Decommissioning of CANDU Nuclear Power Stations
by G.N. Unsworth
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This report summarizes the results of a detailed study of the various procedures and costs associated with decommissioning a CANDU reactor. The three internationally recognized “stages” of decommissioning (mothballing, encasement, and dismantling) are discussed. It is concluded that decommissioning is possible with presently available technology, and the costs could be financed by only a marginal increase in the cost of electricity during the life of the reactor. The environmental impact would be no greater than that of any large construction project.

Ce rapport résume les résultats d’une étude détaillée des diverses méthodes et des coûts associés à la mise hors service d’un réacteur CANDU. Les trois étapes de mise hors service (la mise en réserve, le scellement et le démontage) reconnues internationalement sont examinées. Cette étude conclut que la mise hors service peut être réalisée dans le cadre de la technologie actuelle et que les frais encourus peuvent être financés facilement par un accroissement marginal du coût de l’électricité durant la vie utile du réacteur. L’incidence de l’impact sur l’environnement ne serait pas plus élevée que celle provenant de tout grand projet de construction.
The term "decommissioning" means shutting down and placing a plant permanently out of service. The operation must be capable of being performed safely and in such a manner as to impose no responsibility on future generations. The decommissioning of nuclear reactors will involve the expenditure of material and manpower and will require careful planning. This summary is based on a study of decommissioning a single 600 MW(e) CANDU* reactor station (Figure 1).

The "design" life of a reactor is normally considered to be 30 years and usually this is chosen as the capital repayment period. There is little likelihood that a utility will choose to decommission a reactor before the end of its design life and, indeed, there will be considerable economic incentive to operate it beyond the design life. Therefore, barring major incidents involving damage to the reactor, it is reasonable to assume that a utility will not consider decommissioning a facility until at least 30 years after start-up and, more likely, will not be involved in decommissioning until more than 40 years after start-up.

There are many possible ways to decommission a reactor. They range from simply shutting down the

* CANada Deuterium Uranium
reactor, to completely dismantling the reactor and releasing the site for other uses. It has been agreed internationally\(^8\) that, when referring to nuclear power facilities, three "stages" for decommissioning may be defined. In the order of least complexity to greatest complexity, these are: Mothballing, Encasement, and Dismantling and Removal. Figure 2 shows a schematic representation of the different stages.

**ACTIVITIES PRIOR TO DECOMMISSIONING**

A number of factors must be considered prior to decommissioning a reactor and they may affect the option selected.

The total inventory of radioactive substances on the site must be determined. This allows an assessment of:

- the man-rem\(^*\) exposure expected for any operation,
- the merits of delaying completion of decommissioning to permit the radioactivity to decay,
- the weight, volume and specific activity of the material to be shipped to and buried in a waste repository,
- the weight, volume and specific activity of equipment which will be left on site.

Removal of the fuel, heavy water and radioactive waste material will reduce the long-lived radioactive inventory by approximately 98.5 per cent. The remaining "fixed" radioactivity will be due to activation of pressure tube, calandria and shielding materials. Negligible amounts of fission products and actinides will be present. After two to three years, the primary source of gamma activity is cobalt-60. After 20 years, the rate of decay of total activity will be governed by the half-life of nickel-63 and there will be approximately 10\(^6\) curies of activity. After 25 years, most of the material will meet IAEA transport regulations for Low Specific Activity material\(^9\). The major proportion of the activity is associated with the calandria shell, end shields and associated equipment.

Decontamination will be required if the gamma fields associated with the out-of-core portions of the primary heat transport system are high or if the system is contaminated with fission products and actinides as a result of fuel defects during the life of the reactor. Decontamination costs can be high, and some of the out-of-core portions of the primary heat transport system may be seriously contaminated. Therefore, consideration should be given to allowing the activity to decay (and paying for surveillance costs during the decay period) rather than carrying out decontamination. However, on the assumption that decontamination is to be done, aggressive reagents should be used to ensure that a high decontamination factor is obtained. This is possible since corrosion of the components by these reagents need no longer be a major concern.

In the case of a 600 MW(e) CANDU reactor the cost of a full decontamination would be approximately $1 200 000\(^\ast\). It is assumed that decontamination will reduce the radioactive fields to a level that will not require any significant man-rem expenditures.

Removal of the fuel, heavy water and radwaste will eliminate the capability of operating the reactor and greatly reduce the probability of release of any radioactive material. Therefore, an application to the regulatory authorities for a change in operating licence would be justified so that manpower and surveillance requirements can be reduced.

The availability of facilities for the storage of radioactive waste material and the cost of transportation to the storage site will also affect decisions regarding decommissioning. Decommissioning wastes which contain long-lived radioactivity would be placed in a deep underground waste repository when it is available\(^9\).

Some points that must be considered when developing the specifications for a repository for waste from the decommissioned station and for transporting the waste to it are:

(a) The decontamination procedures associated with decommissioning will be effective in removing long-lived fission products or actinides. Therefore, the material to be stored will be solids of relatively low specific activity. Most of the gamma activity will have short half-lives and will decay fast enough to eliminate the necessity of constructing gamma shielding of high integrity and resistance to aging. The only major concern is to provide facilities that ensure the stored solid components will not corrode or dissolve at a rapid rate.

(b) The fuel will be stored, as described elsewhere\(^4\), and it is expected that the amount of actinides and fission products in the decommissioning wastes will be reduced to negligible values by decontamination. Therefore, the only material containing significant amounts of these radioactive substances will be those that can easily be separated and will have relatively small volumes, e.g., ion exchange resins, decontamination products, etc.

(c) Consideration should be given to retrievable storage. It would seem desirable to store some of the decommissioning wastes in such a fashion that they could be retrieved and re-used after the radioactivity has decayed. There are advantages to this approach since it means the disposal facility does not need to accommodate them and a future scrap value can be attached to some of the waste.

(d) The hazards and risks involved in transporting the decommissioned material will be low and easy to manage, since the specific activity levels are low

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\(^8\) A measure of human radiation exposure; it is the total dose in rem received by the individuals in a given population.

\(^9\) All cost estimates are in 1975 dollars.
and the material will be made up primarily of large solid pieces. It can be assumed that the regulations published by the IAEA\(^3\) will apply.

Time and cost estimates are required to determine what activities are significant cost items and to obtain an appreciation of what effect the cost of decommissioning might have on a utility's financing.

The reactor designer will want to know in which areas the significant cost items lie so that he can investigate whether changes can be made to the original design to reduce decommissioning costs. The owner of a nuclear power plant may use the cost estimates to help decide whether it is more economical to repair a major breakdown or to decommission the reactor.

If sinking fund financing is used to defray the eventual costs, only minor changes in cost per kilowatt hour of electricity would be required to cope with large differences in decommissioning costs (Table 1). Actual decommissioning costs are discussed in the next section.

**Table 1** Increments in power cost required to develop a sinking fund of $100 000 000 after "N" years

<table>
<thead>
<tr>
<th>&quot;N&quot; (years)</th>
<th>Increment in Cost (mills per kilowatt hour)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>0.82</td>
</tr>
<tr>
<td>30</td>
<td>0.45</td>
</tr>
<tr>
<td>40</td>
<td>0.27</td>
</tr>
</tbody>
</table>

**Assumptions:**
- Discount rate = 12% per annum
- Inflation rate = 8% per annum

\[
\text{True discount rate} = \frac{1.12}{1.08} = 1.037 = 3.7\% \text{ per annum}
\]

**DECOMMISSIONING**

**Mothballing**

For "mothballing", the primary containment (piping and equipment associated with the primary cooling circuits) is maintained intact. All systems containing liquids that are radioactive are drained and sealed to prevent escape of contaminated material. The secondary containment (building) is maintained in a condition such that the probability of a release of radioactive material to the atmosphere is no greater than during reactor operation. The atmosphere inside the containment building is controlled to prevent the spread of contamination, and access to the inside of the containment building is controlled. The entire facility is maintained under surveillance, and equipment for monitoring radioactivity both inside and outside the containment building is kept in working order. Inspections are carried out to ensure that both the primary and secondary containment systems are being maintained in an acceptable condition.

The specific actions involved in mothballing are:

1. Remove fuel from reactor and ship all irradiated fuel from used fuel bays off-site.
2. Remove all heavy water and ship it off-site.
3. Decontaminate systems as required.
4. Process and ship to an active disposal area all active waste such as ion-exchange resin, filters, and decontamination solutions.
5. Perform a detailed radiation survey and calculate the total amount of activity on the site.
6. Apply for a change in license which will specify a reduced minimum staff requirement based on the fact that the potential hazards and risks have been reduced.

The surveillance and monitoring requirements will consist of gathering data and submitting reports for quarterly inspection and semi-annual environmental surveys. In addition, effort will be required to maintain and operate the necessary systems.

It is expected that the total cost required for activities necessary to mothball a 600 MW(e) CANDU reactor will be approximately $6 000 000 and these activities will occupy one year. The annual expenses to maintain and operate the mothballed facility would be approximately $80 000. The cost of mothballing will not be affected greatly by changes in reactor size.

When mothballing is complete, the predominant amounts and types of radioactivity remaining will be:

- \(8 \times 10^5\) curies of iron-55
- \(3 \times 10^6\) curies of cobalt-60
- \(7 \times 10^5\) curies of nickel-63
- \(1 \times 10^5\) curies of zirconium-95

After 25 years, the predominant activities will be:

- \(6 \times 10^5\) curies of nickel-63
- \(1 \times 10^6\) curies of cobalt-60
- \(7 \times 10^5\) curies of iron-55

**Encasement**

For encasement, all easily removable parts are dismantled and removed, as are all components that are radioactive to the extent that they will remain a health hazard longer than the life of the proposed encasement structure (<100 years). All radioactive components remaining inside the biological shield are sealed and the building is modified as necessary to provide adequate shielding and containment.

The containment building itself and the ventilation system can then be modified or removed since they are no longer required as part of the safety system. If the containment building is left standing, access to it would normally be permitted without any monitoring of personnel for radiation exposure. Surveillance will be required but at a reduced level from that of mothballing since the only concern is to detect possible escape of...
radioactivity from within the encasement due to deterio-
ration of the encased structure with age.

With an encasement life of less than 100 years, the
vessel and all its internal components, including the
steel shot from the shield tank (used to provide shield-
ing around the reactor), must be removed from the site.

In addition to the steps involved in mothballing, the
following activities are required:

1. Disconnect, cut, and/or remove as much of the pro-
cess piping and equipment as can be handled us-
ning the existing access to the building.
2. Build a water-filled "work bay" in the moderator
room to permit handling and loading of active sec-
tions removed from the core.
3. Remove pressure tubes and ship off-site.
4. Remove and ship off-site all adjuster rods, ion
chambers, flux detectors and other in-reactor equip-
ment that was essentially designed for removal and
for which removal facilities and flasks are available
as routine maintenance equipment.
5. Install a water-tight cover-plate over the outer face
of each end shield. Cut out calandria shell, calan-
dria tubes, and end shield inner tube sheet. Remove
the steel shot and drain the shield cavity or shield
tank.

The total estimated cost for encasing a 600 MW(e)
CANDU reactor is $17 500 000 over a four-year period.
The annual monitoring and surveillance costs are esti-
ated to be $60 000.

It will cost approximately 30 per cent more to en-
cape a station which is double the size of the reference
station, and 20 per cent less for a station which is half
the size of the reference station.

There will be very little activity left after the encase-
ment work is complete. A very conservative (high)
estimate would be 20 curies of cobalt-60 in the vault
liner and one curie of iron-55 in the concrete. There will
be less than 100 millicuries of nickel-63.

The amount of radioactivity that will be sent to
burial will be approximately 10^8 curies each of nickel-
63, iron-55 and cobalt-60.

Dismantling and Removal
This is the most complete method of decommissioning.
Following the steps outlined for mothballing and en-
casement, the boilers are removed and the remainder of
the active material is dismantled and shipped off-site,
including the active concrete from the biological shield.
The remaining equipment and structures are disman-
tled and the material shipped to a local inactive burial
site. Finally, the reactor site is backfilled and graded,
and released without restriction for other uses. After re-
moval is completed, no further surveillance, inspection
or tests will be required.

The total estimated cost for dismantling and removal
of a 600 MW(e) CANDU power station is $30 000 000
over a six-year period.

It is estimated that the dismantling costs for a plant
double the size and half the size of the 600 MW(e) sta-
tion will be 45 per cent greater and 25 per cent less,
respectively, than the costs for dismantling the refer-
ence station.

Dismantling, although the most expensive method,
has the advantage over the others that the site be-
comes reusable and therefore the value of the site is a
credit against the cost.

MAN-REM EXPOSURES

There should be no need to experience higher expo-
sures or have a higher man-rem expenditure as a result
of decommissioning of a nuclear power plant than
would be encountered during normal operation and
maintenance of the plant. Estimated exposures for
each stage of decommissioning are shown in Table 2.
Exposure by ingestion or inhalation of radioactive dust
and gases should be negligible.

Table 2 Man-rem Exposures Involved in
Decommissioning

<table>
<thead>
<tr>
<th>Stage</th>
<th>Total exposure (man-rem)</th>
<th>Average exposure, per man, per year (rem)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dismantling</td>
<td>600</td>
<td>1.0</td>
</tr>
<tr>
<td>Encasement</td>
<td>400 plus</td>
<td>1.0 plus 0.05 during period of surveillance</td>
</tr>
<tr>
<td></td>
<td>0.1/yr of surveilance</td>
<td></td>
</tr>
<tr>
<td>Mothballing</td>
<td>250 plus</td>
<td>1.0 plus 0.1 during period of surveillance</td>
</tr>
<tr>
<td></td>
<td>0.5/yr of surveilance</td>
<td></td>
</tr>
</tbody>
</table>

ENVIRONMENTAL IMPACT

None of the decommissioning stages will have other
than minimal effect on the local environment and, in
fact, the only effect that would not normally be en-
countered with any large construction project would be
that due to disposal of the radioactive inventory.

All shipments of radioactive material will be in ap-
proved shipping containers and made in such a way as
to meet all relevant requirements. These shipments
will not create any undue hazard to the public or result in ex-
posure of the public to levels of radiation above those
permitted by the AECB.

None of the decommissioning activities should
result in the release of any significant amount of active
gases or dust to the atmosphere or otherwise externally
from the containment.

In respect to disposal requirements, the estimated
volumes of the various types of material resulting from
each decommissioning method are low. For dismant-
ling, which involves the highest volume, the specific re-
quirements are:
1. The highly active material will be encased in concrete or lead liners and will occupy approximately 250 m$^3$.

2. The remaining active material will occupy a volume roughly estimated at 7000 m$^3$.

3. The components of systems that are not contaminated will, wherever possible, be sold as scrap but the remaining material to be disposed of will occupy a volume of approximately 25 000 m$^3$.

For encasement, the highly active material will be the same as for dismantling and the volume will therefore be 250 m$^3$. For mothballing, there are no disposal requirements.

**SUMMARY AND CONCLUSIONS**

Table 3 summarizes the more significant data for each decommissioning stage considered. The following conclusions may also be drawn:

1. Decommissioning to any of the three stages is possible and can be done without development of new technologies or equipment.

2. The cost of decommissioning a nuclear power plant should not be a major concern to a utility; it could be covered by sinking fund financing, which would increase the mill-rate by less than 0.2 mills per kilowatt hour for the most expensive process (dismantling and removal). No financial credit is given in this study for the heavy water remaining when the station is decommissioned. The value of this material is comparable to the dismantling costs.

3. Assuming that satisfactory provisions are made for disposal of the fuel, heavy water and radioactive waste, and that suitable sites can be found for disposal of active components, the environmental impact of decommissioning a reactor will be no greater than that of any large construction project.

<table>
<thead>
<tr>
<th>Table 3</th>
<th>Summary of findings of this study</th>
</tr>
</thead>
<tbody>
<tr>
<td>Item</td>
<td>Dismantling and removal</td>
</tr>
<tr>
<td>1. Time required to decommission</td>
<td>6 years</td>
</tr>
<tr>
<td>2. Radiation exposure to personnel during decommissioning</td>
<td>800 Man-rem</td>
</tr>
<tr>
<td>3. Amount of radioactivity on site at end of decommissioning period</td>
<td>Negligible</td>
</tr>
<tr>
<td>4. Amount of radioactivity in disposal at end of decommissioning period (does not include fuel, heavy water or radioactive waste)</td>
<td>$4.2 \times 10^6$ curies</td>
</tr>
<tr>
<td>5. Disposal volume required (does not include fuel, heavy water or radioactive waste)</td>
<td>7 250 m$^3$ of active volume</td>
</tr>
<tr>
<td>6. Number of shipments by truck of active material</td>
<td>300 - 400</td>
</tr>
<tr>
<td>7. Decommissioning cost</td>
<td>$30 000 000</td>
</tr>
</tbody>
</table>

(Note: The breakdown of active and inactive components includes fuel, heavy water, and radioactive waste, while inactive volume refers to inactive equipment disposed of as scrap metal.)
REFERENCES


La présente publication est également disponible en français