# CANDU PRODUCT DEVELOPMENT

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Advanced CANDU reactor design strategy follows an evolutionary approach, taking manageable steps in the development of power plants from today's available designs, and in parallel carrying out longer-term studies to develop future-generation reactor concepts. The major emphasis is on safety, and on reducing cost and schedule. New features are developed and thoroughly proof-tested before introduction into designs, in order to maximise owner confidence.

## INTRODUCTION

Through their operating record in Canada and around the world, AECL-designed CANDU nuclear power plants have established themselves as a clean, successful and cost-effective source of electricity in Canada and abroad. They have proven to be safe, reliable and competitive, consistently achieving high capacity factor rankings year after year, both on an annual and lifetime basis (see Figure 1). Good operational performance is seen across the different sizes of CANDU power plants, and for plants with different owners and jurisdictions. Indeed, in Korea, the Wolsong 1 power plant has achieved exceptional performance. These results are a tribute to the excellence in operations achieved by the performance CANDU utilities such as KEPCO, but they also show that reliable CANDU is achieved time after time. A key factor in this success is AECL's strong commitment to comprehensive research and development programs which support the CANDU design and product development. CANDU was originally developed by a partnership between research and development, engineering and utility operation teams, and this partnership approach continues today. Currently, AECL spends a very significant portion of its own revenue on nuclear R and D, and CANDU owner utilities commit large additional funding to support R and D activities aimed at improving the performance of operating stations. Many of the programs supported by these funds are directed jointly by AECL and the utilities --- direct involvement of AECL's customers in the development of technology in support of CANDU products. This is a long-established approach in CANDU development, to bring together researcher, designer, manufacturer, constructor and operator, as much as possible, so that AECL's product benefits from experience gained by our partners in the CANDU business.

## DEVELOPMENT APPROACH

Development programs presently underway at AECL are intended to meet emerging utility design and performance requirements, by building on unique CANDU strengths and integrating new technologies.
The development strategy is to follow the evolutionary path updating reactor products by taking advantage of features and components successfully proven in operation. This maximises confidence that utility, regulator and other stakeholder expectations can be met.

To this goal, the development strategy is to formulate the requirements and concepts for future-generation advanced designs, and, in parallel, introduce evolutionary improvements to the current CANDU designs for the short and intermediate time frames (Figure 2).

In this approach, the proven features of the CANDU reactor design are retained:

- horizontal channels (pressure tubes)
- heavy water moderator
- fuelling flexibility resulting from high neutron economy
- simple, low-cost fuel bundle

- on-power fuelling
- zirconium alloy pressure tubes.

These features have been integral to the CANDU concept since the development of the first prototype reactors; because the CANDU approach uses a modular pressure tube reactor design, improvements to these features can be applied equally to all future designs.

At the same time, high-level goals have been established within the program to:

- reduce capital costs (including reductions in project schedule)
- reduce operating costs
- develop and further exploit fuelling flexibility
- further enhance safe operation,
  ( including reduced frequency/consequence of human error)
- build-in a high level of plant protection. (Including improved operability).

## CANDU PRODUCTS

Current CANDU products, based on designs proven in successful operation, are the CANDU 6 (715 MWe), with four units in operation and eight under construction, and the CANDU 9, originating from the multi-unit Bruce and Darlington stations, with twelve units in operation by Ontario Hydro. These products represent the state of the art in today's available designs, based on the evolutionary product development process at AECL over the last twenty years. The continuing CANDU development program will also generate opportunities for these products to evolve in the future (see next section).

CANDU 6 nuclear power plants have been operating successfully in Canada, Korea and Argentina for more than twelve years. Additional units are also under construction at Cernavoda in Romania, with Cernavoda unit 1 due to come into service later this year. The latest CANDU 6 units are being constructed at the Wolsong site in Korea and have in-service dates from 1997 - 1999. Figure 3 shows the status of construction at the Wolsong site. These plants have been updated to the recent regulatory requirements and include detailed design adjustments and equipment upgrades to respond to feedback from operators, manufacturers, constructors and regulators. The Wolsong 2,3 and 4 plants represent fully up-to-date CANDU technology.

The CANDU 9 power plant is the single-unit version of the well-established 900 MWe class CANDU reactor, based on a 480 fuel channel calandria, which has operated successfully at the Bruce and Darlington nuclear power plants. The reference design for the CANDU 9, which replicates the 480 fuel channel natural uranium-fuelled Darlington reactor, is termed the CANDU 9 480 NU. Darlington, the latest of the 900 MWe Class CANDU plants, consists of four integrated units with a total output of approximately 3740 MWe. The four units of the plant have been put into service successively over the last few years. Last year, the Darlington units achieved outstanding performance, achieving an average station capacity factor of 86%. Reliable operation is also shown by the low forced outage rate, less than one per year per unit. The CANDU 9 design offers improved economics through reduced capital cost, and shorter construction schedule. Improvements to operation and maintenance support, will enhance performance and safety. The choice of proven design features and components ensures high confidence that cost and schedule targets will be met in a project. Figure 4 shows a CADDS representation of the CANDU 9 480/NU station .

The adaptation of the multi-unit Darlington reactor design to a single unit configuration was studied by AECL for many years, using the same approach which led to the CANDU 6 design adaptation from the earlier Pickering CANDU design. The emphasis has been on retaining the components and features of the reference plant design to ensure a fully-proven product. The conceptual and basic design of the CANDU 9 480 NU has been defined, after an intensive engineering program. This program included a thorough review of design improvement options, and a detailed comparison of the design with both Canadian and Korean design requirements. This included overall requirements such as those in the Korean Standard Requirements Document, KSRED, and also today's applicable regulatory requirements. The remaining design integration will be completed this year, so that the product is ready for early commitment by any interested utility. In addition to the design integration program, a two-year Canadian regulatory review of the product commenced in 1995 January . This review will confirm that the design meets Canadian regulatory requirements in sufficient detail that regulators in any country could proceed with confidence.

AECL has also carried out a comprehensive design program for the CANDU 3, a smaller unit (480 MWe) to meet specific grid and utility requirements. The CANDU 3 uses standard CANDU components and features in a smaller-output design suitable for smaller grid requirements. This Standard Product Design program is in the detailed design stage. The CANDU 3 program has also developed improved construction methods, advanced engineering tools and improved safety features, applicable to all sizes of CANDU. Some of these developments are being applied today on current CANDU construction projects.

## DEVELOPMENT DIRECTIONS

The CANDU product development program has been focussed on generic CANDU features, which can be applied to CANDU designs in general. The program integrates both fundamental and applied research, engineering development and proof-testing, and product design, generate improvements ready for project application. Generic developments emerging from the R&D program, encompass:

- Design features to assist operability with a target of 90% capacity factor
- advanced control room features such as plant display system design
- enhanced 37-element fuel-bundle design
- advanced 43-element CANFLEX* fuel-bundle design (extended burnup)
- fuel with tailored void coefficient
- slightly enriched (SEU - 0.9-1.2% U-235 in U) fuel
- extended life pressure tubes
- integrated tritium-removal/ heavy water upgrading system
- simplified emergency coolant injection system
- 60-year life for non-replaceable components
- faster construction using pre-fabrication and open-top techniques
- improved engineering tools such as integrated CADDS/design definition tools

The development approach is to fully establish and proof-test these features, then incorporate them as appropriate in CANDU products, such as the CANDU 6 or the CANDU 9. For example, improvements in the design of pressure tubes, generated via R and D at AECL's Chalk River Laboratories, have already been incorporated into replacement pressure tubes, and into the Wolsong 2, 3, and 4 nuclear power plants. In this way, AECL's investment in research and development can be applied to today's designs, the CANDU 6 and CANDU 9, as well as to reactor design concepts under development, in parallel.

AECL, in conjunction with utility partners, has initiated a comprehensive study of further enhancements to the CANDU 6 reactor which can be implemented with minimum project risk but which potentially offer significant cost savings and performance improvement. As part of the development process, AECL includes customer-specific considerations, including technology transfer leading to nuclear infrastructure development, and localization and partnering.

AECL has studied adding more channels to the basic 480-channel CANDU 9 reactor and/or slightly enriching the fuel, to produce stand-alone larger CANDU units with outputs up to 1300 MWe. This approach will retain the advantage of proven components and features in the overall framework of the CANDU 9 design. A detailed review of the concept of SEU fuel in CANDU 9 has shown that there are no barriers to the introduction of this fuel cycle approach to reduce fuelling costs and increase reactor power output.

For the longer term, a major advantage of the CANDU reactor is that the fuel cycle can be customized to meet the specific requirements of the CANDU owner and operator. Fuel cycle options include SEU, RU ( **R**ecovered **U**ranium obtained as a by-product from conventional reprocessing of spent PWR fuel), DUPIC (**D**irect **U**se of spent **PWR** fuel **I**n **C**ANDU), and various Thorium cycles. Also, there is considerable current international interest in the CANDU reactor as an efficient burner of ex-weapons plutonium, and in the annihilation of actinides as part of an integrated waste-management strategy.

Additional longer term design evolution will involve more fundamental research activities, (as shown in Figure 2) while continuing with the basic CANDU features of modular fuel channel, simple fuel design with on-power fuelling, etc. By the next century, CANDU development will be aimed at a plant which can be constructed with the reliability and simplicity (and short schedule) of the best conventional thermal power plants; with significant savings in both capital and operating cost compared to today's nuclear projects; and with the flexibility to operate economically in a variety of fuel cycles, optimized for economics, resource conservation and waste minimization. Development by a global team of cooperating researchers, designers, manufacturers, constructors, and utility operators, will contribute to CANDU excellence in reliable electricity generation.

Figures

1) 1994 World Capacity Factor Rankings

2) D.Torgerson Figure of Evolutionary development

3) Picture of current Wolsong site

4) CADDS representation of the CANDU 9 - 480/NU station currently under development.

# The Top Twenty-five

**Lifetime World Power Reactor Performance to December 31, 1994*** *from among 371 reactors over 150 MW*

| Rank | Country | Unit | Type | Year of First Power | Capacity Factor %† |
|---|---|---|---|---|---|
| 1 | | Germany *Emsland* | PWR | 1988 | 91.4 |
| 2 | | Canada *Point Lepreau* | CANDU | 1982 | 91.4 |
| 3 | | Germany *Neckar 2* | PWR | 1989 | 88.8 |
| 4 | | Germany *Grohnde* | PWR | 1984 | 88.0 |
| 5 | | Canada *Pickering 8* | CANDU | 1986 | 87.9 |
| 6 | | Belgium *Tihange 3* | PWR | 1985 | 87.7 |
| 7 | | Canada *Pickering 7* | CANDU | 1984 | 87.2 |
| 8 | | Finland *Loviisa 2* | PWR | 1980 | 86.7 |
| 9 | | Hungary *Paks 2* | PWR | 1984 | 86.1 |
| 10 | | Switzerland *Beznau 2* | PWR | 1971 | 85.9 |
| 11 | | Germany *Philippsburg 2* | PWR | 1984 | 85.4 |
| 12 | | Hungary *Paks 4* | PWR | 1987 | 85.2 |
| 13 | | Hungary *Paks 3* | PWR | 1986 | 85.1 |
| 14 | | Canada *Darlington 4* | CANDU | 1993 | 84.9 |
| 15 | | Canada *Pickering 6* | CANDU | 1983 | 83.9 |
| 16 | | Switzerland *Gösgen* | PWR | 1979 | 83.8 |
| 17 | | Germany *Grafenrheinfeld* | PWR | 1981 | 83.8 |
| 18 | | Korea *Wolsong 1* | CANDU | 1982 | 83.7 |
| 19 | | Finland *TVO 1* | BWR | 1978 | 83.3 |
| 20 | | Spain *Almaraz 2* | PWR | 1983 | 83.3 |
| 21 | | Spain *Asco 2* | PWR | 1985 | 83.2 |
| 22 | | Belgium *Tihange 2* | PWR | 1982 | 83.0 |
| 23 | | Finland *Loviisa 1* | PWR | 1977 | 82.8 |
| 24 | | Finland *TVO 2* | BWR | 1980 | 82.8 |
| 25 | | Hungary *Paks 1* | PWR | 1982 | 82.7 |

*Source Nuclear Engineering International

† Capacity Factor = $\frac{\text{actual electricity generation}}{\text{perfect electricity generation}}$

FIGURE 1
1994 WORLD CAPACITY FACTOR RANKINGS

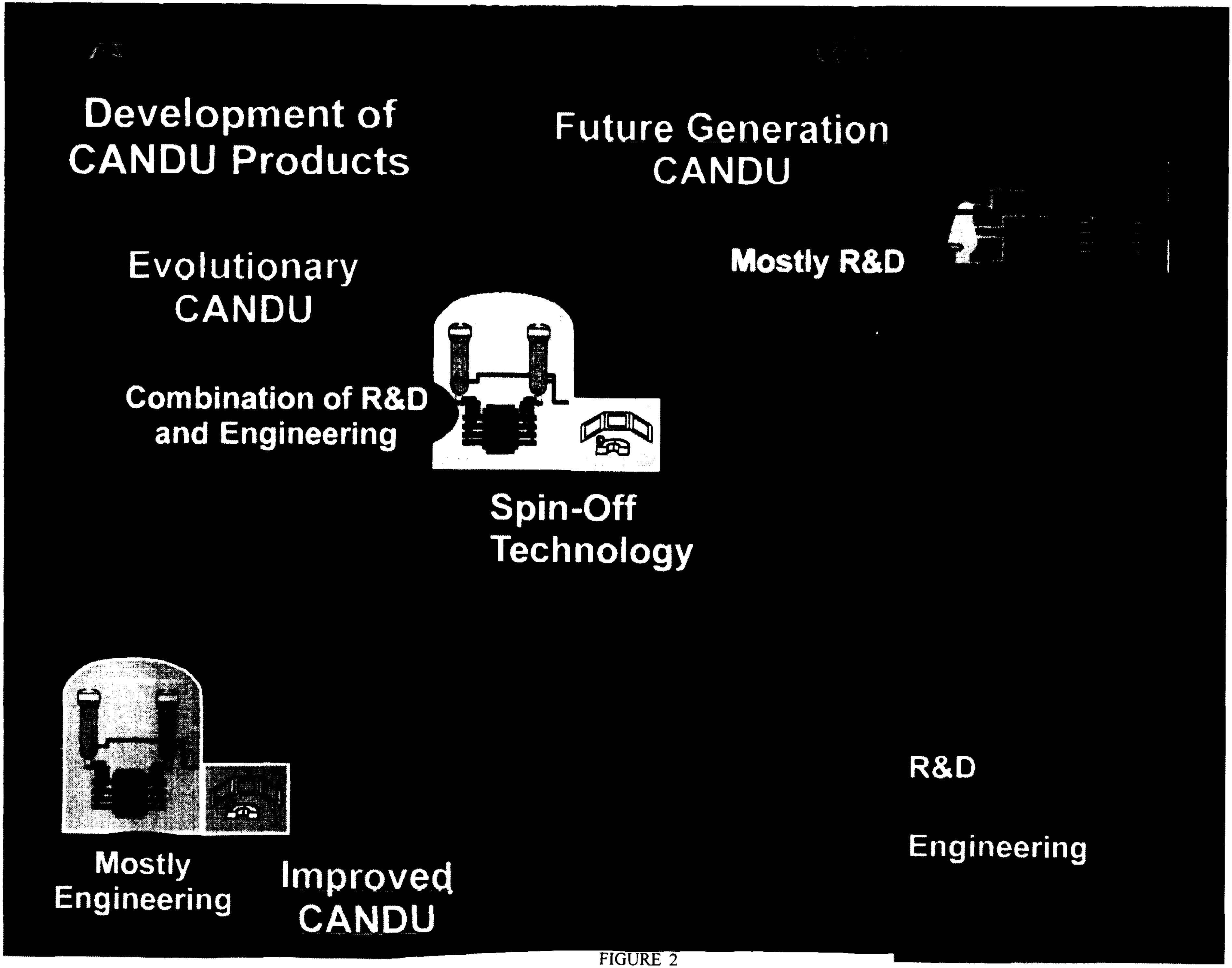


FIGURE 2
D. TORGERSON FIGURE OF EVOLUTIONARY DEVELOPMENT

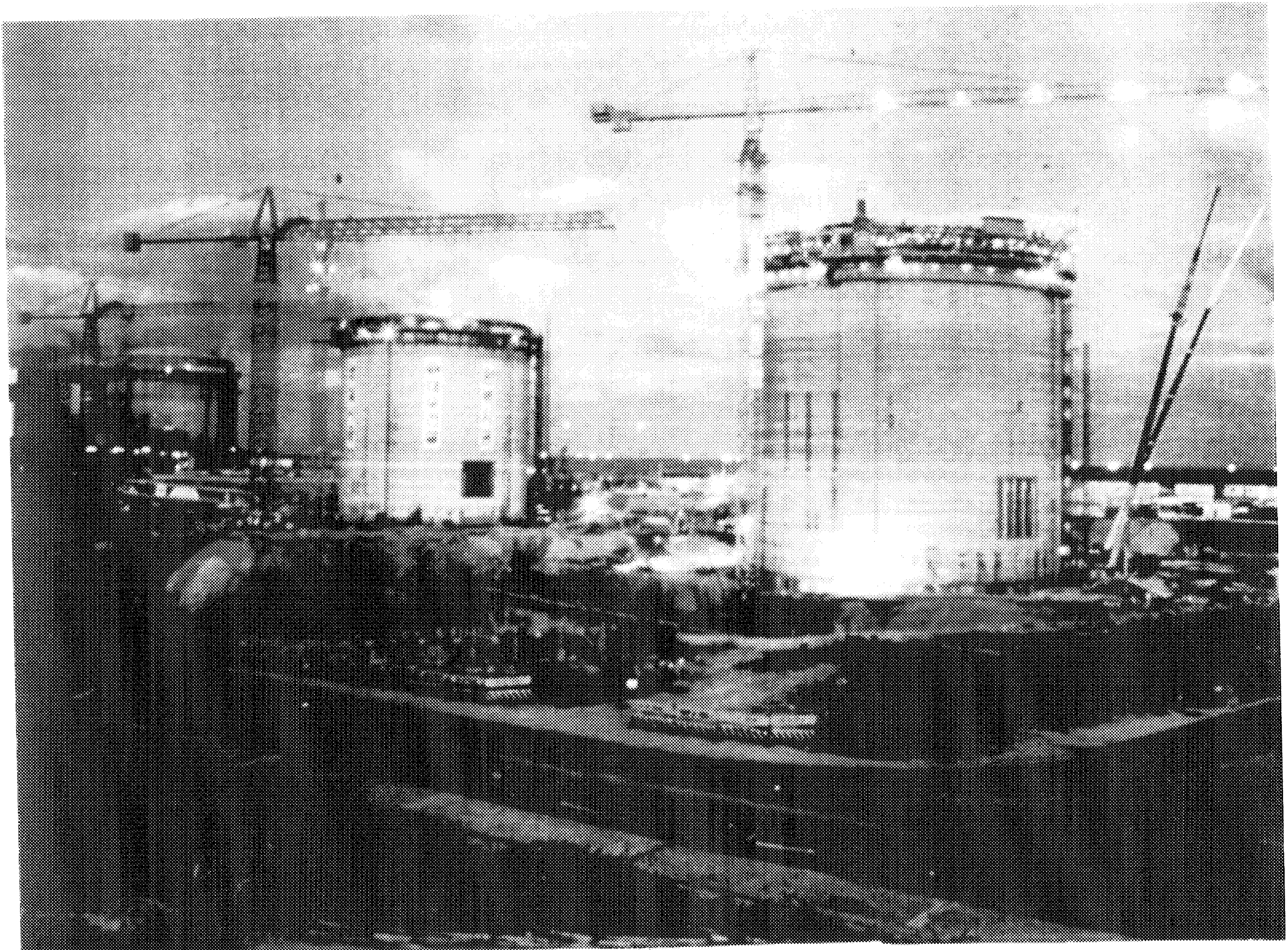

FIGURE 3

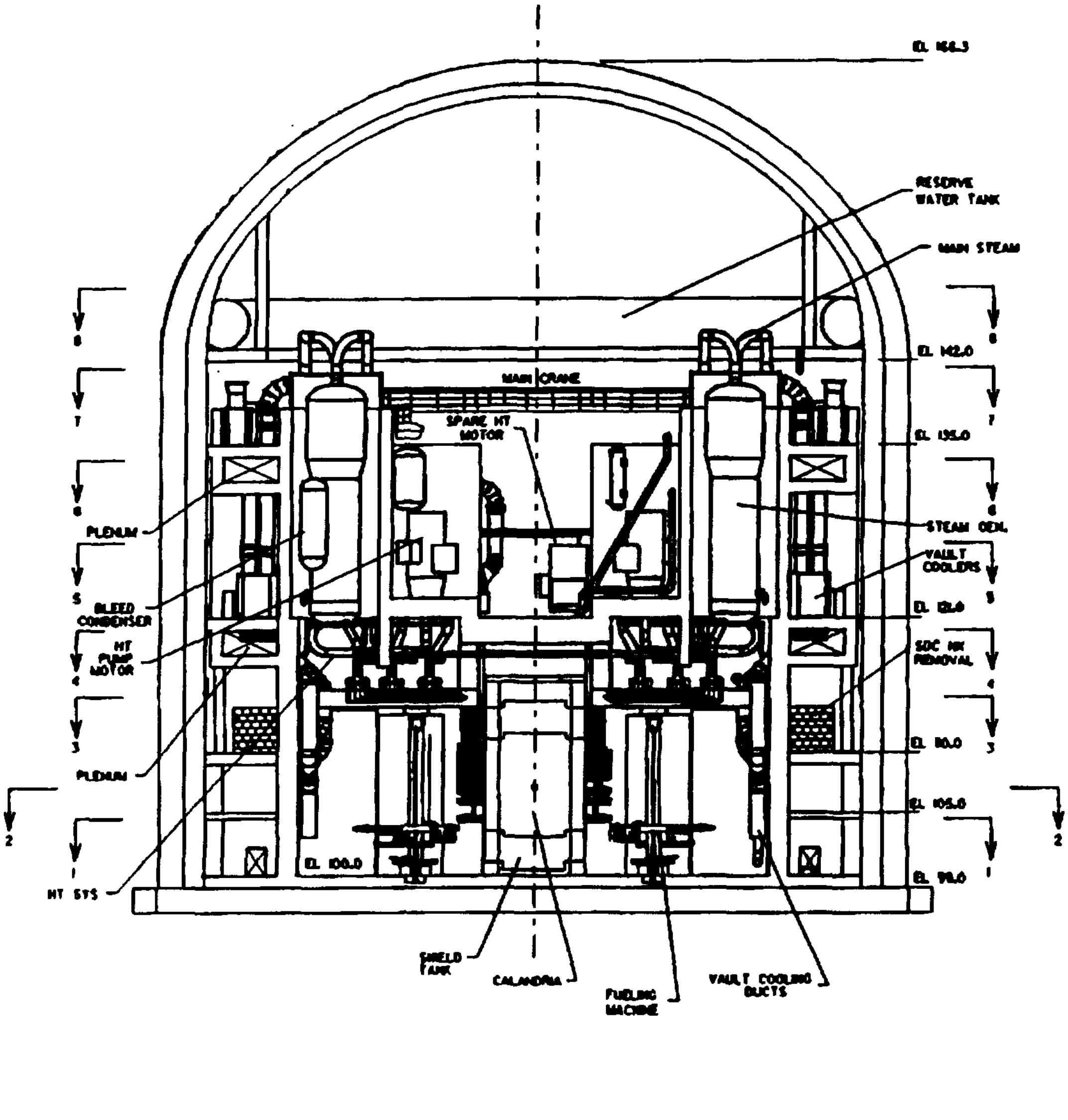


FIGURE 4
CADDS REPRESENTATION OF THE CANDU 9 - 480/NU STATION CURRENTLY UNDER DEVELOPMENT