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CANDU® 6 Nuclear Power Plant and nuclear energy self-sufficiency based on Cernavoda NPP in Romania☆

Jerzy Parkitny *, [a], Mircea Gheorghe[b]

[a]*Atomic Energy of Canada Ltd (AECL®), 2251 Speakman Dr, Mississauga ON, Canada, L5K 1B2*
[b]*S.C. EnergoNucleare S.A. (EnergoNuclear) Sos. Stefan cel Mare, nr 1A, Sector 1, Bucharest, Romania 011736*

Abstract

The CANDU®6 nuclear power reactor design has been in commercial operation since the 1980s and is currently in operation in several countries, including Canada, Argentina, South Korea, China and Romania. CANDU 6 is the proven, mid size version of the CANDU Pressurized Heavy Water Reactor (PHWR). With a gross electrical output in excess of 720 MWe, the CANDU 6 fits easily into most grids. The CANDU design uses natural uranium fuel. Other fuel types can be used, including slightly enriched uranium (SEU), recovered uranium (RU), mixed oxides (MOX), and thorium. On power re-fuelling maintains the reactivity, eliminates the need for re-fuelling outages, and contributes to the availability record of CANDU power plants.

The focus of this paper, apart from summarizing some key technical and operating features of the CANDU reactor design, is to demonstrate how the selection of the CANDU technology can contribute to the development of the country's nuclear industry and economy and allows nuclear self sufficiency, using the Cernavoda Nuclear Power plant (NPP) project in Romania as an example. Similar benefits, in terms of economic development and nuclear energy self-sufficiency, have also been realized by other countries that have selected the CANDU reactor technology.

1. Introduction

The CANDU®6 nuclear power reactor design has been in commercial operation since the 1980's and is currently in operation in several countries, including Canada, Argentina, South Korea, China and Romania.

CANDU technology which is necessary for the design, construction licensing and operation of a nuclear power plant has been and can be efficiently transferred to a recipient country through a technology transfer program. This paper presents the key factors in the transfer of CANDU nuclear technology and provides an overview of AECL experience based on technology transfer to Romania for the Cernavoda Nuclear Power Plant project.

The focus of this paper, apart from a brief overview of the CANDU design, is to demonstrate how the selection of the CANDU technology can benefit a host country, using the Cernavoda Nuclear Power Plant (NPP) in Romania as an example. Similar benefits, in terms of economic development and nuclear energy self-sufficiency, have also been achieved by other countries that have selected the CANDU reactor technology and can also be achieved by any new customer.

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*Corresponding author

Email addresses: parkitnyj@aecl.ca (Jerzy Parkitny *,), mircea.gheorghe@energonuclear.ro (Mircea Gheorghe)

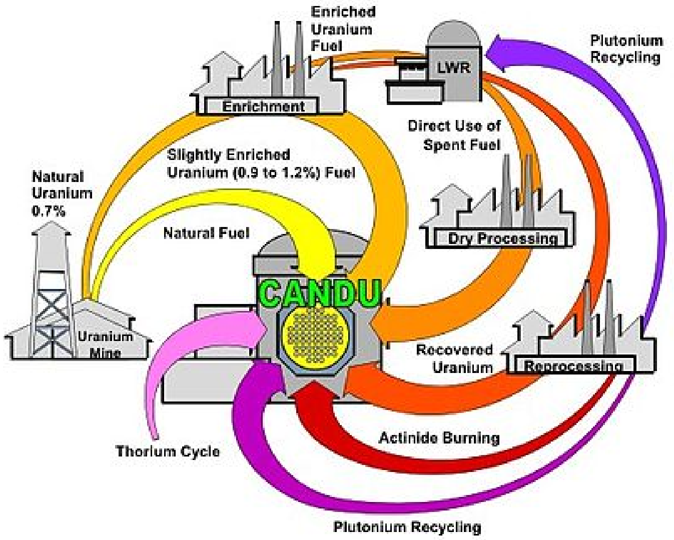

Figure 1: Range of possible CANDU fuel cycles

2. CANDU 6 Technology Overview

CANDU 6 is the proven, mid size version of the CANDU Pressurized Heavy Water Reactor (PHWR) with a gross electrical output of approximately 720 MWe. CANDU 6 fits easily into most electrical grids.

The CANDU design uses natural uranium fuel. An important consideration in selecting a nuclear power plant system is a fact that CANDU reactors can accept a variety of fuel types, including the used fuel from light-water reactors [1–6] i.e.:

- Natural uranium
- slightly enriched uranium (SEU),
- recovered uranium (RU),
- mixed oxides (MOX),
- and thorium.

CANDU Fuel cycle options are shown on Fig. 1. High neutron economy allows CANDU reactors to extract up to twice as much thermal energy from fissile material compared to LWR reactors, depending on the nature of the fissile material [2, 4–6]. CANDU nuclear fuel bundles are located inside pressure tubes (not pressure vessels like PWR or BWR) and cooled by heavy water (D_2O).

The combination of natural uranium and heavy water require the use of a low neutron absorbing moderator (heavy water, with a higher isotopic purity is used as the moderator) and core construction materials to maintain a fission reaction. The result is a highly efficient nuclear process with very little excess reactivity [7] making for maximum utilization of the nuclear fuel.

One of the key features of CANDU system is on power re-fuelling, which maintains the minimum required excess reactivity of the core, eliminates the need for re-fuelling outages, and contributes to the availability record of CANDU power plants.

The CANDU 6 design has been continuously modernized to meet up-to-date Canadian and international licensing requirements, codes and standards, and to take advantage of the operating experience accumulated by CANDU plants.

The Enhanced CANDU 6® (EC6®) reactor is the evolution of the proven CANDU 6 design. The EC6 design has been developed by drawing on the experience and feedback gained from the development, design, construction and operation of eleven CANDU 6 units operating in five countries and it is based on the Qinshan Phase III CANDU 6 plant in China.

CANDU 6 reactors are performing well on four continents with over 150 reactor-years of excellent and safe operation. While retaining the basic features of the CANDU 6 design, the EC6 reactor incorporates innovative features and state-of-the-art technologies that enhance safety, operation and performance.

It is not the intent of this paper to present technical features of the CANDU technology. The technical, operating and safety features of CANDU technology are available on the internet, under the following pathways:

- AECL [8]
- CNSC [9]
- CANDU Owners Group [10]

Further information can also be found through web sites of CANDU technology users, supplemented by proceeding of international conferences. These materials provide plenty of technical details and provide answers to key questions about the CANDU technology.

For a comprehensive description of CANDU PHWR reactors and their technical, operating and safety features refer to the IAEA publications [1, 11, 12].

3. Key Factors for Successful Nuclear Technology Transfer

"The successful transfer depends on establishing a relationship of mutual respect and trust between the giving and receiving organizations (nations)" [13].

Based on AECL experience with transfer of CANDU technology to the recipient country's design, manufacturing and construction organizations, the following factors are considered the key contributors to successful technology transfer:

- The selection of appropriate technology suited to the local manufacturing environment. Nuclear technology transfer is a long-term process. Comprehensive planning to address objectives, realistically examine capabilities of local industry and identify gaps. One of the key prerequisites for the receiving nation is to concentrate on those technologies that offer either significant business opportunity for local industries or have application in other sectors of the economy. This factor alone can determine if the successful transfer is feasible within the intended overall project schedule.

- Well defined scope of the technology and the transfer process and establishment of an organization to coordinate the technology transfer program. Establishment of a lead agency to coordinate the technology transfer enhances the chance of success. Firm and dedicated management of the program is required due to its large scope and diversity.

- A firm commitment (supported by the local government) of human and financial resources is required for the scope of the technology transfer program. The availability of well-educated and skilled workforce is a definite asset.

- Understanding and enforcement of nuclear safety and quality within the industrial infrastructure of the recipient's nation. A nuclear R&D organization would be a definite asset.

A nuclear technology transfer typically covers:

- regulatory licensing;
- fuel cycle (uranium enrichment technology is required for PWR; natural uranium is used for CANDU);
- engineering design and development;
- construction technology;
- project and construction management;
- supporting research and development;
- component or equipment manufacture; and
- commissioning and operation of nuclear power plants.

Three factors which make CANDU technology transfer different from LWR reactors are:

1. the complete fuel cycle, from uranium exploration through fuel fabrication and interim (final) disposal of spent fuel in host country,
2. nuclear fuel flexibility (See Fig. 1),
   These two key factors are critical in allowing a host country to achieve "nuclear energy" self sufficiency.
3. and heavy water production, if desired. (D_2O is required for the first fill up and make up).

A separate, but an important aspect is the licensing of the NPP in a host country. Canadian support for the CANDU 6 project has been two-fold:

- the Canadian regulator, Atomic Energy Control Board (AECB) in the past and the Canadian Nuclear Safety Commission (CNSC) at present, provided a full support to the counterpart agency in the host country;

- AECL worked with the licensee providing support in the preparation and submission of applications for construction and operation licenses, and in interactions between the licensee and the local regulator during the review and approval process.

These two processes, carried out in parallel, led to a successful licensing to construct and operate the CANDU NPPs in the countries listed in this paper.

4. CANDU Technology Transfer to Romania

Romanian nuclear industry was created in early eighties to support a challenging and ambitious program of constructing up to sixteen CANDU units. As part of the National Nuclear Energy Program:

1. New nuclear related industrial base has been developed and the existing industries expanded and modernized, both categories benefiting from the CANDU technology transfer and know-how.
2. R&D capabilities have been developed together with a nuclear engineering program at Polytechnic University of Bucharest.

The Romanian nuclear industry had been a major contributor in construction of Cernavoda Units 1 and 2 by supplying 40% (by weight) of equipment for Unit 1 and 60% (by weight) for Unit 2, as well as performing Cernavoda Unit 1 and 2 construction and installation scope of work [14].

The following is a summary of the increasing localization (from 1990s onward) of the CANDU technology in Romania:

- **Nuclear energy self-sufficiency**

  Both the CANDU nuclear fuel and heavy water (D_2O) are produced by the Romanian industry:

  - CANDU technology with its natural uranium allows for localization of fuel production. CANDU nuclear fuel is manufactured at The Nuclear Fuel Plant (FCN) Pitesti [15]. FCN was established in 1992 and manufactures 100% of the fuel required for Cernavoda NPP's Units 1 and 2, and in the future will manufacture the nuclear fuel for Units 3 and 4.
  - The heavy water required for the CANDU Heat Transport System and the Moderator System is manufactured by ROMAG-PROD [16]. ROMAG-PROD commenced heavy water production in 1988 and by now possesses one of the largest heavy water production capacities in the world. Since 2001, ROMAG-PROD has also become an exporter of nuclear grade heavy water.

- **Contribution to the development of the country's nuclear industry and economy:**

  - Transfer of technology (design) from AECL for critical nuclear CANDU systems and process equipment. Establishment of RAAN-SITON SA (aka CITON-Centre of Technology and Engineering for Nuclear Projects) [17].
  - CITON has played a significant role in the Romanian nuclear program resulted from the acquisition of the CANDU plant design technology through cooperative/licensing agreements and its further development.

- **Localization of manufacturing for key CANDU equipment**

  - An important factor is that the size and weight of CANDU 6 pressure boundary/process equipment as well as fuel handling equipment can be handled (with proper technology transfer and qualification of manufacturing processes) by companies involved in manufacturing of conventional power plant equipment.
  - The following key CANDU equipment has been manufactured by the Romanian industry – see Table 1.
  - Some examples of the Romanian manufacturing companies that successfully adopted CANDU manufacturing technology and manufactured equipment for Cernavoda NPP:

    • **DOOSAN-IMGB – castings and forgings for heavy equipment [18]**

    In the 80's, IMGB was a significant supplier of nuclear components and equipment for the domestic and Eastern-European countries (based on the

Table 1: Key CANDU equipment

Equipment	Remarks
Pressurizer, ASME Sec III, Class 1	Manufactured for Cernavoda 2
Degasser Condenser, ASME Sec III, Class 1	Manufactured for Cernavoda 2
Major Heat Exchangers – Shutdown Cooler, Moderator HX etc, ASME Sect III Class 1 and 3	Manufactured for Cernavoda 2
Reactivity Mechanism Deck	Manufactured/assembled for Cernavoda 1 and 2
Feeder and Feeder Header Frame	Manufactured/assembled for Cernavoda 2
Fuel Handling Equipment	Manufactured/assembled for Cernavoda 2
CANDU Fuelling Machine	Tested for Cernavoda 2
Equipment and Personnel Air Locks	Manufactured/assembled for Cernavoda 1 &2
Calandria (CANDU Reactor)	Manufacturing technology acquired. Partially manufactured for Cernavoda 3.
Steam Generators	Manufacturing technology acquired. Equipment planned to be manufactured for Cernavoda 3.

American/Canadian and Russian standards), but this production has been ceased. IMGB has been privatized, and is now part of DOOSAN. At present DOOSAN IMGB has the capacity and capability to produce belt and shell forgings for the reactor vessels and heat exchangers as per ASME standards.

• VULCAN S.A. – PHT collectors and feeders [19]

VULCAN acquired technology for manufacturing nuclear components for Cernavoda CANDU NPP. The product line included components like: feeders and feeder header frame assembly, fittings, bends and hangers.

• SC TITAN ECHIPAMENTE NUCLEARE SA (TEN) – fuel handling equipment [20]

SC TITAN was established in 1982 as part of the national Nuclear Energy Program. It has acquired CANDU manufacturing technology and manufactured equipment for Cernavoda NPP: New Fuel Transfer Equipment, Fuelling Machine Head and Support Cradle Assembly, equipment for CANDU fuel handling, seismic snubbers.

• FECNE SA (FABRICA DE ECHIPAMENTE PENTRU CENTRALE NUCLEARO-ELECTRICE) – calandria, heat exchangers, vessels [21]

FECNE (initially part of IMGB) joined the National Energy Program in 1980's. Based on the technology transfer agreements between AECL/CANDU manufactures and IMGB/FECNE, FECNE manufactured the following nuclear (ASME SECT III) equipment for Cernavoda 1&2: Pressurizer and Degasser Condenser, Ion Exchange Columns, Shutdown Cooler HX, Moderator HX as well as the Reactivity Mechanisms Deck, Water/ Air tanks for the reactor Emergency Core Cooling system, the Equipment and Personnel Airlocks with electro-pneumatic driving and inflatable seals; shielding doors with safety system interlocks, heaters for thermal cycle, intermediate heat exchangers for the BOP etc.

• AVERSA S.A. – mid-size pumps http://www.aversa.ro

AVERSA joined the joined the National Energy Program in 1980's. Their scope of supply for Cernavoda 1 & 2 included various types of small and medium pumps for

NSP and BOP application.

•GENERAL TURBO S.A – 700 MWe steam turbines for nuclear application [22]

General Turbo initially part of IMGB, became an independent company in the early 1990's. The factory has the capability to manufacture major parts for the turbine generator assembly (turbine LP shell, generator stator and rotor, stop valves, etc.), under license from General Electric for CANDU 6 applications. General Turbo manufactured and delivered those parts as well as pumps and other process equipment for Cernavoda NPP.

• UZUC SA PLOESTI – heat exchangers, pressure vessels [23]

UZUC manufactured equipment for the pilot and production Heavy Water Plants and auxiliary equipment for the research nuclear reactor of I.C.N. Pitesti. Commencing in the 1980's UZUC has fabricated nuclear equipment for Cernavoda NPP. The range of products included Shell and Tube Heat Exchangers, D_2O Upgrader Columns, Pressure Vessels.

• HESPER SA, Bucharest – Hydraulic and Pneumatic Equipments [24]

HESPER acquired the technology and manufactured Hydraulic and Pneumatic Equipment for Cernavoda NPP.

5. CANDU 6 Nuclear Power Plants in ROMANIA

The CANDU 6 NPP in Romania is located in Cernavoda on the Danube-Black Sea Canal, near Constanta.

This is the only nuclear power station in Romania (currently with two operating reactors) and the only CANDU nuclear power station in Europe.

The owner and operator of Cernavoda units 1 and 2 is the Romanian nuclear state utility, Societatea Nationala Nuclearelectrica [25]. Cernavoda units 1 and 2 supply approximately 18% of Romania's electricity demand and in addition, Cernavoda Unit 1 supplies approximately 35 G-cal annually for the heating of the town of Cernavoda.

Figure 2: Cernavoda Unit 2, Reactor Building, Heavy Water Upgrader and Turbine Building (Right to Left)

The table 2 illustrates CANDU 6 NPP delivery history and capability.

In order to take advantage of the familiarity with the existing technology, the excellent operating record of Unit 1 and 2 as well as the advanced status of civil construction of Cernavoda Unit 3 and 4, SC EnergoNuclear SA [26] has been established and has been working with the shareholders, CNCAN (Romanian regulator) and AECL on securing a construction license for units 3 and 4 by the year 2013.

The Cernavoda units 3 and 4 design is based on Cernavoda 2 (reference plant) and will meet the current safety goals for new built nuclear plants in Europe. The updated design will implement significant safety and security related improvements to bring the Cernavoda units 3 and 4 NPP to the level of safety equivalent to that of Generation III nuclear reactors.

- **Romanian economic highlights, January, 2011**

  "the European Commission, Energy Directorate issued a favourable opinion concerning the completion of Units 3 and 4 of the Cernavoda Nuclear Power Plant, in accordance with the provisions of Article 43 of the EURATOM Treaty. The technical evaluation was conducted by the EC Energy Directorate and included meetings with representatives of company EnergoNuclear and experts of AECL Canada–the license provider for the CANDU technology, the

Table 2: CANDU 6 NPP delivery history and capability

In service	Plant name, location	Status
1996	Cernavoda 1, Romania	On Budget / On Schedule
1997	Wolsong 2, Republic of Korea	On Budget / On Schedule
1998	Wolsong 3, Republic of Korea	On Budget / On Schedule
1999	Wolsong 4, Republic of Korea	On Budget / On Schedule
2002	Qinshan, Phase III, Unit 1	On Budget / 6 weeks ahead of schedule
2003	Qinshan, Phase III, Unit 2	On Budget / 4 months ahead of schedule
2007	Cernavoda 2, Romania	On Budget / On Schedule

National Commission for the Control of Nuclear Activities and experts from the Nuclear Agency and Radioactive Waste. The project for Units 3 and 4 of the Cernavoda Nuclear Power Plant will include a set of substantial improvements in compliance with the current international nuclear security standards. The project will also comply with the principles established under the June 2009 EU nuclear safety directive."

6. Conclusions

Nuclear technology encompasses a wide range of skills and disciplines and involves many sectors of the economy. Each nuclear power plant requires an investment of billions (milliards) of Euros/Dollars and the human resources employed in the design, manufacture, construction and operation of the plant may well exceed 5,000 people at the peak. The acquisition of the diverse nuclear technologies is a long term process spanning, in most cases, the construction of several nuclear plants.

AECL has designed and built a versatile nuclear system with high neutron economy, simple design, on-power refuelling, and fuel flexibility. The relative simplicity of construction, the fuel-cycle flexibility, and the ability to customize localization based on any level of domestic infrastructure makes the CANDU technology an attractive option for introducing nuclear power to the emerging nuclear markets.

Clearly, it is advantageous to concentrate on a technology, which can then be introduced and developed by a host country at a pace and timing consistent with the nation's economic and industrial goals.

Governments are interested in the overall aspects of the technology and in most cases, will establish the expected degree and timing of the technology transfer. The utility, on the other hand, needs no other technology than that required to successfully maintain and operate the plant.

As illustrated throughout the paper the CANDU design and its accompanying technology is very well suited towards localization.

Countries such as Romania that are interested in energy self sufficiency have greatly benefited from this design, through not only the increase of their technical capabilities but also by guaranteeing their own independent energy supply.

The CANDU design and its fuel cycle flexibility offers these and many other benefits to any potential customer interested in developing its own nuclear power solution for its energy issues.

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