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ATOMIC ENERGY OF CANADA LIMITED

L'ÉNERGIE ATOMIQUE DU CANADA LIMITÉE

INDUSTRIAL PROCESS HEAT FROM CANDU REACTORS

Chaleur industrielle fournie par les réacteurs CANDU

J.W. HILBORN, J.S. GLEN, W.A. SEDDON, and A.G. BARNSTAPLE

Paper presented at the First Annual Conference of the *Canadian Nuclear Society*, Montreal, June 1980

Chalk River Nuclear Laboratories

Laboratoires nucléaires de Chalk River

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RÉSUMÉ

On a démontré à grande échelle que les réacteurs CANDU peuvent fournir de la vapeur industrielle aussi bien que de l'électricité et, ce, fiablement et économiquement. Les avantages de cette co-production sont à l'origine du concept d'un parc industriel adjacent au Complexe électronucléaire de Bruce en Ontario. Pour des besoins en vapeur se situant entre 300 000 et 500 000 lb/h (38-63 kg/s) à un facteur de charge annuel s'élevant à 80%, le coût estimatif de la vapeur d'origine nucléaire à la sortie du Complexe de Bruce atteint $3.21/MBtu ($3.04/GJ). La vapeur d'origine nucléaire est au moins 30% moins cher que la vapeur provenant de la combustion du mazout sur le même site. L'application la plus prometteuse à court terme de la chaleur nucléaire se trouvera probablement dans l'industrie chimique dévoreuse d'énergie. L'énergie nucléaire peut remplacer le charbon et le pétrole importé dans les provinces de l'Est si son prix reste compétitif mais le charbon et le gaz peu coûteux que l'on trouve dans les provinces de l'Ouest peuvent inciter les industries dévoreuses d'énergie à s'établir près de ces sources énergétiques. Il est possible qu'à long terme on ait recours à la chaleur nucléaire pour extraire le pétrole des sables bitumineux de l'Alberta.

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ABSTRACT

It has been demonstrated on a large scale that CANDU reactors can produce industrial process steam as well as electricity, reliably and economically. The advantages of cogeneration have led to the concept of an Industrial Energy Park adjacent to the Bruce Nuclear Power Development in the province of Ontario. For steam demands between 300,000 and 500,000 lb/h (38-63 kg/s) and an annual load factor of 80%, the estimated cost of nuclear steam at the Bruce site boundary is \$3.21/MBtu (\$3.04/GJ), which is at least 30% cheaper than oil-fired steam at the same site. The most promising near term application of nuclear heat is likely to be found within the energy-intensive chemical industry. Nuclear energy can substitute for imported oil and coal in the eastern provinces if the price remains competitive, but low cost coal and gas in the western provinces may induce energy-intensive industries to locate near those sources of energy. In the long term it may be feasible to use nuclear heat for the mining and extraction of oil from the Alberta tar sands.

NUCLEAR HEAT FOR INDUSTRY

To date nuclear power throughout the world has been used almost exclusively for the generation of electricity. There are two significant exceptions: in Switzerland the 970 MWe Gösgen pressurized water reactor is supplying 100,000 lb/h (12.6 kg/s) of process steam to a cardboard factory [1]; in Ontario at the Bruce Nuclear Power Development operated by Ontario Hydro, five CANDU reactors are providing up to 5.4 x 10^6 lb/h (680 kg/s) of steam for heavy water production [2].

When completed, the Bruce Nuclear Power Development, built by Ontario Hydro, will be one of the world's largest nuclear energy centres. Maximum energy production from the Douglas Point reactor and the four Bruce A reactors totals 10,000 MW thermal or 3200 MW electrical. Figure 1 is a simplified block diagram showing how high pressure steam (4.2 MPa, 254°C) is diverted from the turbines to two steam transformer stations which produce medium pressure steam (1.24 MPa, 193°C) for the two heavy water plants. One of the steam

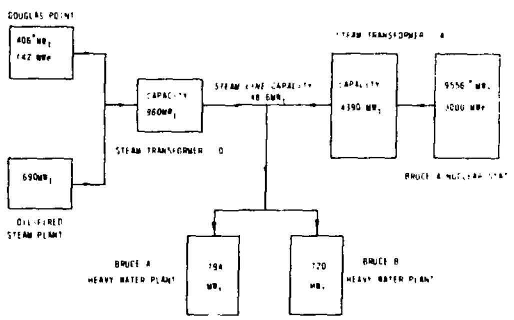

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FIGURE 1: STEAM TRANSPORT SYSTEM AT THE BRUCE NUCLEAR POWER DEVELOPMENT

transformer stations receives steam from Douglas Point or the oil-fired plant, while the other takes steam from any one or any combination of the four Bruce A reactors. At maximum production one heavy water plant requires a steam flow of 2.7 x 10^6 lb/h (340 kg/s). The corresponding reactor power diverted from electricity production is about 1/3 of the heat output of one Bruce reactor.

Insulated pipelines up to 1.7 m in diameter carry medium pressure steam from the steam transformer stations to the heavy water plants. The total length of pipeline from the two transformer stations is 3.4 km. Assuming maximum production of heavy water the reserve capacity of the existing steam supply system is approximately 10×10^6 lb/h (1260 kg/s) or 3500 MW thermal; and more than 20% of that capacity can be supplied with a reliability of 99%. No other nuclear plant can match the existing capability of the Bruce plant for the dual production of process steam and electrical power.

ENERGY PARK CONCEPT

There are two basic reasons for using heat directly instead of converting it to electricity: lower cost and conservation of fuel. When electricity is generated in steam-driven turbines, approximately 1/3 of the original heat can be converted to electricity, so that only 1/3 of the fuel, whether it be uranium, oil or coal, is actually being used by the consumer of electricity. If the consumer needs heat only, obviously it should be 3 times more efficient to use the heat directly from the source and not indirectly in the form of electricity. But it is not that simple; the distribution of heat is costly. If consumers are widely dispersed, the factor of 3 advantage in fuel efficiency is not enough to balance the cost of providing insulated pipe lines to carry steam or hot water from a central heating plant. To be practical and economic, nuclear heating from CANDU reactors must be on a large scale and the consumers must be reasonably close to the reactors. Hence the concept of an Industrial Energy Park adjacent to the Bruce Nuclear Power Development [3]. If a steam pipeline is built to serve one or two large industrial plants, then it may be feasible to provide low cost steam to smaller industries through branch pipelines. A survey of 100 industrial steam users is currently being conducted by Atomic Energy of Canada Limited. Agencies contributing to the Energy Park concept are the Bruce County Economic Development Committee, the Ontario Energy Corporation, the Ontario Ministry of Industry and Tourism, Ontario Hydro, and Atomic Energy of Canada Limited.

COGENERATION

The term "cogeneration" is commonly used to describe the dual production of heat and electricity from a single energy source. The two products can be supplied in a fixed ratio, or the ratio can be varied according to demand. In general the most efficient arrangement is the production of electricity by a back pressure turbine operating at a selected outlet temperature, such that the outlet steam from the turbine can be used for industrial processes or space heating. To achieve peak efficiency from cogeneration all of the energy and all of the capital equipment should be fully utilized. In practice there is always some energy wasted.

At the Bruce complex, all of the reactor steam can be used for electricity production, or any fraction of that steam up to 15% of the maximum total output can be diverted to the heavy water plants. This arrangement offers great flexibility in supplying a variable heat and electricity demand, but it is not the most economic because the capital equipment is never fully utilized. However the direct use of nuclear steam is energy efficient to the extent that the 2/3 heat loss from electricity production is avoided. Over the long term this energy efficiency could be an important factor in conserving uranium suppplies and maintaining the cost competitiveness of nuclear steam.

COST OF NUCLEAR STEAM

Recent Ontario Hydro estimates assume that steam supplied to outside customers from the Bruce Nuclear Power Development will result in curtailed electrical production. This curtailing steam is costed on the basis of a system average replacement value of an equivalent amount of steam generated elsewhere by nuclear and coal-fired stations. Because of the higher overall costs associated with coal-fired stations, the system average steam cost is substantially higher than the cost of nuclear steam alone. For example, in 1979 coal-fired steam averaged about $3.19/MBtu whereas high pressure nuclear steam averaged $1.17/MBtu. The combined *system average was $2.13/MBtu.*

Preliminary cost estimates for medium pressure steam delivered to the Bruce site boundary (~3 km) are shown in Table 1.

TABLE 1: ESTIMATED COSTS OF MEDIUM PRESSURE STEAM* DELIVERED TO BRUCE SITE BOUNDARY (1980)

	$/MBtu
System average (nuclear and coal) replacement cost of curtailed electrical production	2.12
Proportional capital, operating, maintenance and amortization of the Bruce steam supply system (i.e. steam transformers, condensate plant and pipelines)	0.43
Capital cost of duplicate steam pipelines to site boundary	0.57
Expansion of water treatment plant	0.06
Corporate overheads	0.03
Total	$3.21

*Demand 300,000-500,000 lb/h (38-63 kg/s); annual load factor 80%.

For comparison, oil-fired steam at the Bruce site cost about $4.80/MBtu in 1979, with crude oil at $15/barrel. Figure 2 shows the increase in Bruce nuclear steam costs with decreased demand and load factor.

Annual escalation in the cost of nuclear process steam at the Bruce site is projected to be 4.7%, which is less than half of the present inflation rate of 10% per year. If that ratio persisted for 20 years the cost of nuclear steam in 1980 dollars would decrease by factor of 2.7 to $1.20/MBtu. Hence escalation of fossil fuel prices is probably the most important factor determining the future competitive position of nuclear steam at the Bruce site.

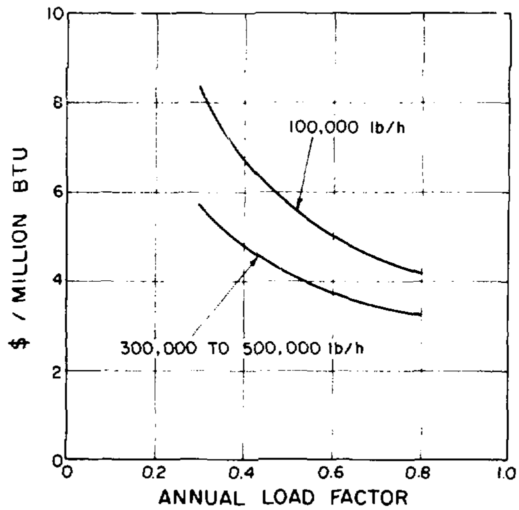

FIGURE 2: ESTIMATED 1980 COSTS OF BRUCE MEDIUM PRESSURE STEAM DELIVERED TO THE SITE BOUNDARY

SELECTING SUITABLE INDUSTRIES

The smallest CANDU reactor currently being built (600 MWe, 2000 MWt) produces far more steam than is required by any single industrial plant. In fact the industrial steam demand for all of Ontario is equivalent to the total steam production of four Bruce reactors. Hence the main object of the present study is to identify energy-intensive industries which might find it advantageous to locate new plants near existing CANDU reactors. Such plants could use a small fraction of the reactor steam as the Bruce heavy water plants do.

The six industrial groups listed in Table 2 account for 90% of the energy consumed by Canadian industry; and the tabulated ratios of energy cost to value-added are a measure of the economic importance of energy in various manufacturing and refining processes [4]. In broad terms value is added by the manufacturing effort expended in converting raw materials and energy to finished goods.

TABLE 2: ECONOMIC IMPORTANCE OF ENERGY IN SELECTED CANADIAN INDUSTRIES (1977)

Industrial Group	Ratio of Energy Cost to Value-Added (%)
Pulp and Paper	17.4
Primary Metals	12.8
Petroleum and Coal Products	6.9
Chemicals and Chemical Products	13.6
Non-metallic Mineral Products	15.4
Food and Beverage	4.4

The Pulp and Paper industry is the largest energy user (27%) and most of the energy is at temperatures below 300°C. It is noteworthy that the first industrial use of nuclear steam in Europe is for cardboard production. In Canada, proximity to raw materials is a major factor in siting new plants, and in the near term it is unlikely that it will be economic to locate pulp and paper mills near existing CANDU generating stations.

Only 15% of the energy used in the Primary Metals industry is compatible with CANDU steam temperatures and there appears to be little scope for substitution. However, special electricity rates for industries located close to a nuclear generating station would be of great significance.

The Petroleum and Coal Products group is largely dominated by refineries. About 40% of the energy requirements are at low temperature but the ratio of energy cost to value-added is only 6.9%. Most of the energy used is produced by the refineries themselves, but how much is from true waste is not known at this time.

The Chemicals and Chemical Products group consumes 9% of industrial energy, using significant quantities of oil, gas and electricity. The ratio of energy cost to value-added is 13.6%, which is twice that of the Petroleum and Coal Products group. Within the Chemical Industry the Industrial Chemicals group is the most energy-intensive, with a 34% ratio of energy cost to value-added.

The Non-Metallic Mineral Products group is similar to the Primary Metals group in that only 15% of the consumed energy is at a low enough temperature to be supplied by CANDU reactors; hence there is little incentive to locate near a nuclear generating station.

The Food and Beverage industry is the least energy intensive of the six selected groups, consuming only 5% of the total energy used by Canadian industry. The ratio of energy cost to value-added (4.4%) is also the least of the six.

It is concluded from this brief review of the major energy consuming industries in Canada that manufacturers of Industrial Chemicals should have the greatest incentive to use nuclear steam on a large scale.

SUBSTITUTION FOR OIL AND COAL

During the first six months of 1979, net imports of crude and refined oil averaged about 200,000 barrels per day. Canadian industry consumes about 250,000 barrels per day, 27% of which is attributed to Pulp and Paper and 7% to Chemicals [5]. For comparison, nuclear steam supplied to the Bruce Heavy Water Plants is equivalent to 20,000 barrels of oil per day or 10% of net imports. Although there is considerable potential for saving oil by nuclear heating, it is too early to predict how soon that potential will be realized. In the near term, the single most important factor is the price of delivered nuclear steam. Apart from conventional cogeneration the competition is western coal and gas, and energy-intensive industries can choose to locate near those sources of energy if there is an economic advantage in doing so.

A potential long term application of nuclear heating is the mining and extraction of oil from the Alberta tar sands [6]. A full scale plant produces 150,000 barrels of synthetic crude per day, and the energy input required is equivalent to about 50,000 barrels per day. This external energy could be derived from Alberta coal or from uranium. If the coal must be transported several hundred kilometres, nuclear energy from uranium can compete with coal; and on a 20 year time scale it may be preferable to reserve Alberta coal for export.

ENERGY SELF-SUFFICIENCY

Ontario, Quebec and New Brunswick have taken a significant step towards energy self-reliance by constructing nuclear generating stations instead of oil or coal-burning stations. CANDU nuclear plants built by Ontario Hydro have already saved more than $1.5 billion in foreign exchange on the purchase of imported coal. By 1990 it is projected that this figure will have grown to $16 billion [7]. By that time nuclear power from 21 reactors will be supplying more than half of Ontario's electrical energy. Average daily production at the Bruce complex alone currently replaces 20,000 tonnes of coal or 115,000 barrels of oil. The next important step is to use part of the nuclear energy directly in the form of steam for industrial processes, as already demonstrated by the Bruce heavy water plants.

CONCLUSIONS

- The direct use of nuclear steam for industrial processes has been thoroughly demonstrated on a large scale.
- Industrial use of CANDU nuclear steam can best be implemented by locating new energy intensive industries near existing reactors; hence the concept of an Industrial Energy Park.
- The most promising industry in the near term is the chemical industry.
- The estimated cost of medium pressure steam delivered to the Bruce site boundary is $3.21/MBtu (1980 dollars), which is 30% cheaper than oil-fired steam based on the Canadian oil price of $15/barrel.
- Annual escalation in the cost of nuclear steam at the Bruce site is projected to be 4.7%, which is about half the current inflation rate.
- Oil imports can be significantly reduced by using nuclear heat for industrial processes.
- A potential long term application of nuclear heating is the mining and extraction of oil from the Alberta tar sands.

CONVERSION FACTORS

British units are used for the heat content and mass flow of steam because these are still the predominant units encountered in industry.

10^6 Btu = 1 MBtu = 1.055 GJ

10^6 lb/h = 126 kg/s

$1.00/MBtu = $0.948/GJ

1 barrel (oil) = 0.159 m^3

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