Advanced CANDU Reactor: An Optimized Energy Source of Oil Sands Application

by

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Atomic Energy of Canada Limited (AECL) is developing the ACR-700™ (Advanced CANDU Reactor-700™) to meet customer needs for reduced capital cost, shorter construction schedule, high capacity factor while retaining the benefits of the CANDU experience base.

The ACR-700 is based on the concept of CANDU® horizontal fuel channels surrounded by heavy water moderator. The major innovation of this design is the use of slightly enriched uranium fuel in a CANFLEX® bundle that is cooled by light water. This ensures: higher main steam pressures and temperatures providing higher thermal efficiency; a compact and simpler reactor design with reduced capital costs and shorter construction schedules; and reduced heavy water inventory compared to existing CANDU reactors.

ACR-700 is not only a technically advanced and cost effective solution for electricity generating utilities, but also a low-cost, long-life and sustainable steam source for increasing Alberta’s Oil Sand production rates. Currently practiced commercial surface mining and extraction of Oil Sand resources has been well established over the last three decades. But a majority of the available resources are somewhat deeper underground require in-situ extraction. Economic removal of such underground resources is now possible through the Steam Assisted Gravity Drainage (SAGD) process developed and prototype tested in-site. SAGD requires the injection of large quantities of high-pressure steam into horizontal wells to form reduced viscosity bitumen and condensate mixture that is then collected at the surface.

This paper describes joint AECL studies with CERI (Canadian Energy Research Institute) for the ACR, supplying both electricity and medium-pressure steam to an oil sands facility. The extensive oil sands deposits in northern Alberta are a very large energy resource. Currently, 30% of Canada’s oil production is from the oil sands and this is expected to expand greatly over the coming decade. The bitumen deposits in the oil sands are mixed with sand at varying depths and consistencies, and are therefore difficult to extract. For many deposits, at moderate depths, the bitumen can be extracted without surface mining, by injecting steam into the deposit at pressures of 2-3 MPa. The hot steam creates a low-viscosity steam-oil mixture which can be pumped out and processed. This technique is known as SAGD (Steam Assisted Gravity Drainage).

An innovative configuration for the ACR has been developed by AECL to provide a particularly economic energy supply tailored to oil sands needs steam at 6.5 MPa from the ACR steam generators is first passed through a high-pressure turbine, then directly from the turbine exhaust to an oil sands boiler. In this way, electricity is generated from ACR steam at an effective (marginal) efficiency of close to 100%, before the remaining energy is used to supply a (tertiary) steam delivery to the oil sands. Because the oil sands themselves are the primary heat sink, no condenser or associated cooling water are needed for the turbine, so that the balance of plant cost is relatively low. Engineering and economic studies have been completed to confirm that this approach is achievable, and that such an ACR steam supply would be highly competitive economically.

Based on favourable economic and environmental conditions, the ACR-700 design offers a cost-effective and growth-oriented steam supply and co-gen electricity for Oil Sands. The CANDU approach ensures nearly zero emission of climate change gasses and alternative energy sources, such as natural gas. The synergetic capability of ACR-700 to produce electrolytic hydrogen, oxygen and heavy water are further benefits with substantial additional commercial value.

This paper reviews the technical base and the opportunities for an ACR-700 at Alberta Oil Sand and shows the benefits to potential users.
**KEYWORDS: CANDU, ACR, SAGD**

I. Introduction and Background

The Alberta oil sands bitumen deposits comprise one of the largest sources of hydrocarbon in the world, and have emerged as the fastest growing, soon to be dominant, source of crude oil in Canada. The oil industry has made great strides in improving the effectiveness of gathering this resource. In particular, alternatives to open-pit mining have been developed which enable in-situ recovery of underground deposits with a minimum of environmental disruption. The main challenge that remains is the large quantity of energy needed in the process of extracting the oil and upgrading it to commercial levels. For a typical in-situ extraction project, about 18% of the energy content of the oil produced is used up in the extraction process, while a further 5-10% (depending on oil production strategy) is used in generating hydrogen to upgrade the bitumen to synthetic crude oil.

The large energy requirement for the oil sands extraction process represents a challenge with regard to both environmental impact and security of supply. The use of natural gas, the current energy supply, has impacts in terms of air quality (via NOX and other emissions) and also represents a large greenhouse gas emissions component. As the oil sands industry expands, the availability of natural gas also becomes a concern, as does price and price stability.

With this background, the opportunity for nuclear reactors to provide an economical, reliable, virtually zero-emission source of energy for the oil sands becomes very important. Over the last few years, developments in oil sands extraction technology, and developments in CANDU technology through the Advanced CANDU Reactor (ACR®), have converged so that a practical, economical match of nuclear energy to the oil sands is now available.

In this paper, the energy requirements of the latest oil sands extraction operations are reviewed, the adaptation of ACR to meet these needs is summarized, and economic and feasibility issues are evaluated. The paper includes economic survey studies by AECL, and an independent study by the Canadian Energy Research Institute for a typical example of an ACR applied to oil sands production.

II. Summary of Oil Sand In-Situ Production

1. SAGD Facility Description

Steam Assisted Gravity Drainage (SAGD) is an enhanced oil recovery process applicable to in situ recovery of crude bitumen from deep oil sands deposits. A typical application involves two horizontal wells drilled in parallel, with one a few metres above the other. During the start-up phase, medium pressure steam is circulated in both wells to heat the reservoir of bitumen-sand mixture by conduction. The heating reduces the viscosity of the bitumen, increases its mobility, and establishes pressure communication between the two wells along their length, so that a flow of fluids can occur from the upper well to the lower well.

Once communication is established, the lower well is placed on production and the upper well begins injecting steam, representing the start of “normal” SAGD operations. Continued steam injection gradually creates a steam chamber above the well-pair, which expands upwards to the top of the reservoir and laterally until contact is made with similar steam chambers from adjacent well-pairs.

The steam injection rate through the upper well is increased until the desired reservoir operating pressure is achieved, then varied to maintain that pressure. Driven by this pressure and by gravity, liquid bitumen and water flow as a mixture from the upper well to the lower well. The mixture then flows to the surface where it is processed to recover the bitumen and recycle the water through cleanup plant and closed-cycle boilers. The flow rate from the production well (lower well) is controlled so that the “bottom hole” (in-well) temperature of the produced fluids is several degrees Celsius below the saturation steam temperature at the operating pressure. This prevents steam from breaking through into the production well.

Steam injection continues until the steam/oil ratio (number of m³ of steam injected to produce one m³ of crude bitumen) reaches a value where it is no longer economic to continue. Over the life of each well-pair, production typically requires an average steam-oil ratio of 2-3. SAGD is capable of recovering well over 50% of the initial volume of crude bitumen in place.

Steam is usually generated at a central plant and then distributed to the injection wells. The central plant also serves as the processing site for produced fluids and gases.

To establish a reference project output for the purpose of this comparison, working from output levels of 62,400 m³/d of 100% quality steam (see Table 2), an assumed cumulative steam/oil ratio of 2.5 was applied to derive a hypothetical SAGD project size. Based on an operating capacity of 93%, the result was consistent...
with a 23,200 m³/d (146,000 b/d) bitumen production SAGD operation in northwestern Alberta, targeting a high-quality Athabasca resource.

A project of this size is large relative to existing commercial SAGD projects; however, several companies are proceeding with projects in the 12,700 m³/d (80,000 b/d) to 15,900 m³/d (100,000 b/d) range and beyond. For example, one of the largest projects, envisages a series of stages of 35,000 bbl/day or 50,000 bbl/day bitumen each, with four to eight stages expected, giving an ultimate potential output of 140,000 to more than, 300,000 bbl/day. (The first stage of this project is expected to start production this year).

The energy requirements for the oil sand production facility are primarily the medium pressure steam and also significant electricity demand for the facility itself. A typical figure of merit would be that a 100,000 barrel/day bitumen production operation would need of the order of 300MWe equivalent in steam flow, and an electricity demand of from 50—150 MW. The electricity demand can vary significantly with the facility design, principally according to the degree of water recycling and cleanup adopted by the facility. Actual examples of energy demand are discussed further below in section 4. Overall, the magnitude of energy demand is such that, given enough flexibility in configuring the ACR steam and electricity outputs, an oil sands facility with more than 100,000 bbl/day output may be suitable for consideration as an ACR client.

III. Summary of ACR-700 Design

1. Summary of Key Features

The ACR-700 design is an evolutionary development of familiar CANDU technology, adding a carefully chosen set of innovations to the major improvements in economics, operations and safety margins. With a gross electrical output of approximately 728 MWe, the ACR follows the same size range as AECL’s standard CANDU 6 design, allowing much of the extensive experience base in CANDU 6 design, construction and operation to be utilized.

The ACR-700 design is rooted in the proven principles and characteristics of the CANDU system, and uses standard features of CANDU pressure tube technology built up over many decades of operation:

- Modular horizontal fuel channel,
- Available simple, economical fuel bundle design,
- Separate cool, low-pressure heavy water moderator with back-up heat sink capability,
- On-line/at power fuelling,
- Fuel cycle flexibility with high neutron efficiency,
- Passive moderator/shield tank heat sinks surrounding the pressure tube core,
- Two robust, quick acting, passive shutdown systems.

The following key features, derived from the enabling technologies, are incorporated into the design concept of the ACR

- Slightly enriched uranium fuel (nominally 2% U-235), contained in CANFLEX bundles to achieve burn-up (approximately 20 MWd/kgHM) and with further increases as operational experience increases,
- Light water replacing heavy water as the reactor coolant,
- More compact core design with reduced lattice pitch, reducing heavy water inventory and providing a highly stable core neutron flux,
- Enhanced safety margins, due to optimized power profile and void reactivity,
- Higher coolant system and steam supply pressure and temperature resulting in an improved overall turbine cycle efficiency,
- Reduced emissions from radiolysis of heavy water,
- Improved performance through advanced operational and maintenance information systems, and improvements to project engineering, manufacturing and construction technologies.

A simple diagram of the ACR-700 design is shown in Figure 1, and main design parameters are given in Table 1. A more detailed description of the ACR is given in Reference 1.

2. Summary Of Implementation Features

- Construction schedule: The standard ACR construction schedule is 36 months, with a complete project schedule (Contract Effective Date to in-service) reducing from 60 months for a first of a kind unit, down to a target of 48 months for a replication unit. This is an evolutionary reduction from the construction schedules achieved for current, conventional CANDU units. The first unit of the recent Qinshang CANDU 6 project was brought into service in 71 months, one month ahead of schedule, and future CANDU 6 projects are targeted to have a total project schedule of 66 month. The ACR can achieve still further schedule reductions by design for totally modular construction, by reduced commissioning time for the main coolant
system (due to the switch to light water coolant); the reduced number of fuel channels in the core to be installed and inspected.

- Operating costs: A companion paper gives a detailed review of ACR operability. However, overall figures of merit of an operating cost of less than 1 cent/kWh can be assumed, with a capacity factor greater than 90%.

IV. Assessments of ACR as Energy Supply for Oil Sands Facilities

AECL has carried out recent studies looking at the following topics:

- Adaptation of ACR configuration to steam and electricity cogeneration for oil sands application
- Economic comparisons of ACR energy with the conventional energy option, natural gas
- Review of feasibility issues with siting an ACR in the oil sands producing region

AECL has worked with oil companies, independent experts and with the Canadian Energy Research Institute to understand the requirements of this application and to develop realistic models for economic comparison. CERI's current studies of ACR and natural gas economics form an independent reference point from which further work can be done to optimise ACR applicability for the oil sands.

1. Adaptation of ACR Configuration

The fundamental product of a CANDU nuclear power plant is steam, from the reactor coolant system steam generators. Thus, adapting a secondary heat cycle to exchange the energy from this steam, and generate process steam for oil-sands application is, in principle, straightforward. As discussed above, the steam pressure desired as the starting point for delivery to SAGD oil wells, can vary with the circumstances of the oil field, from 2-6 Mpa. In addition to steam supply, SAGD production facilities can be significant consumers of electricity. The rapidly increasing level of industrial activity associated with the oil sands industry is increasing overall regional electricity demand. The result is that cogeneration of steam and electricity is a naturally advantageous configuration to consider for the ACR.

In practice, each large oil-sands project will have its own unique characteristics in terms of: steam supply magnitude and quality; desired steam pressure; geographic location; electricity demand; etc. As a result, for each project, an ACR configuration would be defined which is adapted to meet individual project needs while optimising ACR economics as far as possible.

While working with oil companies at an early stage, to better understand their specific requirements, AECL has defined a range of configurations to take advantage of ACR characteristics and provide suitable oil sands production support.

For lower steam pressures and smaller-scale electricity production, the ACR steam supply (at 6.5MPa) is passed first through a high-pressure turbine, emerging at a suitable pressure (~2.5 – 3.5MPa) to pass through a tertiary boiler, where remaining heat is transferred to SAGD oil-well steam supply at 2-3 MPa. This configuration is shown in Figure 2. For an ACR-700, the typical outputs would be:

- ~140 MWe (net)
- 420,000 bbl/day steam
- Steam supply pressure 2.2Mpa

The production rate of bitumen using this steam would depend on the steam-oil ratios required in the SAGD wells. For steam-oil ratios of 2-2.5, the bitumen production rates would be 168,000 – 210,000 bbl/day.

This configuration has some advantages in economics, because of the very efficient system configuration, but has more limited flexibility in terms of adjusting steam and electricity outputs.

For high steam pressures and/or a greater degree of electricity production or lower steam delivery, an alternate configuration has been considered (Figure 3). In this case, the steam supply to the turbine and the steam supply to the tertiary, oil sand boiler would be in parallel. By suitable choice of feed water heating system conditions to match the return feed water conditions to the nuclear side, from the tertiary boiler, the drain temperature is chosen to match the feed water temperature requirements. This configuration can deliver steam at pressures up to 5 or even 6 MPa, and has a great deal of flexibility in adjusting steam versus electricity outputs.

Other ACR configuration adaptations are also being considered. However, economic evaluations so far have been based on these options.

As discussed below, these ACR configurations have been studied at to confirm feasibility from the viewpoint of siting, equipment supply, licensability, and economics. The configurations are based on the use of the standard ACR-700 nuclear steam supply design with no changes; that is, adaptations are restricted to the Balance of Plant configuration. Configurations that adapt the nuclear steam supply of the ACR would also be possible, but would involve a substantial degree of
2. ACR Economics

Usually, nuclear power plant economic assessments can be organized around a single “figure of merit” parameter, because the plant delivers a single product – electricity. In this case, the ACR is configured to deliver both steam and electricity, so that the economic comparison, or energy cost estimation, is more complicated. If the local market price for electricity is lower (in equivalent MW energy terms) than the price of steam, then it is advantageous to configure the ACR to deliver more steam and less electricity. Conversely, for a higher electricity price, the opposite is true. For this reason, at this early stage, AECL has attempted to identify fixed parameters that are oriented to equivalent costs between steam and electricity. In this way, the relative costs of the energy for different configurations reflect the efficiency of each configuration, rather than the “market bias” which may be introduced for a given set of assumptions. In the studies done so far, since steam is the fundamental energy product for the oil sands, the assumption is that the price of electricity is fixed, leaving the price of steam as the variable to be calculated.

2.1 Initial Studies

Initial studies of ACR economics were carried out with the configuration (a) above, and with the pre-conceptual design of the ACR. In these studies, the application of an “N’th-unit” repeat-plant ACR was considered, and nuclear economics were compared with natural gas as the alternative. The studies also considered the economic impact of CO₂ emission credits, if these were available to the nuclear option. They also considered the impact of the costs charged for emissions of SO₂, NOX, VOC’s (volatile organic compounds) among other air pollutants associated with the natural gas option.

The main economic assumptions for this initial study were based on energy trends to the year 2000, and included:

- Assumed plant-gate electricity price: $45/MWh
- Assumed natural gas cost at site: $45/GJ
- Assumed total cost of supplying natural-gas steam to the oil sands facility; $4/bbl of bitumen (composed of $3.10/bbl fuel cost and $0.9/bbl capital and operating charges)

The reference case for the study was the ACR configuration described in 4.1 (a) above, with a net output of ~140 Mw and steam supply for 210,000 bbl/day of bitumen (assuming a steam and ratio of 2:1).

The study also looked at different target values of return on investment for the capital expenditure target values of return on investment for the capital expenditure for the ACR; - the other most significant economic parameter. The study concluded that, for an “N’th unit” (repeat unit) ACR-700, with a return on investment of 14%, the ACR steam price would be more than 10% cheaper than steam from a natural gas boiler, neglecting any CO₂ or pollution credits.

The study also concluded that, for the case where emissions to the Fort McMurray air shed are constrained for SO₂, NOX, VOC’s, the savings in emission costs for the ACR are:

- >$20,000/day for SO₂, NOX and VOC’s
- >$50,000/day for CO₂ credits at year 2000 assumption of $7.50/tonne

These savings represented 3.7% and 9% respectively in comparison with the natural gas case.

As noted above, these credits would significantly increase the ACR cost advantage, if applied.

2.1.1 CERI Economics Study

Most recently, AECL commissioned an independent study by CERI (Canadian Energy Research Institute) to compare the economics of ACR-supplied energy with natural gas. This study provides a more up-to-date evaluation using most recent assumptions on configurations and economics and compares identical energy supplies from the nuclear and natural gas options respectively to ensure an apples-to-apples comparison. The study identified comparable ACR and natural gas supplied configurations each delivering both steam and electricity. This enabled the optimum gas configuration cogenerating electricity and steam for a typical large-scale SAGD operation. A common economic model was also developed, using parameters such as gas and electricity costs based on recent norms, but without attempting to extrapolate or forecast future prices. Table 2 gives values of the main parameters.

The results of the study show that, based on a gas price of $4.25 Cdn/GJ (equivalent to $3.25 US/mm btu reference price on the NYMEX commodity exchange), the nuclear option achieves a 10% advantage in steam cost. For comparison, current 2003 gas prices have averaged $5.76 US/MMBtu so far, and long-term prices are predicted to trend in this direction based on the costs of LNG imports and arctic gas supply. The study also looked at energy price sensitivity to changes in key parameters. The results are shown on Table 3. Economically, the potential for a nuclear advantage is shown in a lower sensitivity to main parameters. A 25% increase in capital cost (the most significant
nuclear parameter) would increase steam costs by 20% from $8.61/tonne to $10.30/tonne, while a 25% increase in the price of natural gas would increase steam cost from $9.42/tonne to $11.78/tonne. In practice, the volatility of natural gas prices has been significantly greater than this. The result shows that, in this regard, nuclear has a significant advantage in cost risk. The study also looked at the impact CO\textsubscript{2} emissions costs on the comparison. The current reference basis for CO\textsubscript{2} costs or credits is the value of $15/tonne, stated by the Canadian government as an envelope to short-term CO\textsubscript{2} costs in its Kyoto strategy. This CO\textsubscript{2} cost would add 18% to the cost of natural gas-supplied steam.

Further work is continuing to better understand the economics of the ACR option in comparison to other fuel alternatives, and to define the costs of different ACR configurations and site-specific costs in more detail. Clearly, though, the ACR is able to offer significant economic potential, along with the elimination of air emissions.

3. Project Feasibility

AECL’s initial studies confirmed project feasibility at the basic level.

- The ACR can be positioned on the ground at the typical SAGD production sites, meeting civil engineering requirements for foundations, seismic resistance, extreme weather, etc.
- The ACR can be configured based on a high degree of water conservation and recycle, to meet stringent local water use requirements
- As in other CANDU applications, the ACR would comply with all federal and provincial environmental protection requirements and expectations
- The ACR is designed for highly modular equipment and structure assembly, construction and installation. As such, risks and costs due to construction in a remote site can be kept to a minimum by the large fraction of the work done in offsite module fabrication. The ACR is designed to enable road shipment of all modules from Edmonton to the Fort McMurray and other site areas.
- The timing for a first ACR unit on-line, 2011, is consistent with typical timing for the building of proposed SAGD projects to full-scale production.

In the more recent evaluation work, the CERI study identified some important considerations affecting this application for the ACR. Further AECL work will study these considerations and identify ways to successfully address each issue:

- **Staged Production and Risk Profile**

SAGD projects have typically been planned in stages, steadily increasing in total capacity as each successive stage comes on stream. This enables oil companies to reduce market risks and distribute decisions on capital outlays over an extended period, with offsetting revenue steadily increasing. The selection of ACR energy supply involves a large one-time capital commitment.

Mitigating this issue is AECL’s current track record of on-time, on-budget completion of CANDU 6 power reactor projects in Wolsong, Korea, and Qinshan, China, as well as the fact that the ACR economic competitiveness, shown above, is consistent with the ACR on-stream at the time the project reaches full production, as a replacement for gas-fired capacity.

- **Steam Distribution**

Since individual SAGD oil wells would need to be placed at varying distances apart, the economics of a central steam source such as the ACR, will depend on the cost of transporting steam to the individual wells.

For some proposed projects, the individual wells are planned to be arranged around a single central distribution source, with a radius of one or two kilometres, which would be very compatible with the ACR. In other cases, where steam distribution may be over several kilometres, the ACR configuration (e.g. choice of steam pressure) would have to be carefully chosen, to minimize energy losses and distribution costs.

- **Design Optimization**

As noted in the discussion on configuration, a range of ACR adaptations can be considered, varying in electricity and steam output and steam pressure. The lowest cost ACR configuration may not exactly match the lowest cost oil production configuration and vice versa. To obtain the best application, the lowest total project cost should be considered, ideally by a joint process of optimising the total facility configuration.

- **Water Access**

The northern Alberta oil sands region is an area with limited water sources, and now an increasing industrial demand. It will be necessary to configure any individual project to ensure minimal use and diversion of local water sources, so that overall regional water use planning guidelines can be met. This will particularly affect the design of electrical production elements of the plant.
4. Additional Economic Options

As noted earlier, the upgrading of bitumen from the oil sands into synthetic crude oil requires a considerable amount of hydrogen. The current method of producing hydrogen is by steam methane reforming, with natural gas as the feedstock. An alternative method of producing hydrogen is by electrolysis. Until relatively recently, this has not been an economically competitive option for the large scale of hydrogen production under consideration here. However, a number of developments make the electrolytic production of hydrogen an option to consider.

- The capital cost of large-scale electrolysis units has been reduced considerably in recent years. New cell technology has reduced capital costs to ~$170/kW, which would be lower than typical capital costs for steam methane reformers.

- Based on recent relationships between natural gas and electricity prices, the operating costs of an electrolysis unit have been higher than those for a steam methane reformer, since ~50 kWh is needed to produce each 1 kg of hydrogen at the efficiencies of current low-cost electrolysis cells. However, as the natural gas market in North America is changing, this relationship may change.

- The change to deregulated electricity markets means that an electrolysis operation can take advantage of daily variations in electricity price. A recent study by AECL (reference 2) showed that this could be a significant benefit. Accounting for storage of hydrogen during low price production periods, to make up for strategic reduction in production during high price periods, could reduce the overall price of hydrogen produced, by 15 percent or more, for a typical electricity price history in Alberta.

Overall, as the energy market evolves, the option of locally produced electrolytic hydrogen may prove to be of economic interest. For the ACR, there is another important synergy arising from this option. As a by-product of the pure hydrogen stream arising from an electrolytic production unit, a synergistic heavy water production plant can be added very cost-effectively. This means that a further cost saving for the overall plant can be introduced, via heavy water production using the CECE (Combined Electrolysis and Catalytic Exchange) method.

V. Conclusions

The need for clean, sustainable energy supply to enable the full-scale exploitation of Alberta’s oil sands reserves has been discussed on many occasions over the years. Now, the depletion of conventional North American oil and gas resources, the ratification of the Kyoto treaty and parallel concern over air quality balancing the need to make the most effective use of Canada’s energy resources, all increase the relevance of a nuclear energy solution. The ACR, an advanced, affordable development of the CANDU reactor family, presents an economically attractive, adaptable option, which can be adapted to wide variations in configuration to meet individual oil-sands project specifications. Recent studies have established that ACR offers a cost advantage over the current energy source, natural gas. Studies of two different configurations give consistent results indicating about a 10% cost advantage for ACR over natural gas, at a relatively low-end natural gas price assumption. Because nuclear is a zero-emissions operating technology, ACR offers air-quality and climate change benefits as well, which can translate into a further significant economic benefit. For example, credit for foregone SO\(_2\), NO\(_X\) and VOC’s emissions would be worth 3-4% in cost reduction, while full credit for CO\(_2\) emissions reduction, at $15/tonne, would have a value about 18%.

Already, studies done to date confirm that an ACR energy supply is feasible; offers significant cost advantage; provides clean air and CO\(_2\) mitigation benefits; and can be adapted to the needs of oil-sands projects.

This confirms that an ACR sited as part of an oil-sands production facility is a practical proposition. AECL will pursue further studies to explore how to gain the maximum benefit from this important energy option.

Figures:
1. Schematic of Typical ACR plant
2. Co-gen Configuration Diagram a)
3. Co-gen Configuration Diagram b)

Tables:
1. ACR Main Design Parameters
2. Main Parameters, CERI Economic Model
3. Steam Supply Cost Sensitivities

References:


### Table 1
**ACR Main Design Parameters**

<table>
<thead>
<tr>
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<th>Value</th>
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<td>Nominal plant electrical output</td>
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<td>Reactor coolant system pressure</td>
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<td>Reactor coolant system outlet temperature</td>
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<td>Fuel design</td>
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### Table 2
**Main Parameters, Economic Model**

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<tr>
<td>Natural gas price (plant gate)</td>
<td>Cdn $4.25/GJ (equivalent to US $3.50/mm btu NYMEX)</td>
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<td>Project energy supply</td>
<td>62,400 m³/day steam</td>
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Table 3
Steam Supply Cost Sensitivities

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<tr>
<td>Opex (+25%)</td>
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<tr>
<td>Electricity Price (-25%)</td>
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<tr>
<td></td>
<td></td>
<td>Gas Price (+25%)</td>
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<td>CO2 Offsets ($15/t)</td>
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<td>Capex (+25%)</td>
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<tr>
<td></td>
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<td>Opex (+25%)</td>
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$ Per Tonne of 80% Quality Steam

6 7 8 9 10 11 12 13
Figure 1 Schematic of Typical ACR Plant
Figure 2  ACR-700 Co-generation Diagram a)
Figure 3 ACR-700 Co-generation Diagram b)

Note: *Water volume is corrected to 4°C and 0.1 MPa.