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ATOMIC ENERGY
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L'ÉNERGIE ATOMIQUE
DU CANADA LIMITÉE

URANIUM ENRICHMENT: AN OPPORTUNITY WINDOW

ENRICHISSEMENT DE L'URANIUM: PORTE D'ACCÈS AU MARCHÉ INTERNATIONAL

H.K. RAE and J.G. MELVIN

Presented by H.K. Rae to the Canadian Nuclear Association International Nuclear Conference
The Westin Hotel, Winnipeg, Manitoba, Canada
1988 June 12 – 15

Chalk River Nuclear Laboratories   Laboratoires nucléaires de Chalk River

Chalk River, Ontario

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RÉSUMÉ

Le Canada est le plus grand producteur et exportateur d'uranium du monde; une grande partie de celui-ci est enrichie ailleurs pour l'utiliser sous forme de combustible de réacteurs à eau légère (LWR). La possibilité d'une entreprise canadienne d'enrichissement de l'uranium est donc une question perpétuelle. Les progrès récents réalisés en techniques d'enrichissement de l'uranium et leurs conséquences pour l'offre et la demande du travail de séparation laissent supposer qu'il y a une porte d'accès au marché international pour le Canada.

L'occasion d'accès pour le Canada découle de trois conséquences particulières des techniques nouvelles:

1. la majeure partie de la capacité mondiale d'enrichissement de l'uranium est assurée par les installations de diffusion qui, en raison de leurs grands besoins d'électricité (plus de 2000 kW•h par unité de travail de séparation (UTS)(SWU)), sont à la merci de la concurrence que constituent les procédés nouveaux;

2. la diminution des coûts d'enrichissement augmente les raisons économiques d'utiliser le combustible d'uranium légèrement enrichi (ULE)(SEU) dans les réacteurs CANDU - ce qui permet une possibilité de marché au Canada;

3. les procédés nouveaux permettent un enrichissement économique à échelle beaucoup plus petite - ce qui réduit considérablement l'investissement nécessaire pour l'accès au marché et est comparable au besoin possible d'ULE au Canada.

La possibilité a une limite de durée. Avant la fin de ce siècle, l'industrie de l'offre d'enrichissement se sera adaptée aux procédés nouveaux et les relations à long terme entre clients et fournisseurs se seront établies. Pour saisir cette occasion, le Canada doit devenir un fournisseur crédible au cours de ce siècle.

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ABSTRACT

Canada is the world's largest producer and exporter of uranium, most of which is enriched elsewhere for use as fuel in LWRs. The feasibility of a Canadian uranium-enrichment enterprise is therefore a perennial question. Recent developments in uranium-enrichment technology, and their likely impacts on separative work supply and demand, suggest an opportunity window for Canadian entry into this international market.

The Canadian opportunity results from three particular impacts of the new technologies:

1. The bulk of the world's uranium-enrichment capacity is in gaseous diffusion plants which, because of their large requirements for electricity (more than 2000 kW·h per SWU), are vulnerable to competition from the new processes.

2. The decline in enrichment costs increases the economic incentive for the use of slightly-enriched uranium (SEU) fuel in CANDU reactors, thus creating a potential Canadian market.

3. The new processes allow economic operation on a much smaller scale, which drastically reduces the investment required for market entry and is comparable with the potential Canadian SEU requirement.

The opportunity is not open-ended. By the end of the century the enrichment supply industry will have adapted to the new processes and long-term customer/supplier relationships will have been established. In order to seize the opportunity, Canada must become a credible supplier during this century.

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TABLE OF CONTENTS

1. INTRODUCTION

Canada is the world's largest producer and exporter of uranium and is likely to retain a substantial share of the uranium market for many decades. Most of the uranium exported from Canada is subsequently enriched for use as fuel in light-water reactors. The value added by enrichment is at least equal to the export value of the natural uranium. The feasibility of a Canadian uranium-enrichment industry is therefore a perennial question and has been examined in several studies and project assessments (1,2) during the past fifteen years, but no action has resulted.

The negative outcome of past studies is due to two main factors. First, the CANDU reactor does not require enriched fuel, so that enrichment has not been a strategic requirement which would attract government support. Second, an enrichment plant of commercial size represented a very large investment, some billions of dollars. Faced with these circumstances, the government of Canada adopted a policy of "benign neutrality", and the private sector chose not to launch a project.

A paper presented at the 1986 CNA conference (3) described the competitive challenge facing the CANDU system and identified slightly-enriched uranium (SEU) fuelling as one possible response. A companion paper at the present conference (4) enlarges on the potential benefits of SEU. During the past year, we have completed an assessment of the feasibility of a uranium-enrichment industry in Canada as an adjunct to the SEU evaluation and in the context of changing technological and market conditions. The results of this reassessment, reported here indicate that the opportunity exists for profitable entry by Canada to the international uranium-enrichment market.

In order to delineate the opportunity, this paper will examine both sides - supply and demand - of the enrichment market, the impacts of changing enrichment technology, and the influence of these factors on the prospects for a Canadian initiative.

2. THE ENRICHMENT MARKET

2.1 Demand

Uranium is enriched by the performance of separative work which concentrates the 235 isotope while rejecting the 238 isotope. The value is measured in separative work units (SWU) and the SWU is an international commodity. [The SWU is a theoretical concept, like entropy; it has dimensions of mass, not work, and is usually stated in kilograms].

Total demand for separative work depends on the total population of reactors and on their energy production. The dominant class of reactor is the LWR which typically requires an initial inventory of some 400 SWU/MWe and a feed of 100 SWU per MWe-year.

The separative-work requirement of a given reactor population can be estimated quite accurately, so the population is the principal uncertainty in calculating future requirements. Because the time from initial decision to build a reactor to first fuel loading is typically a decade, the reactor population at the end of this century, or at least its maximum size, is known today. The separative-work requirement to the year 2000 can therefore be estimated within a band of uncertainty. The uncertainty is associated with actual versus planned reactor completion dates, reactor capacity factors and refuelling strategies. The requirements band in Figure 1 embodies forecasts by the NEA (5), Nukem (6) and Urenco (7).

In the early 1970s the projected growth of nuclear-electric capacity foreshadowed a much larger demand for enrichment and a potential shortage of separative-work capacity. The projected growth did not materialize and there is no consensus today on the prospects for rapid growth in the new century.

2.2 Enrichment supply

Present and planned Western world commercial enrichment capacity is summarized in Table 1 (8).

Up to the late 1970s, the United States was the only enrichment supplier in the Western world, using its three gaseous diffusion plants. The total capacity of these plants as upgraded was 27 MSWU/a by 1983, but has recently been reduced to about 20 MSWU/a by closure of the Oak Ridge plant.

The Eurodif diffusion plant, operated by COGEMA in France, was brought into production during 1978-81 and has a capacity of 10.8 MSWU/a.

The Urenco consortium, a British-Dutch-West German partnership, brought the gas centrifuge to commercial application in 1977 and now operates three plants, one in each member country, with a total capacity of about 2 MSWU/a.

There is a 'Helikon' gas-jet plant in South Africa, a diffusion plant in Argentina and a recently-announced gas centrifuge plant in Brazil. Little information is available regarding the capabilities of these plants, but they are believed to be small and are not significant commercial suppliers.

There is enrichment capacity in the USSR, from which some 3 MSWU/a are marketed in the West. China also has enrichment capability.

Japan is developing its own gas centrifuge technology; a demonstration plant is now operating and a commercial-scale plant is scheduled to start up in 1991. Japan does not plan to become an exporter of separative work, or even to become self-sufficient, but regards a domestic capability of about 30 percent of the domestic requirement as adequate assurance of security of supply.

The United States Department of Energy (USDOE), having cancelled a large gas centrifuge plant at Portsmouth, Ohio, is now developing only one next-generation process, atomic vapour laser isotope separation (AVLIS). No firm schedule for commercial deployment of AVLIS has been published and the future course of the USDOE enrichment business is under debate. Main issues include repayment of the capital investment to the U.S. Treasury, long-term power supply contracts with electric utilities, and "privatization", or some other restructuring, of the enrichment industry.

2.3 Supply/demand balance

Supply and demand data for the OECD countries have been plotted in Figure 1. There is an apparent surplus of capacity to the end of the century, or later.

The United States is the major supplier and the gaseous diffusion process (USDOE + Eurodif) is dominant. The new capacity planned by Urenco and Japan is entirely in gas centrifuges.

Figure 1 refers to the Western countries as a whole, but the balance would not be very different for the entire world.

Taken at face value, the picture suggests a stable situation with slow, predictable market growth allowing the established suppliers to expand in timely fashion, thus affording little opportunity for entry by new suppliers.

The stability, however, is more apparent than real. The changing technology of uranium enrichment has economic implications that threaten the long-term viability of the diffusion plants, which now dominate the enrichment industry. This may open the door to new competitors. The most significant technologies in this context are the gas centrifuge and AVLIS.

Cost and performance data on uranium-enrichment processes are closely guarded, so rigorous assessment is not possible, but price trends and the published plans and statements of the major players provide useful indications, which are consistent with the known technical characteristics of the processes.

The large separation factor and small power consumption of the gas centrifuge offer a substantial advantage over gaseous diffusion, if the capital cost and the reliability of the machines can meet certain targets. The two factors, cost and reliability, are of crucial importance because some tens of thousands of individual centrifuges are required in a plant of commercial scale. The Urenco consortium claims to have met and exceeded its targets, and to be the lowest-cost producer of separative work (9). The Urenco claims are supported, at least by implication, in the "competitive price" projections, shown in Figure 2, in which the USDOE assigns the upper curve to Eurodif and the lower to URENCO (10).

The U.S. strategy aims to retain, and eventually regain, market share in the face of declining international prices and has two thrusts: first, efficiency improvement and cost reduction in the diffusion plants, and second, the phased introduction of AVLIS.

The competitive vulnerability of gaseous diffusion stems from its heavy consumption of electric power. The specific energy consumption of more than 2000 kW·h/SWU, mainly in the form of electric power to drive the gas circulators, is inherent because the small separation factor requires huge recirculation rates of the uranium hexafluoride gas within the cascade. If, for example, the affordable cost of producing one SWU of separative work were $80, then an electric power price of four cents per kilowatt-hour would leave nothing to cover the costs of depreciation, operation and maintenance.

Both the U.S. and the Eurodif diffusion plants are operating in a load-balancing mode in order to minimize costs by taking advantage of the availability of off-peak power. This mode of operation has been made technically feasible by the addition of controls and interstage hexafluoride storage capacity; it is economically possible because demand is less than capability, so that the plants can be operated at reduced capacity factor. Both the USDOE and the Eurodif plants are reported to be operating at capacity factors in the range 40 to 60 percent (11).

The economic production rate of the U.S. plants, as conditioned by electric power costs, is believed to be about 13 MSWU/a, representing a capacity factor of 65 percent.

Another key variable is tails concentration. By stripping less U-235 from the natural uranium feed, the amount of separative work required to produce a given quantity of enriched product can be reduced. The optimal tails assay depends on the price of natural uranium, increasing as this price declines.

The economics are further complicated by the existence of stockpiles of low-cost uranium feed material and of enriched product. In the 1988 fiscal year, for example, the USDOE plans to deliver 12.5 MSWU while producing only 4.5 MSWU, with the balance drawn from inventory (12).

The steady increase in demand (Figure 1) will force the diffusion plants to higher throughput and therefore higher unit cost. The gas centrifuge plants appear to be cost-competitive with the diffusion plants under current conditions and, unlike the diffusion plants, can be expanded incrementally to match the market. The possibility therefore exists of direct competition between the existing diffusion plants and new gas centrifuge capacity for each increment of demand. In the absence of accurate cost data for either process, this scope for new capacity cannot be defined.

The gas centrifuge exists as a proven commercial process with scope for further development to enhance its competitive position. In the longer run, perhaps about the end of the century, the proponents of AVLIS expect that process to enter the competition. It is not clear when, if ever, AVLIS will become the dominant technology.

The prospects outlined above are illustrated in Figure 3, showing a decrease in the production from the diffusion plants and the growth of new separative-work output. The new capacity would be a mixture of gas centrifuge and AVLIS plants, in a ratio depending on the relative economics of the two processes and on the marketing strategies of the U.S. and other countries. These projections are necessarily speculative because firm data are not available, but they are consistent with published information, with the characteristics of the processes and with the increasing cost of electric power.

There is thus a potential opportunity for blocks of new capacity to keep pace with reactor construction and the retirement of the diffusion plants.

Urenco, in association with Duke Power Co. and Fluor Daniel Inc., is currently attempting to organize a joint enterprise to build a 1 MSWU/a gas-centrifuge plant in the U.S. Figure 3 suggests that the world market could support several more such plants during this century.

3. THE CANADIAN OPPORTUNITY

3.1 The potential

Advances in uranium-enrichment technology are creating a competitive opportunity for new producers in Canada or elsewhere, but that is not all. The same advances promise declining enrichment costs which will tend to increase the demand for separative work, by increasing the optimal level of enrichment for LWRs, and will also increase the economic incentive for the use of SEU in CANDU reactors, thus creating a domestic market in Canada.

Studies by both AECL and Ontario Hydro are defining the benefits of SEU. In the case of existing CANDU reactors, the benefits include decreased fuelling cost and fuel throughput. The design of new reactors could benefit to an even greater extent by exploiting the scope for design improvement and heavy-water inventory reduction.

The size of the potential Canadian demand during this century is probably less than 300 000 SWU/a, which is small by international standards and very small relative to the minimum economic size of a diffusion plant, say 5 MSWU/a. The new processes, however, are economic at a much smaller scale than a diffusion plant. The initial Urenco plants began operation with capacities of 200 000 SWU/a and only one of the three has yet grown to 1 MSWU/a.

The potential domestic demand thus represents an effective base load for an enrichment plant. This fortuitous match is a new factor which drastically alters the Canadian situation.

Reduced investment risk is a corollary benefit of the smaller scale. The massive projects evaluated in past studies required investments of several billion dollars, to be recovered entirely from export sales; the present opportunity would require an investment about one-tenth as large and could be based on a domestic market. The initial capacity could then be expanded in appropriate stages as and when justified by export sales.

The potential for export sales is large. Canada annually exports some ten thousand tonnes of uranium, worth about one billion dollars. The value of enriched uranium is approximately double the value of the corresponding quantity of natural uranium. Thus, if even half of Canada's uranium were exported as enriched product, the added value would be about $500 million per year; the required separative work would be about 4 MSWU.

3.2 The window

While the opportunity is particularly attractive to Canada as a major uranium producer, it is open to others, not least to the established enrichment suppliers. At present the forward market is largely uncommitted, while utilities negotiate in a buyers' market and the major suppliers postpone new plant commitments and pursue their AVLIS development programs.

Before the end of the century, however, it is likely that commitments will have been made, long-term customer/supplier relationships established and the window of opportunity for market entry closed.

The technology for uranium enrichment, whether diffusion, centrifuge, or laser, does not exist in Canada and is closely held by its owners, for both commercial and non-proliferation reasons. The scale of effort that might realistically be applied in Canada would not be sufficient to establish a commercial uranium-enrichment industry within the available time.

To illustrate, it might be possible to assemble the technological skills and develop a gas centrifuge to the pilot-plant stage in, say, five years. At least a further five years would be needed to develop a commercial level of confidence in the reliability and life-expectancy of the machines, as Urenco has done and as Japan is now doing. The program would cost some hundreds of millions of dollars.

The Canadian perspective can be summarized in three conclusions:

1) Present circumstances offer an opportunity for Canadian entry into the enrichment business.

2) The opportunity is not open-ended, but will fade within this century.

3) The available time does not allow independent development of the required technology to the level of commercial competitiveness.

4. A CANADIAN STRATEGY

In light of the opportunity, a reasonable Canadian goal would be: To be in business as a credible supplier with a domestic baseload within this century. In view of the time constraint, the most plausible route is some form of joint venture that would provide access to the necessary technology.

The most likely technology for the initial plant is that of the gas centrifuge, which is commercially proven and thus entails minimum technological risk. The only alternative, AVLIS, is still in the development stage, may not become competitive within the time available and, in any event, is less likely to be shared by either of its leading developers - the United States and France. In this context, the gas centrifuge is seen as second-generation technology and laser isotope separation as a promising third generation. The Canadian venture, though based initially on the gas centrifuge, would expect to phase in AVLIS, or other third-generation technology, at the appropriate time and would therefore need a strong R&D effort.

The Chalk River laboratories of AECL are well positioned to provide a substantial R&D capability in the area of laser isotope separation. In the past, the laser photochemistry unit concentrated on basic research into multi-photon-decomposition (MPD) phenomena; this effort is directed at possible laser-based processes for heavy water production by hydrogen isotope separation.

In principle, MPD offers an attractive route to uranium enrichment. The process would operate on uranium hexafluoride, in common with existing enrichment processes, and would avoid the AVLIS necessity of handling molten uranium. Effort on MPD enrichment in the U.S. was terminated some years ago in favour of AVLIS, but this decision is not necessarily valid in another country and at a later time. The strong MPD background of the AECL laboratories provides a base for possible application of this process to uranium.

In addition, a small AECL program on the selective ionization and separation of uranium isotopes in metal vapour, the AVLIS process, has recently demonstrated the principle of a very high separation factor.

An effective base of laser isotope separation science and technology is thus ready for rapid expansion as required.

As the world's largest uranium producer, Canada has a clear interest in uranium enrichment to increase the product value. As a leader in the application of nuclear power, Canada possesses much of the technology and infrastructure to support a uranium-enrichment industry. The existing nucleus of laser-process skills could readily be directed to the development of a third-generation uranium-enrichment process, and the track record of nuclear power development in Canada gives grounds for confidence in the outcome of such a program.

An enrichment enterprise based initially on proven gas centrifuge technology and with the potential to introduce a laser-based process at the appropriate time, is an attractive possibility for Canada and for a suitable joint-venture partner.

5. CONCLUSIONS

5.1 Uranium enrichment is a desirable activity for Canada, as a means of increasing the export value of the uranium resource.

5.2 Technological change is reducing the cost of enrichment, thus making slightly enriched uranium (SEU) desirable, if not essential, for the Canadian nuclear power program.

5.3 A decision by Ontario Hydro to convert to SEU would create a domestic market of approximately the size required to support economic operation of a minimum-scale enrichment plant.

5.4 The new technology promises to reduce the investment required for an enrichment plant to a level well within the financial means of Canada.

5.5 The opportunity created by technological change is not open-ended; action is required soon to establish a Canadian presence in the new supplier/customer patterns which will evolve between now and the end of the century.

5.6 An independent Canadian program would require a decade or more of process development and would thus risk foreclosure of the market opportunity.

5.7 The risks and the lead time for a Canadian plant could be reduced by proceeding in two stages, launching the enterprise with proven gas centrifuges and introducing AVLIS, or other third-generation enrichment technology, in later expansions.

5.8 The initial stage would depend on the proprietary technology of a foreign partner. The new technology would be developed in a joint program involving a substantial Canadian contribution.

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Table 1

Enrichment Capacities to 2000

(Tonnes SWU/a)

COUNTRY	Method	1984 (actual)	1985 (actual)	1990	1995	2000
France	Diffusion	10 800	10 800	10 800	10 800	10 800
Germany F.R. (a) Netherlands (a) United Kingdom (a)	Centrifuge	1 250	1 650	3 000	4 500	6 000
Japan	Centrifuge	50	50	250	1 200	2 800
United States	Diffusion	19 500	19 500	19 500	19 500	19 500
OECD Total		31 600	32 000	33 550	36 000	39 100

(a) Total for the URENCO.

Source: Summary of Nuclear Power and Fuel Cycle Data in OECD Member Countries, 1986. Nuclear Energy Agency, Paris.

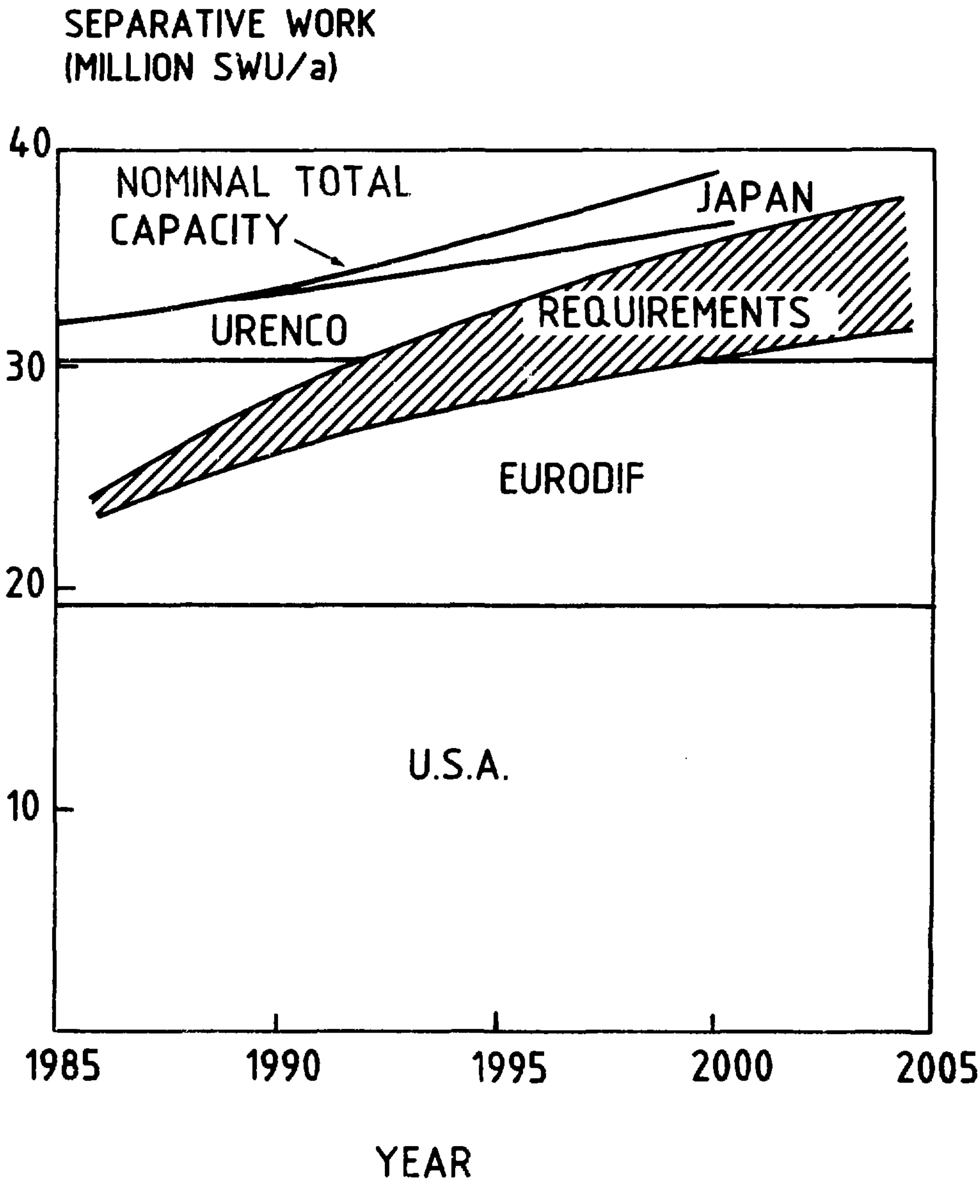

FIGURE 1:
SEPARATIVE WORK REQUIREMENTS AND CAPACITY, WESTERN WORLD.

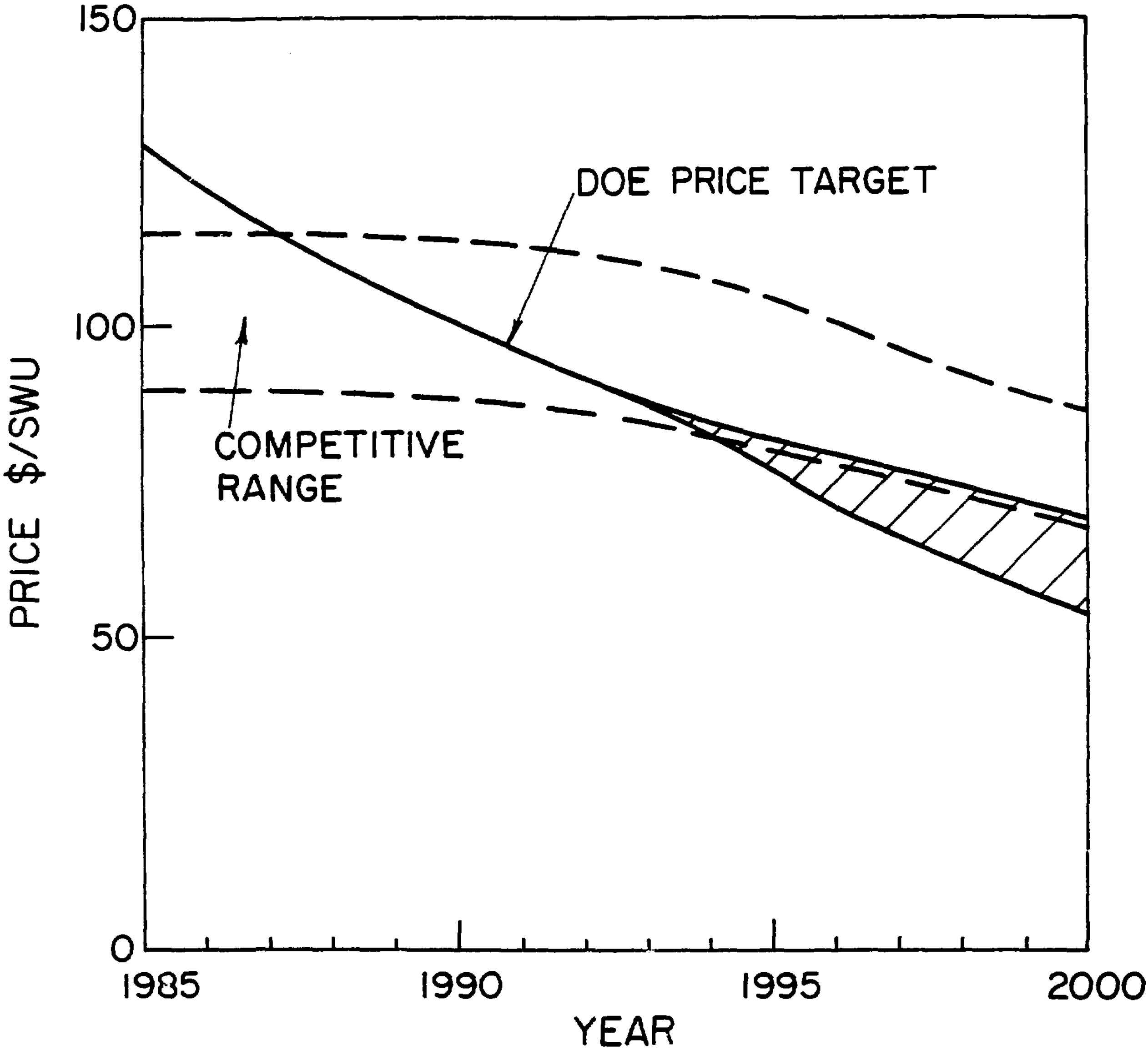

FIGURE 2

URANIUM ENRICHMENT PRICES

[PROJECTIONS BY U.S. DOE]

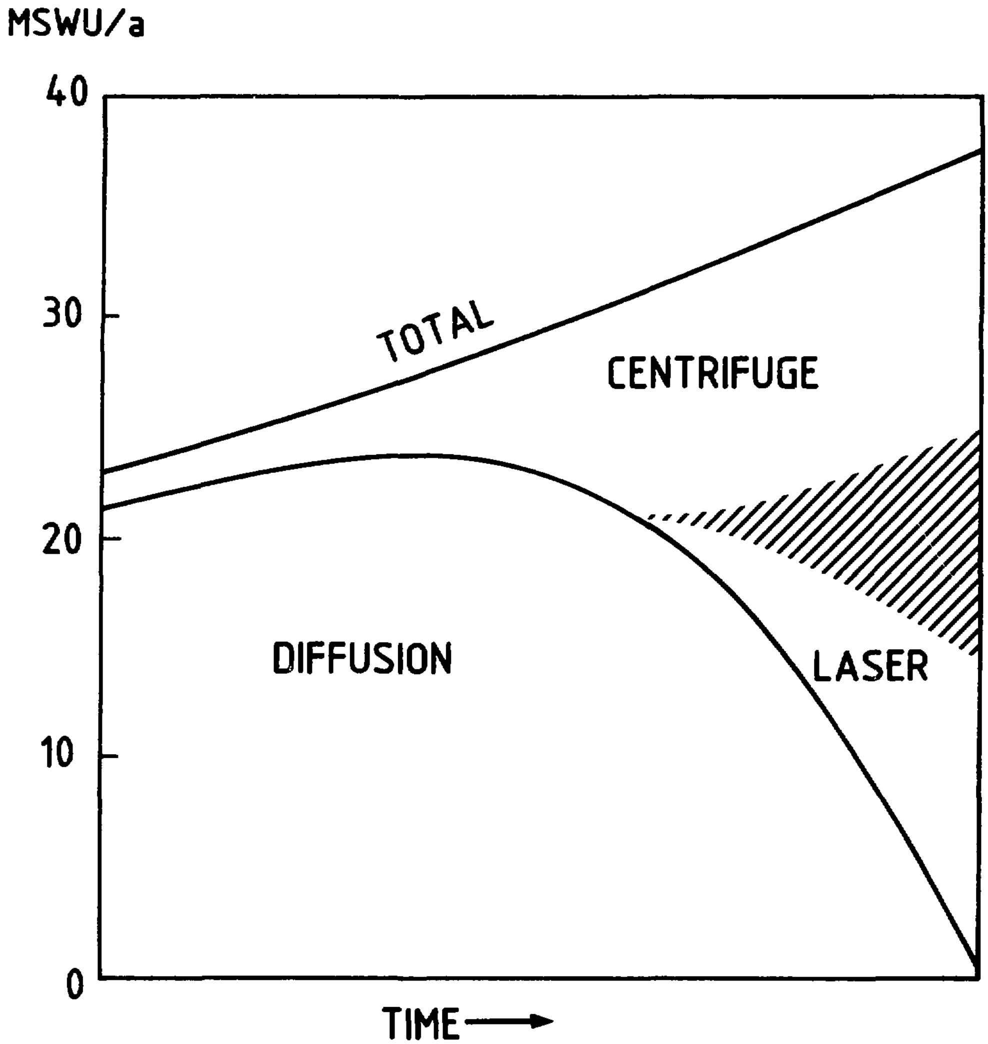

FIGURE 3:
SEPARATIVE WORK PRODUCTION
(POSSIBLE DISTRIBUTION AMONG PROCESSES.)

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