REGIONAL COGENERATION VIA ELECTRICAL UTILITIES OPERATING ON NUCLEAR ENERGY AND COAL: ENERGY AND ENVIRONMENTAL BENEFITS

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Received January 2009, Accepted March 2009
No. 09-CSME-16, E.I.C. Accession 3102

ABSTRACT

The use of electrical-utility cogeneration from nuclear energy and coal is examined for improving regional efficiency regarding energy-resource utilization and environmental stewardship. A case study is presented for a large and diverse hypothetical region which has nuclear and fossil facilities in its electrical utility sector. Utility-based cogeneration is determined to reduce significantly annual use of uranium and coal, as well as other fossil fuels, and related emissions for the region and its electrical-utility sector. The reduced emissions of greenhouse gases are significant, and indicate that electrical utility-based cogeneration has a key role to play in combating climate change.

LA COGÉNÉRATION RÉGIONALE VIA LES SERVICES ÉLECTRIQUES FONCTIONNANT À L'ÉNERGIE NUCLÉAIRE ET AU CHARBON : ÉNERGIE ET AVANTAGES ENVIRONNEMENTAUX

RÉSUMÉ

L'utilisation de la cogénération dans les services électriques, à partir d'énergie nucléaire et de charbon, est examinée pour améliorer l'efficacité régionale en ce qui concerne l'utilisation de la ressource énergétique et d'intendance environnementale. On présente une étude de cas pour une région étendue et hypothétique qui dispose de l'énergie nucléaire et fossile dans ses secteurs utilitaires électriques. On a déterminé que la cogénération dans les services utilitaires de base réduit de façon significative l'utilisation annuelle d'uranium et de charbon ainsi que d'autres énergies fossiles, et réduit aussi les émissions de gaz à effet de serre reliées pour la région et son secteur de services utilitaires électriques. La réduction des émissions de gaz à effet de serre est significative, et indique que la cogénération dans les services électriques utilitaires joue un rôle majeur dans la lutte aux changements climatiques.

1. INTRODUCTION

A case study is conducted in which the potential benefits are investigated of cogeneration (or combined heat and power) using the facilities of electrical utilities in a hypothetical region. The main advantage of cogenerating thermal and electrical energy is that less input energy is consumed than would be required to produce the same products in separate processes. Additional benefits often include more economic, safe and reliable operation, as well as reduced environmental emissions [1]. The latter is primarily attributable to reduced energy consumption and the use of modern technologies in large, central installations. The reduced emissions of greenhouse gases can be significant, allowing cogeneration to contribute notably to mitigating climate change.

The hypothetical region is assumed to have the following characteristics:

- a diverse economy, including many types of industry with a range of heating needs,
- a large population (approximately 10 million),
- an electrical-utility sector that predominantly uses uranium and coal in thermal power plants, and hydroelectric plants,
- a large land area (over 200,000 square kilometers), with the population and industry spread over it, so that energy needs are geographically dispersed rather than concentrated in a small area, and
- a climate that varies over the year, with temperatures reaching 30°C in summer and -30°C in winter, so that heating and cooling are likely required.

It is noted that the hypothetical region somewhat resembles the Canadian province of Ontario, which has been investigated by the author previously [2-4].

The case study considers the potential impact of utility-based cogeneration in the hypothetical region, relative to the situation in which cogeneration is applied only in a very restricted manner, with the objective of determining the possible annual benefits derivable from utility-based cogeneration.

2. BACKGROUND

2.1. Cogeneration Technology and Applications

Nuclear and fossil-fuel thermal power plants form the basis of most cogeneration systems. In thermal power plants, a fossil fuel or uranium resource is converted to heat in the form of steam or hot gases, which is subsequently converted to mechanical energy and then to electricity. Approximately 25% to 50% of the heat is converted to electricity, with the remainder rejected as waste to the environment. Cogeneration systems are similar to thermal power plants, but some of the generated heat is delivered as a product in such forms as steam or hot water, with a sacrifice in electricity production. Cogeneration therefore involves the simultaneous production of thermal and electrical energy. In such systems, steam can be extracted from one or more points on the turbines and exported to nearby heat users, or steam can pass through part of the steam turbines and then be diverted for use in heating. The waste heat rejection is reduced, allowing overall cogeneration efficiencies based on both the electrical and thermal energy products of 80% to 90% to be achieved [1]. Cogeneration can be applied in plants of varying sizes, ranging from those for single buildings to utility-scale facilities.

Two main categories of heat demands can normally be satisfied through cogeneration:

- residential, commercial and institutional (RCI) processes (e.g., space and water heating), which require large quantities of heat at relatively low temperatures.

- industrial processes (e.g., drying, heating, boiling), which require heat at a wide range of temperatures. Thermal energy-intensive industries are numerous and include chemical, petrochemical and metal processing, fertilizer and cement production, manufacturing and construction, pulp and paper processing.

The use of a central heat supply to meet the heat demands of the RCI sector (which is taken here to include the institutional sector) is often referred to as district heating, and has been applied extensively. It is noted that cogenerated heat can even be used to drive absorption chillers for space cooling, rather than using more conventional electrically driven chillers.

2.2. Recent Developments in Cogeneration

Many types and applications of cogeneration systems exist. Cogeneration systems are in use throughout the world. Most of these are based on fossil-fuels. The size and type of a cogeneration system are normally selected to match as optimally as possible the thermal and electrical demands.

Cogeneration has been investigated recently from many perspectives. For instance, the prospects have been examined for residential total energy systems incorporating cogeneration [5] and for cogenerating heat and electricity from CANDU nuclear power plants [6]. The latter report is consistent with a past opportunity for utility-based cogeneration promoted in Ontario, Canada [7]. The electrical utility stated that large supplies of heat in the form of steam or hot water are available at several of its stations around the province, at as high as 230°C for nuclear and 510°C for coal-fired stations. Cogeneration based on new and advanced technologies has also been proposed, including one using coal gasification and solid oxide fuel cells [8]. Trigeneration (i.e., cogeneration with cooling as a third product) systems have also been assessed [9] as have their potentials for integrating beneficially with district energy systems [10]. Other related technical factors have also been studied, such as utility/cogeneration inter-tie electrical protection [11].

Cogeneration plants have been analysed thermodynamically [12]. Advanced thermodynamic analysis methods based on exergy [13] for assessing and improving efficiency have been applied to cogeneration facilities [13, 14] and related technologies such as district heating and cooling [13-15]. Exergy analysis is not considered but, as noted earlier, has been applied elsewhere by the author to utility-based cogeneration [15]. Design, synthesis and optimization aspects of cogeneration systems have also been examined. Design criteria have been identified for distributed cogeneration plants [16], and the synthesis of industrial utility systems has been examined for cost-effective decarbonisation [17]. The optimal design of gas turbine cogeneration plants was recently studied [18], as have economic factors, like demand charges and their impact on the optimization of cogeneration dispatch in deregulated energy markets [19].

2.3. Cogeneration Electrical-Utility Facilities

The hypothetical region is assumed to utilize a mix of energy sources for its electricity generation, including nuclear energy and coal. Hydraulic energy may be used, but is not considered in this case study because it can not be used for cogeneration. For the electrical generation stations considered here, the efficiency based on electrical energy are assumed, based on a previous report [1], to be 37% for coal-fired plants and 30% for nuclear plants. The largest energy loss is the heat rejected from the condensers in cooling water. Thus, efficiency can be markedly improved for both types of plants if the thermal energy rejected by the condensers is used, i.e., if cogeneration is implemented.

Many cogeneration systems are possible based on coal and nuclear electrical stations. A significant degree of flexibility exists in the current system for utility-based cogeneration within both individual station units and multiple unit stations. In addition, many enhancements of the existing system are possible using advanced cogeneration technologies.

Many existing electrical generation and cogeneration systems utilize natural gas as fuel, and natural gas-based cogeneration systems may play an important role in future utility-based cogeneration. The importance of natural gas is in part related to its relatively low greenhouse gas emissions, compared to other fossil fuels. Nonetheless, the present work concentrates on coal and uranium, the fuels assumed used in the utility sector of the hypothetical region.

2.4. Prior Assessments of Regional Cogeneration from Electrical Utilities

Investigations of the energy, environmental, health, and economic benefits of utility-based cogeneration have been carried by the author for Ontario, Canada, focusing on annual assessments [2, 3] as well as cumulative assessments over time periods of decades [4].

In addition related techno-economic studies have been reported [20-23].

Also, analyses such as the one reported here have been carried out for many similar technologies, e.g., a comparative assessment of environmental and health impacts of electrical power generation, including nuclear-based processes, has been reported by [24]. Options for nuclear energy beyond electricity generation, including the provision of heating, have been investigated [25] and are important given the predictions for increased nuclear energy utilization [26-29].

3. DEMANDS AND MARKETS FOR THERMAL ENERGY

Potential markets in a region for utility-cogenerated thermal energy, which exist mainly in the RCI and industrial sectors, are a portion of the total thermal-energy demands. These markets depend on many factors, both technical and non-technical:

- *Heat characteristics and availability*: The quantity, supply rate and temperature of supplied heat must satisfy all demand requirements and, in addition, the system must be able to accommodate actual variations in heat-demand parameters (quantity, temperature, etc.). In this area, cogenerated heat from nuclear plants is usually at a lower temperature and thus less valuable than that from fossil-fired plants. Furthermore, heat must be available when it is in demand, either by cogenerating when heat is demanded or storing the heat during periods between its generation and utilization.
- *Distance*: Users and suppliers of thermal energy must be located within a suitable distance of each other. Given nuclear plants tend to be few, large and separated by large distances, rather than spread out geograhpically, the potential contributions for nuclear-derived heat are lower than those for fossil-derived heat.
- *Infrastructure, attitude and economics*: An overall infrastructure and all relevant technologies must exist for all cogeneration steps, including heat supply, distribution, storage and utilization. In addition, the attitude towards the idea must be positive for all parties involved, including suppliers, distributors, users and others. Furthermore, the economics for cogeneration options normally need to be competitive with or superior to the economics for other non-cogeneration options. This statement presumes a traditional economic approach, but the inclusion of externalities such as environmental costs can substantially increase the economic competitiveness of cogeneration, and policy reasons (e.g., environmental) can render cogeneration alternatives desirable even if not economically competitive.

4. COGENERATION SCENARIOS

Six scenarios are considered in which the effects of implementing electrical utility-based cogeneration are examined for the region. The scenarios are assessed by evaluating the changes in quantities such as energy consumption and environmental emissions when cogeneration is implemented. To provide an understanding of the behaviour of the electrical-utility sector, the regional effects of cogeneration for the scenarios are separated out for the electrical-utility sector.

4.1. Base Case

Annual data for the region and its electrical-utility sector, against which the scenarios are assessed, are provided for

- energy requirements for heating (Fig. 1),
- energy use for the region (Fig. 2), including values for primary energy forms and the secondary form electricity,
- energy use for the region's electrical-utility sector (Fig. 3),
- environmental material emissions (Table 1).
- environmental non-material emissions (Table 2).

4.2. Scenarios

Six cogeneration scenarios are considered. The scenarios involve the use of heat from basic or advanced utility-based cogeneration networks to supply some of the heat demands of the RCI and/or industrial sectors. The details for each scenario are provided in Table 3. The scenarios are intended to span possible wide range of market penetration for utility-based cogeneration, with Scenarios A and C assuming the least penetration and Scenario F assuming the most.

Table 1. Annual material emissions for the region and its electrical-utility sector (kilotons)

	SO_2	NO_X	CO_2	CO	Particulates	V.O.C.[a]	Spent uranium
Region	1400	600	150,000	3500	800	800	1
Utility sector	300	100	30,000	10	10	1	1

[a] V.O.C. denotes volatile organic compound.

Table 2. Annual non-material emissions for the region and its electrical-utility sector

	Thermal pollution[a] (PJ)	Radiation[b] (10^{15} Bq)
Region	600	10
Utility sector	600	10

[a] Thermal pollution is heat emitted to bodies of water that cause appreciable temperature rises.

[b] Radioactive emissions from non-nuclear-energy sources are not included, e.g., radioactivity in coal-station stack gases.

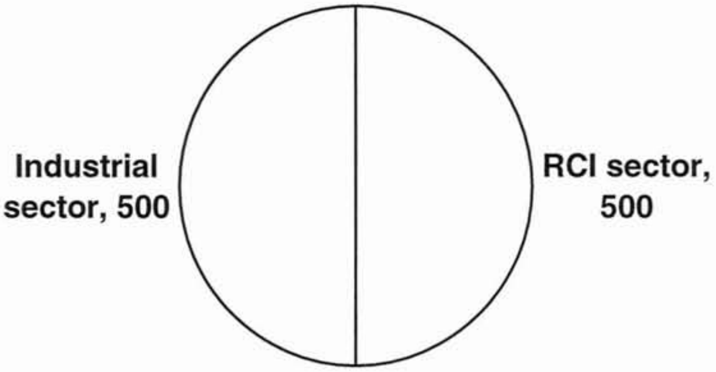

Fig. 1. Annual energy requirements in the region for heating, by sector (PJ).

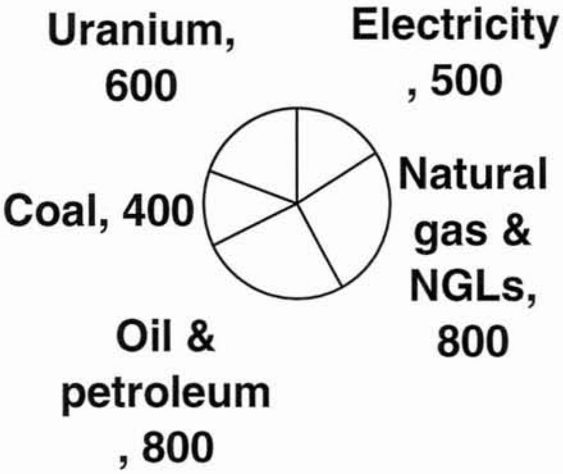

Fig. 2. Annual energy use in the region (PJ). NGLs denotes natural gas liquids. Uranium energy of is taken to be heat delivered by fission.

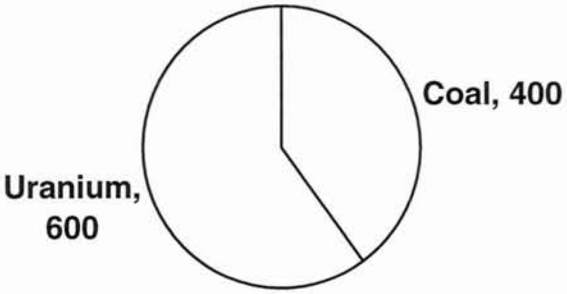

Fig. 3. Annual energy use in the electrical-utility sector of the region (PJ). Uranium energy of is taken to be heat delivered by fission. Hydraulic energy use is not shown.

Table 3. Descriptions of the electrical utility-based cogeneration scenarios

Scenario	Type of utility-based cogeneration network	Sector receiving utility-cogenerated heat	Proportion of sector heat demands met via utility-based cogeneration
A	Basic	RCI	Small
B	Advanced	RCI	Large
C	Basic	Industrial	Small
D	Advanced	Industrial	Large
E	Basic	RCI and industrial	Small
F	Advanced	RCI and industrial	Large

The scenarios consider two hypothetical utility-based cogeneration networks: basic and advanced. The basic network is founded on a current network of thermal electrical stations having little cogeneration, with only minor cogeneration modifications implemented in some nuclear and coal stations. The advanced network consists of a modified network, where some multi-unit stations are separated and located near heat demands, and where advanced cogeneration technologies are used along with current-technology thermal stations modified for cogeneration. For the advanced network, government intervention through legislation and incentives to promote cogeneration is assumed sufficiently great to result in significant market penetration for cogeneration and the perception of cogeneration as a conventional heating technology. Thermal energy storage is used in both networks, especially for coal stations, which operate much more intermittently than nuclear stations.

Based on a prior study of electrical generating stations [1], for both utility-based cogeneration networks (i) overall efficiencies are taken to be 85% for nuclear or coal cogeneration, (ii) electrical efficiencies (in %) are approximated by the expressions $32-(0.11)T$ for nuclear cogeneration and $40-(0.074)T$ for coal cogeneration, where T denotes the cogenerated-heat temperature (in °C), and (iii) thermal efficiencies are given by the differences between the corresponding overall and electrical efficiencies.

In all scenarios, half of the cogenerated heat is used to offset electricity provided by the electrical utility to users for heating. The other half of the cogenerated heat is used to offset the non-electrical utility energy resources (e.g., natural gas and oil) used by others for heating. Also, 33% of the cogenerated heat is assumed to be produced from coal and 67% from nuclear energy. These are presumed to be the same proportions from which electricity is generated from them. To supplement the cogenerated electricity, current-technology non-cogenerating coal and nuclear generating stations are used, again in the same proportions as cited above.

4.3. Thermal Demands Satisfied with Cogenerated Heat

The portions of the heat demands to be met by utility-cogenerated heat are estimated by considering the factors discussed in section 3. Considering these factors, it is assumed for the RCI sector that

- utility-cogenerated heat temperatures permit for all scenarios 100% of the heat demands to be satisfied, as they are all at low temperatures,
- 35% of heat demands are within a servicable distance of the cogeneration plant for scenario A, and 60% for scenario B, and
- 25% of potential users find the infrastructure/attitude/economic conditions favourable enough to use cogenerated heat for scenario A, and 65% for scenario B.

Similarly, it is assumed for the industrial sector that

- utility-cogenerated heat temperatures permit 100% of low- and medium-temperature industrial heat demands to be satisfied for scenarios C and D, and 30% of high-temperature demands for scenario C and 40% for scenario D,
- 30% of low-, 23% of medium- and 15% of high-temperature demands are located within a servicable distance of the cogeneration plant for scenario C, while the corresponding values are 60%, 45% and 30% for scenario D, and
- 40% of potential users find the infrastructure/attitude/economic conditions favourable enough to use cogenerated heat for scenarios C and D.

Consequently, the six scenarios considered can be quantitatively described as follows:

A a basic utility-based cogeneration network supplies a small portion (10%) of the annual heat demand of the RCI sector;

B an advanced utility-based cogeneration network supplies a significant portion (40%) of the annual heat demand of the RCI sector;

C a basic utility-based cogeneration network supplies a small portion (5%) of the annual heat demand of the industrial sector;

D an advanced utility-based cogeneration network supplies a significant portion (10%) of the annual heat demand of the industrial sector;

E a basic utility-based cogeneration network simultaneously supplies the portions of the heat demands for the RCI and industrial sectors referred to in scenarios A and C, respectively; and

F an advanced utility-based cogeneration network simultaneously supplies the portions of the heat demands for the RCI and industrial sectors referred to in scenarios B and D, respectively.

5. RESULTS AND DISCUSSION

Results for the cogeneration scenarios are presented relating to the region, including the RCI and industrial sectors which use the cogenerated heat, and its utility sector, where cogeneration occurs.

5.1. Region

The thermal energy requirements supplied by cogeneration in the RCI and industrial sectors are presented in Table 4. Note that the percentage values in that table apply to the columns. For instance, the values in the second column in Table 4 provide the percentage of the total heat demand in the RCI sector met via cogeneration, while the values in the rightmost column provide the percentage of the total heat demand in the combined RCI and industrial sectors met via cogeneration.

Table 4. Percentage of annual heat demand met by cogeneration, by sector[a]

Scenario	RCI	Industrial	RCI and industrial
A	10	0	5
B	40	0	20
C	0	5	3
D	0	10	5
E	10	5	10
F	40	10	30

[a] Percentage values apply to columns.

The scenario assessment results are provided in the form of percentage annual reductions in the region for energy use (Table 5) and environmental emissions (Table 6). Note that the results in these tables are all expressed as a percentage change relative to the corresponding values for the base case. The key points demonstrated are that, for all scenarios considered, energy use and environmental emissions decrease for the region. In addition, regional electricity-generation requirements decrease for all scenarios. Most of the regional environmental benefits are associated with the reductions in the use of coal and other fossil fuels, rather than nuclear energy, but a portion of the benefits are due to a substitution of uranium for fossil fuels. The reductions observed in environmental effects for each of the scenarios considered are clearly significant.

Table 5. Percentage reductions in regional energy use[a]

Scenario	Electricity	Natural gas & NGLs[a]	Oil & petroleum	Coal	Uranium	Total
A	5	3	0.5	20	7	5
B	25	10	2.0	40	30	17
C	3	1	0.3	10	3	3
D	6	2	0.6	20	5	5
E	8	4	0.7	20	9	6
F	30	15	2.6	40	35	21

[a] NGLs denotes natural gas liquids.

Table 6. Percentage reductions in regional emissions[a]

Scenario	Material emissions						Non-material emissions		
	SO_2	NO_X	CO_2	CO	Particulates	V.O.C.	Spent uranium	Thermal pollution	Radiation
A	5	3	4	1	1	1	7	20	7
B	14	9	12	3	2	2	30	70	30
C	5	3	3	1	1	0	3	10	3
D	7	4	5	1	1	1	5	10	5
E	7	4	5	1	1	1	9	20	9
F	18	12	15	4	2	3	35	80	35

[a] Notes on V.O.C., thermal pollution and radioactive emissions are as in Tables 1 and 2.

5.2. Electrical-Utility Sector

The percentage of coal and uranium that are used for cogeneration in coal and nuclear power plants, respectively, are listed in Table 7.

Table 7. Percentage of utility fuel used for cogeneration

Scenario	Coal	Uranium
A	10	10
B	80	50
C	6	5
D	10	2
E	20	10
F	100	50

Percentage reductions in the region's electrical utility-sector are presented for energy use (Table 8) and environmental emissions (Table 9). Electricity, natural gas and NGLs, oil and petroleum and others are not shown in Table 8 because the use of each in the utility sector does not change for the scenarios.

The key observation in Tables 8 and 9 are that, for all scenarios considered, energy use and environmental emissions decrease for the electrical-utility sector.

Most of the reductions observed for all scenarios in environmental effects for the utility sector are significant and are mainly associated with reductions in the use of coal. A portion of the benefits are due to a substitution of uranium for fossil fuels.

Table 8. Percentage reductions in regional energy use in utility sector

Scenario	Coal	Uranium	Total
A	20	7	10
B	40	30	30
C	10	3	6
D	20	5	10
E	20	9	13
F	40	35	40

Table 9. Percentage reductions in regional emissions by utility sector

Scenario	Coal-related emissions[a]	Uranium-related emissions[b]	Thermal pollution[c]
A	20	7	20
B	40	30	70
C	10	3	10
D	20	5	10
E	20	9	20
F	40	35	80

[a] Includes emissions of SO_2, NO_X, CO_2, CO, particulates and V.O.C.s.

[b] Includes emissions of spent uranium and radiation.

[c] Attributable to both uranium and coal use.

6. CLOSING REMARKS

Some important regional and utility-sector results are highlighted in Table 10 for each scenario. The implications of these findings are significant. For the region,

- electricity consumption decreases by between 3% for low penetration of utility-based cogeneration and 30% for high penetration, thereby permitting regional electrical generation to decrease by correspondingly, and
- emissions of carbon dioxide, a principal greenhouse gas, decrease by 3% to 15%, demonstrating that utility-based cogeneration can conribute significantly to mitigating global warming and, subsequently, climate change.

For the electrical-utility sector, utility-based cogeneration permits reductions of

- 10% to 40% in coal use and coal-related emissions,
- 3% to 35% in uranium use and related emissions, and
- 10% to 40% in carbon dioxide emissions.

Table 10. Percentage reductions in key parameters for the region and its electrical-utility sector

	Regional parameters		Electrical-utility sector parameters		
Scenario	Electricity consumption	CO_2 emissions	Coal use	Uranium use	CO_2 emissions
A	5	4	20	7	20
B	24	12	40	30	40
C	3	3	10	3	10
D	6	5	20	5	20
E	8	5	20	9	20
F	30	15	40	35	40

The case study consequently suggests that electrical utility-based cogeneration in a region could be beneficial in that, for the same services delivered, cogeneration permits increased efficiency and reduced energy consumption and related emissions, and can increase the utilization of nuclear energy by substituting it for other fuels. This conclusion presumes that cogeneration can be implemented at the region's thermal power stations and that potential markets for utility-cogenerated heat exist in the region in the RCI and industrial sectors. It would therefore be worthwhile for regions like the hypothetical one considered here to investigate with their electrical utilities and other relevant parties options for cogeneration, and to develop and where appropriate implement such a plan.

Note that implementation decisions are complex and must involve the many stakeholders involved, including local and regional governments, electrical utilities, electricity and heating/cooling customers, fossil fuel companies and industry. The interests of the stakeholders where they differ need to be balanced in determining which cogeneration options to adopt and barriers to regional utility-based cogeneration need to be overcome.

ACKNOWLEDGMENTS

The author is grateful for the support provided by the Natural Sciences and Engineering Research Council of Canada.

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