemical-exchange processes are at the pilot-plant stage, one in France and the other in Japan. Both processes depend on the preferential transfer of one uranium species from one phase to another, with the small separation factor being multiplied by counter-current flow; they are similar in principle to the GS process for heavy water production. The processes do not seem to be regarded as main-line challengers, but they have the advantage that the technology for construction and operation is conventional and they are proliferation-resistant by virtue of inherent limitations. It is possible that one of these processes might be interesting for the relatively low enrichment appropriate to CANDU.

The most dramatic recent development was the 1985 decision by the U.S. to place all its bets on AVLIS, Atomic Vapour Laser Isotope Separation, as the key element in a strategy to regain market share. The process, based on the selective ionization of U-235 atoms in a stream of metal vapour and their subsequent deflection onto a charged collector, is now in the demonstration stage. Technological challenges include high-powered tunable laser development, the generation of a directed stream of uranium vapour, and its later collection as a liquid. Because of its high selectivity, the process yields the required enrichment in a single stage. It is claimed that AVLIS will reduce the cost of enrichment to less than half that of current processes.

Another laser-based process is MLIS, Molecular Laser Isotope Separation, which works by selectively dissociating those molecules in a jet of uranium hexafluoride gas in which the uranium atom is the 235 isotope. To provide adequate selectivity of laser energy absorption, the gas is cooled to a very low temperature by expansion in a supersonic nozzle. The enriched product falls out of the gas stream as UF_5 particles. While this process lost out to AVLIS in the U.S. competition, it offers certain advantages, at least in principle. One advantage is that the feed is UF_6, the common currency of the fuel cycle industry, rather than uranium metal as required by AVLIS.

Two plasma-based processes, the plasma centrifuge and ion cyclotron resonance, are in the laboratory and preprototype stages, respectively. Both processes operate on a stream of uranium ions. In the centrifuge process, the column of ions is rotated by a magnetic field at high angular velocity, perhaps ten times that of a gas centrifuge, to obtain separation of the lighter and heavier ions. In the cyclotron resonance process, a magnetic field, oscillating at the cyclotron frequency of uranium-235, causes these ions to increase the diameter of their helical paths and thus fail to pass through slots which therefore filter them out of the stream. Present indications are not encouraging, but better understanding of the processes at the theoretical level could well lead to significant improvements.

6.2 The Canadian Scene

Although Canada is a major producer of uranium, there has been no direct involvement in enrichment technology. In order to launch a uranium enrichment industry, Canada would have to obtain the relevant technology, through an R&D program or by acquisition from others. The technology is closely held by its developers, for reasons of proliferation sensitivity and of commercial value. This means that Canadian access to the technology would be difficult and would hinge on considerations other than straight cash. However, Canada is not without bargaining chips; various arrangements founded on joint venture or barter can be envisaged.

It would be possible for Canada to develop its own technology and there are reasons why such a course might be preferred. Competence, even excellence, is available in Canada in the scientific fields underlying each of the processes; we have the foundations on which to build. Strong engineering capability exists in many of the required areas, notably lasers, plasmas and chemical processing. And Canada has a proven ability to manage technological projects.

At AECL we are currently assessing the technologies in terms of their economic potential and their adaptability to Canadian requirements and resources. We are also attempting to define the scope and nature of the business opportunity to identify possible strategies and participants.

We are not far enough along in our study to offer specific recommendations but for the reasons given in this paper, our outlook has become increasingly positive. We believe that the technological barriers are less fearsome than at first supposed, that they could be surmounted within the time and resources that might be available, and that the rewards to Canada and to Canadian industry would justify the effort.

7. CONCLUSIONS

7.1 Planned improvements in LWR design and operation, amplified by substantial decreases in the future cost of uranium enrichment, represent a strong challenge to the traditional advantage of CANDU.

7.2 The principal challenges to CANDU are in two areas: capital cost and fuel economy. There is scope for effective responses in both areas.

7.3 Fuelling of CANDU with slightly enriched uranium, which is a rational response to declining separative-work costs, would retain the advantage of fuel economy over the LWR, and could also assist in capital cost reduction.

7.4 The combination of enriched fuel for CANDU and new technology for uranium enrichment creates the opportunity for an enrichment industry in Canada.

7.5 The timing is right. The world enrichment market is likely to remain saturated during the interval required to develop a Canadian capability, and then to resume expansion.

REFERENCES

1. "U.S. Uranium Enrichment: Options for a Competitive Program". Congressional Budget Office, October 1985.

2. "Nuclear Energy and Its Fuel Cycle. Prospects to 2025". NEA/OECD, Paris, 1982.

3. Searl, Milton F. "The Relationship of Electricity to Aggregate Economic Activity in Industrial Economies - Some Empirical Observations". Fifth Annual International Meeting of the International Association of Energy Economists, New Delhi, India, January, 1984.

4. J.R. Longenecker, "The Impact of Advanced Enrichment Technology on the Future Uranium Market". Tenth International Symposium held by the Uranium Institute, London, September, 1985.

5. "The Economics of the Nuclear Fuel Cycle". NEA/OECD, Paris, 1985.

6. "Data Base for a CANDU-PHW Operating on a One-Through, Slightly Enriched Uranium Cycle". Atomic Energy of Canada Limited, Report AECL-6594, July, 1979

7. P.S.W. Chan, and A.R. Dastur, "Checkerboard Fuelling - The Key to Advanced Fuel Cycles in Existing CANDU Reactors", Sixth Annual Conference, CNS, Ottawa, 1985 June 3-4.

8. I.J. Hastings, T.J. Carter, G. MacGillivray, R.D. MacDonald, and J. Judah, "Canadian High Burnup Fuel Experience", Atomic Energy of Canada Limited, Report AECL-8772, 1985 June.

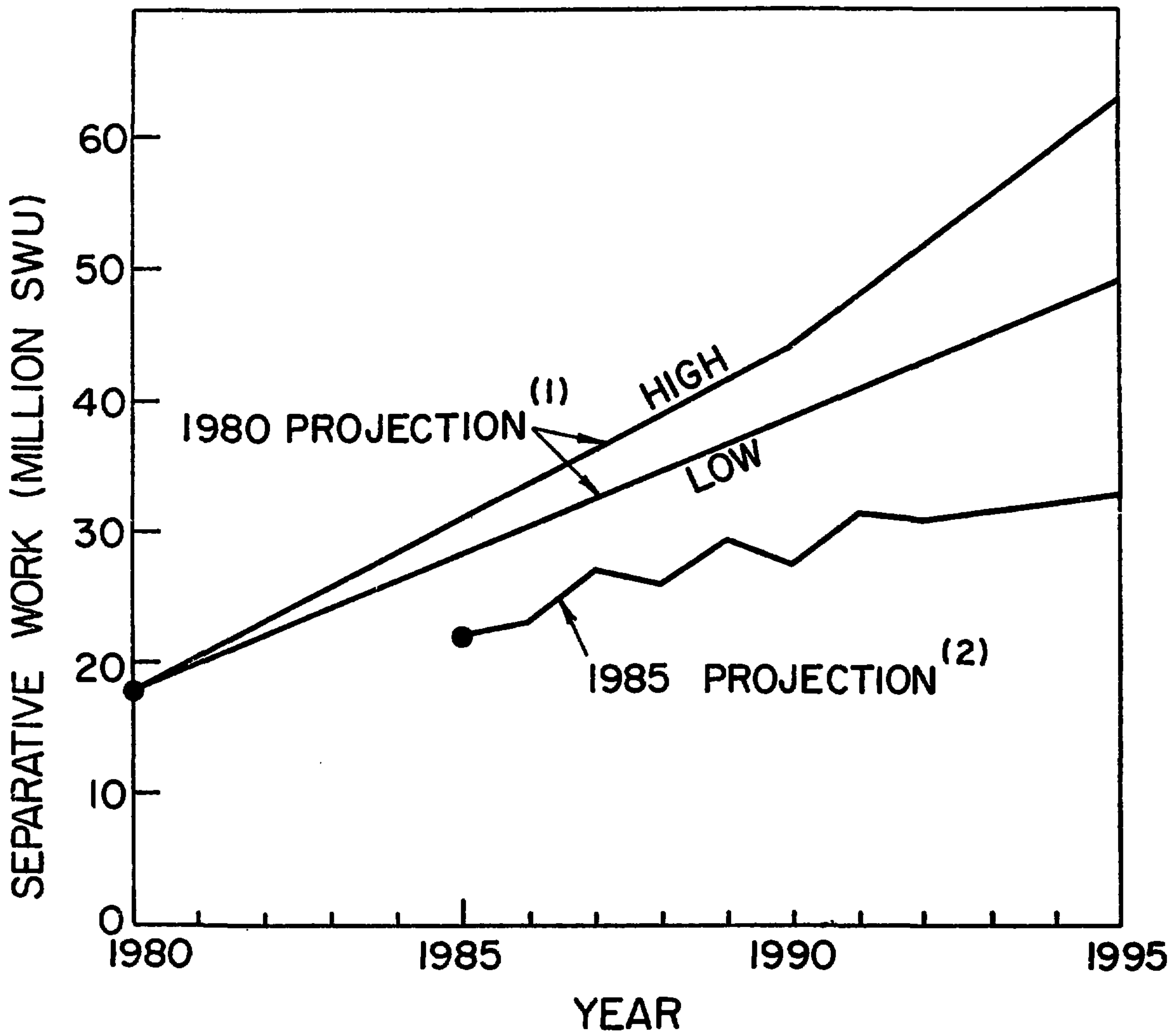

FIGURE 1

SEPARATIVE WORK REQUIREMENTS, WESTERN WORLD

(1) NEA "YELLOW BOOK", 1982

(2) U.S. CONGRESSIONAL BUDGET OFFICE, 1985

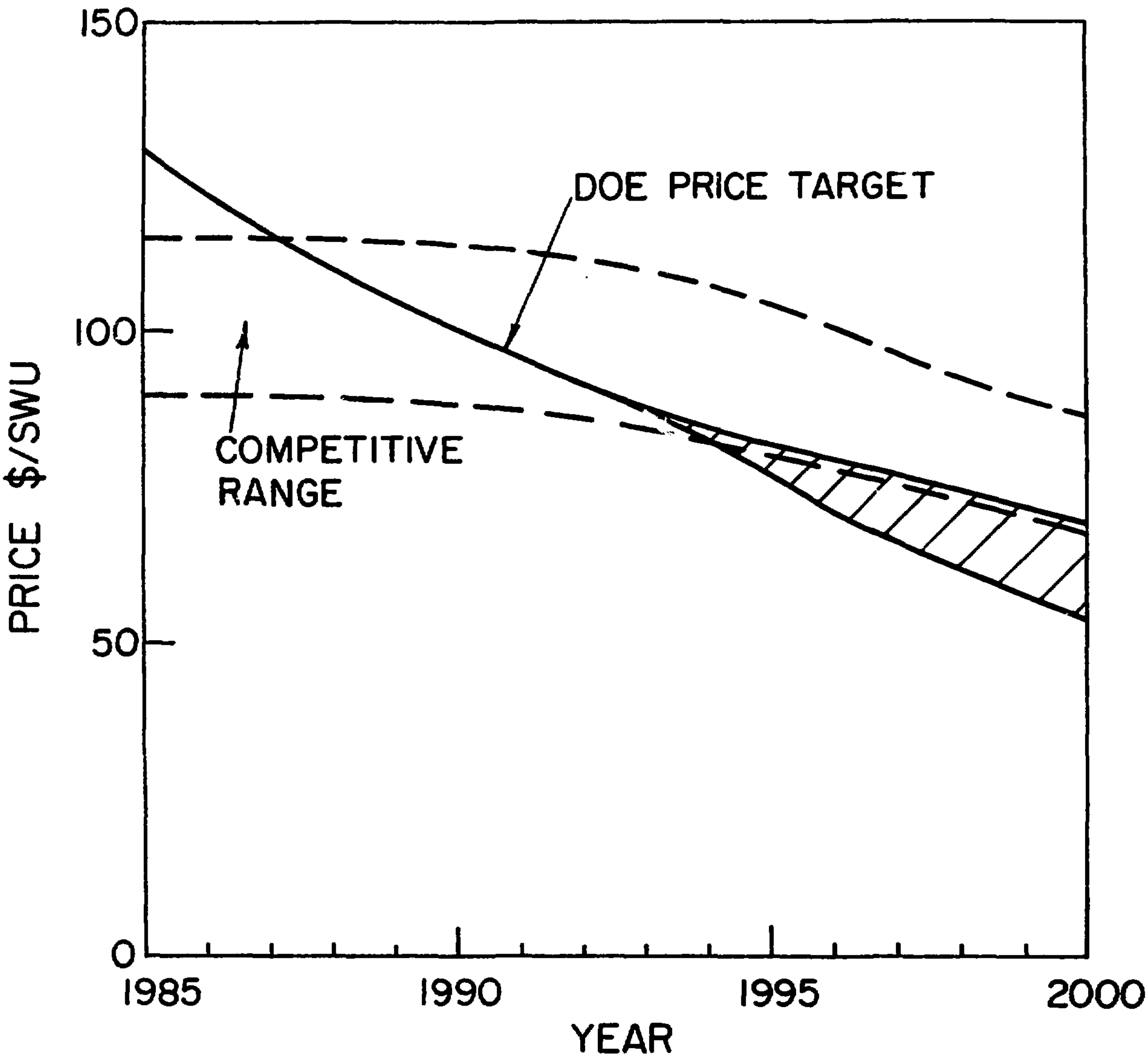

FIGURE 2

URANIUM ENRICHMENT PRICES

[PROJECTIONS BY U.S. DOE]

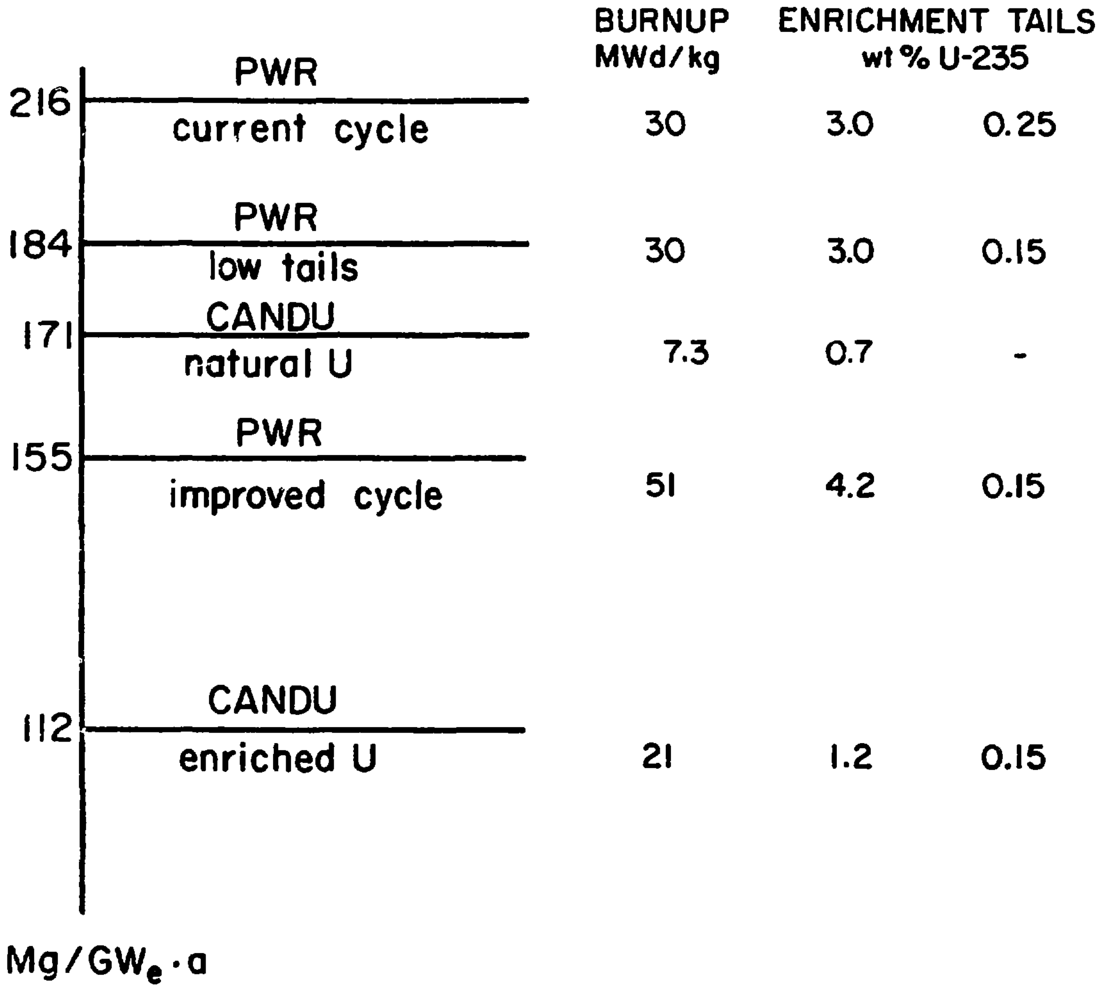

FIGURE 3

ONCE-THROUGH FUEL CYCLES

URANIUM UTILIZATION

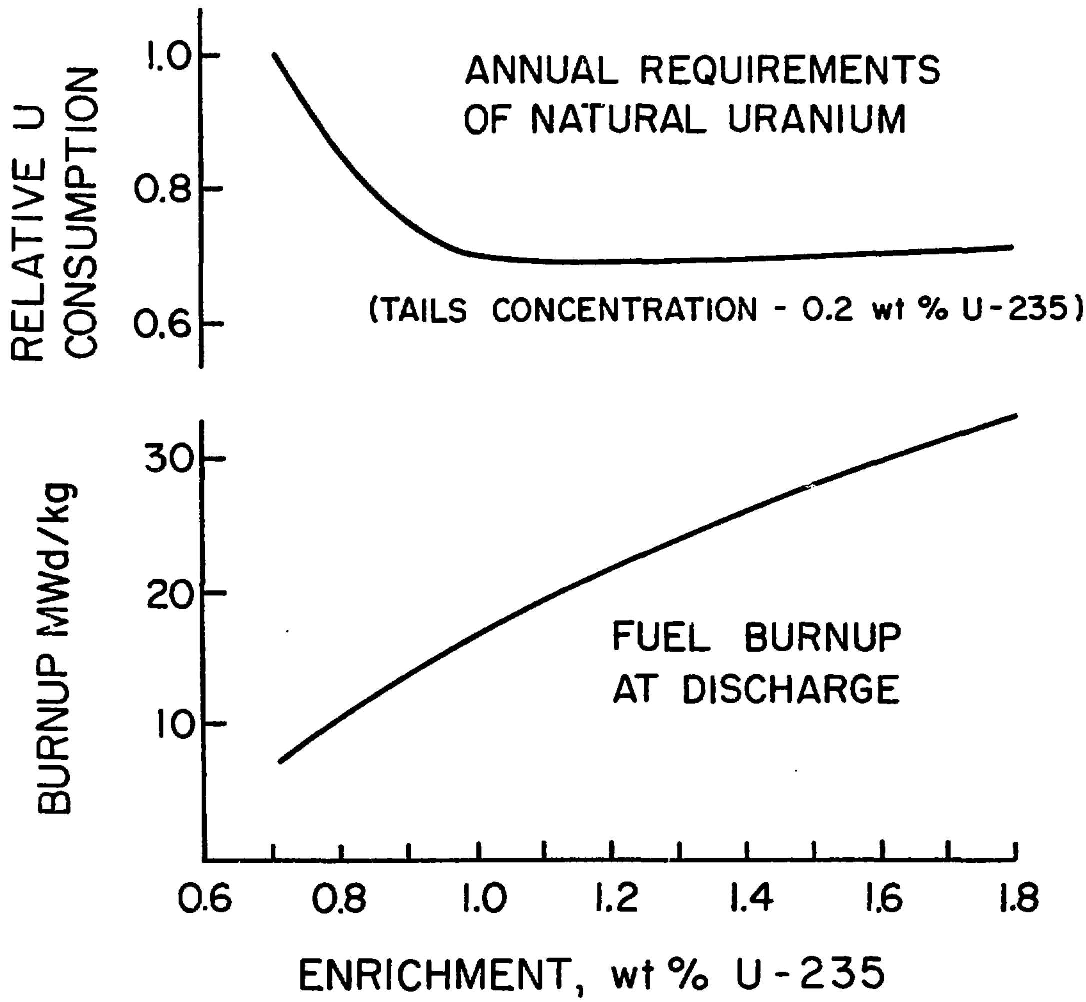

FIGURE 4

ENRICHED FUEL IN CANDU

SAVINGS IN FUELLING COSTS
ENRICHED vs. NATURAL CANDU

20 GW_e
80% CAPACITY FACTOR

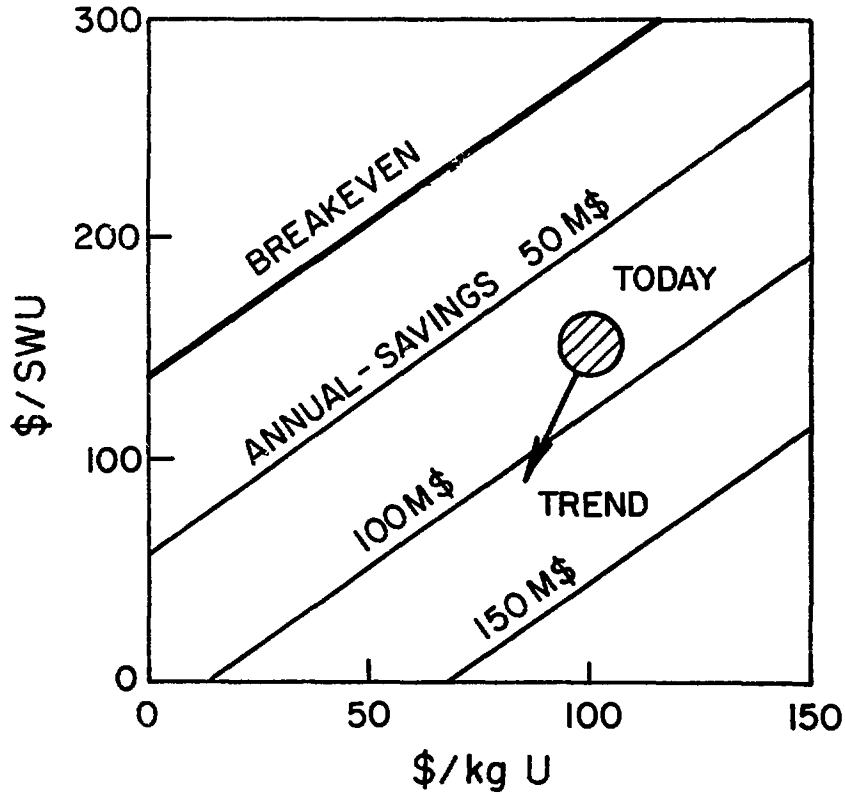

FIGURE 5

ISSN 0067 - 0367

To identify individual documents in the series we have assigned an AECL- number to each.

Please refer to the AECL- number when requesting additional copies of this document

from

Scientific Document Distribution Office
Atomic Energy of Canada Limited
Chalk River, Ontario, Canada
K0J 1J0

Price: A

ISSN 0067 - 0367

Pour identifier les rapports individuels faisant partie de cette série nous avons assigné un numéro AECL- à chacun.

Veuillez faire mention du numéro AECL- si vous demandez d'autres exemplaires de ce rapport

au

Service de Distribution des Documents Officiels
L'Energie Atomique du Canada Limitée
Chalk River, Ontario, Canada
K0J 1J0

Prix: A

8-87