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CANDU FUEL CYCLES - PRESENT AND FUTURE

by

A.J. MOORADIAN

Presented at the 9th Annual Conference of The Japan Atomic
Industrial Forum (JAIF) Tokyo, 10-12 March 1976

Chalk River Nuclear Laboratories
Chalk River, Ontario
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Cycles de combustible CANDU - Le présent et l'avenir*

par

A.J. Mooradian

Résumé

La filière électronucléaire canadienne, qui a maintenant fait ses preuves commercialement, est fondée sur un cycle de combustible (uranium naturel) à passe unique caractérisé par une grande utilisation de l'uranium et une grande efficacité de conversion. Ce cycle, qui se termine sur un stock récupérable de combustible irradié, est fondé sur le concept des réacteurs CANDU lequel est maintenant bien compris. Les deux options de stockage du combustible, l'active et la passive, toutes deux étudiées, sont décrites dans ce rapport.

Le développement futur de la filière CANDU est orienté vers la conservation de l'uranium par des recyclages de plutonium et de thorium. La pleine exploitation de ces options exige qu'on attache une importance continue à la conservation des neutrons, à l'efficacité de l'extraction et aux procédés de refabrication du combustible. Les résultats d'études récentes sont commentés dans ce rapport.

*Présenté au 9ème Congrès annuel du Forum industriel japonais, Tokyo, 10-12 mars 1976.

L'Energie Atomique du Canada, Limitée
Laboratoires Nucléaires de Chalk River
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ABSTRACT

The present commercially proven Canadian nuclear power system is based on a once-through natural uranium fuel cycle characterized by high uranium utilization and a high conversion efficiency. The cycle closes with secure retrievable storage of spent fuel. This cycle is based on a CANDU reactor concept which is now well understood. Both active and passive fuel storage options have been investigated and will be described in this paper.

Future development of the CANDU system is focussed on conservation of uranium by plutonium and thorium recycle. The full exploitation of these options requires continued emphasis on neutron conservation, efficiency of extraction and fuel refabrication processes. The results of recent studies are discussed in this paper.

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CANDU FUEL CYCLES - PRESENT AND FUTURE

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INTRODUCTION

The first CANDU* reactor to be commissioned in Canada was NPD (for Nuclear Power Demonstration), which came into service in 1962. Since that time commitments and firm plans for nuclear installations have grown to 15,500 MWe** (see Table 1). Of this, 2500 MWe is now operational and Canada ranks 6th amongst the nations of the world in nuclear energy production. About 5% of the country's electrical energy is now produced from CANDU reactors.

Like other industrialized nations, Canada is facing a shortage of low-cost fossil resources. There is little doubt that nuclear capacity will continue to be installed at a lively pace. Our projections indicate a nuclear capacity of 133,000 MWe by the year 2000. Most, if not all, of this capacity is expected to be committed to the CANDU-PHW concept (the Pickering Pressurized Heavy Water type of reactor) for the following reasons[1]:

1) The first commercial station (Pickering) has proved to be an exceptionally reliable performer.
2) There is now a well-established heavy water production industry (see Table 2).
3) Both an industrial and a regulatory infrastructure are in place to service and monitor the industry.
4) The fuel cycle is simple - natural uranium once-through. The system economics has from the beginning been based on zero value for spent fuel. I shall show later that spent fuel management places a negligible burden on power costs.
5) It uses uranium very efficiently both with regard to reactor inventory and continuing operation (see Table 3).

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* CANDU - CANada Deuterium Uranium

** Megawatts of electrical capacity

The reactor itself is well known to you in Japan and it is not my intention to describe it in this paper. Instead, I would like to address this paper specifically to the questions associated with closing the present once-through fuel cycle and the results of our recent studies of alternative CANDU fuel cycles designed to exploit the neutron economy of the CANDU reactor.

CLOSING THE ONCE-THROUGH NATURAL URANIUM FUEL CYCLE

The composition of uranium (see Table 4) in CANDU spent fuel approximates that of the tailings from enrichment plants. This uranium is unlikely to be of value except as blanket material for fast reactors. Nevertheless, CANDU reactors are exceptionally good converters and therefore the spent fuel contains significant quantities of fissile plutonium, which constitutes a major fuel resource in its own right. It is therefore the Canadian philosophy that the once-through fuel cycle should be closed by the secure, retrievable storage of spent fuel until such time that its processing is either in the utility or in the national interest. The utility interest is likely to focus on economic incentives while the national interest would likely focus on security of fuel supply. As I will point out later, these two objectives need not be incompatible and can be met by a coherent fuel cycle development program.

The generating utility is owner of the spent fuel and, therefore, retains the responsibility for its secure, retrievable storage.

Ontario Hydro is the first Canadian utility to generate significant quantities of spent fuel and has for several years been working in cooperation with AECL to develop a plan for interim storage which will satisfy the requirements of the regulatory authority in Canada — the Atomic Energy Control Board[2]. The objective is to develop a central site for storage of spent fuel to be operational by 1985. The storage requirements at reactor sites are being sized on this basis. For example, the Pickering station original construction included a storage pool with the capacity of five station years. To bring reactor site storage into conformity with the central storage plan, an additional 10 station years of storage capacity has been authorized for Pickering 'A'. Similarly, Pickering 'B' will have five station years of spent fuel storage which will be enough to carry it until the central site is in operation. The same principle for the design of reactor site capacity is being followed for the Bruce and Darlington stations.

Three steps will be required before the central storage site can be placed in service:

- evaluation of concepts,	1976
- public participation,	1976-1979
- design and construction,	1979-1985

The target dates for licensing approval are:

- site approval,	December 1981
- construction license,	July 1982
- operating license,	November 1985

At the moment, three concepts have survived preliminary evaluation: Pool Storage, Convection Vaults, and Concrete Canisters[3].

POOL STORAGE

Experience with water-cooled spent fuel bays in Canada dates back 27 years to the start-up of the NRX Reactor at Chalk River. In addition, at NPD there is a further 13 years of in-service experience; at Douglas Point, 8 years; and at Pickering, 4 years (see Figure 1). All of these systems have operated well. However, they cannot be considered passive systems since both the purity and the temperature of the water must be controlled. Their outstanding attribute is that even young fuel, fresh from the reactor, can be closely packed and stored at high density. There is little doubt that pool storage is the only alternative available at the reactor sites. Whether or not this is the best concept for long-term storage at a central site is still being evaluated. Figure 2 shows the pool storage concept developed for a central storage site.

CONVECTION VAULT

An example of the convection vault concept is illustrated in Figure 3. In this case spent fuel is sealed in stainless steel cans and stacked into cylindrical, vertical assemblies. Cooling is provided by air driven natural convection. The attribute of this system is that relatively high density storage can be achieved and the system is passive, requiring little upkeep and maintenance.

CANISTER STORAGE

Figures 4, 5, 6 and 7 illustrate this concept. The reference canister is a concrete container about 5 metres in height and 2.5 metres in diameter. Each canister will hold 216 Pickering size bundles of fuel (4.4 tonnes). The internal cavity measures about 75 cm. Cylindrical assemblies of fuel are sealed in stainless steel containers under inert atmosphere. Several such cans of fuel are stacked one on top of another inside a second steel can which is the full height of the cavity and which is seal welded after loading. The space between the outer can and the concrete is filled with lead. Cooling is provided by natural air convection over the outer surface of the concrete canister. It is estimated that five year old spent fuel will generate about 2 kW in each of these assemblies.

This concept is being both experimentally and economically assessed at the Whiteshell Nuclear Research Establishment. The first step in this experiment was the construction of a full-scale, electrically heated prototype. Two additional canisters have been built and one is now loaded with spent fuel and the second is being prepared for loading. The experimental results to date are very encouraging. One of the principal concerns was the conductivity of the concrete. This has proved to be higher than anticipated. The thermal gradient across the concrete shell is less than 45°C.

COMPARATIVE EVALUATION

Tables 5 and 6 are results from a recent economic and land use evaluation of the three concepts[4]. It was assumed that by the year 2000 the installed Canadian capacity will have grown to 133,000 MWe and that the entire accumulated spent fuel arisings (125,000 tonnes) will have to be transported an average distance of 1350 kilometres to the central storage site. The following observations are noteworthy:

(1) Although the pool and convection vault allow a high packing density of spent fuel, this advantage is not proportionally reflected in site area requirements which differ by only a factor of two.

(2) The total area of land needed for a major program of generation is very modest. If need be, land of quite high value could be utilized with negligible penalty to power generation costs.

(3) Any of the three concepts adds less than 2% to the cost of power generation. An assumed life of 50 years was used for costing purposes on the assumption that before that period had elapsed, the fuel would be processed and fission products would be sent to permanent disposal. However, a sinking fund for perpetual care would add only about 25% to the costs in Table 6.

(4) Since all three concepts are obviously acceptable on economic and land use criteria, the final decision will likely be influenced as much by less quantifiable considerations.

It is clear that an alternative, more complex fuel cycle will have to offer significant advantages to Canadian utilities before they would be prepared to turn away from the simplicity and known economy of the present once-through natural uranium system.

FUTURE CANDU FUEL CYCLES

World wide, the uranium exploration and mining industry is still young and immature. Its orderly development has been perturbed by military stockpiling, a long period of price stagnation, and the threat of limited demand implied by periodic, over-optimistic announcements of the early intrusion of fusion energy and fast reactors. Simultaneously, the real and rapid increase in commitments of thermal reactors needed to secure the national energy supplies of many nations has led to a sense of uncertainty in future uranium supply. This in turn has led to a uranium policy in Canada designed to protect the commitments of Canadian utilities with a 30 year forward reserve of uranium.

In the face of a reasonably secure fuel supply situation and the present uncertainties in fuel processing and radioactive fuel fabrication costs, it is unlikely that a compelling case can be made in Canada for an early commitment of commercial-scale reprocessing and refabrication plants. Nevertheless, it is clearly in both our national interest and that of the world energy supply situation that the CANDU reactor system be developed for as high a uranium utilization as possible. The development of fuel conserving options which can be invoked without a change in reactor concept and supporting infrastructure would remove a major source of indecision on the part of utilities which face long lead times and major capital commitments.

It has been known for many years that the CANDU concept offers unusually good potential for fuel conservation by virtue of the neutron-conserving characteristics of the heavy water moderator. However, until the past few years, our research and development resources have been largely preoccupied with the task of establishing the commercial viability of the CANDU reactor. Since the successful commissioning of Pickering, we have been turning our attention to the examination of a number of fuel cycle options which use essentially the same reactor concept as that of the commercial CANDU reactors. These studies are by no means exhaustive but have been sufficient to redirect our future development program[5] [6].

A summary of the more pertinent findings is given in Table 7[7]. Four types of fuel cycles are presented in the order in which they are most likely to be invoked. All of these cycles are based on plutonium from natural uranium burners as the only source of enrichment. The inventory includes the natural uranium required to generate the plutonium used in the second, third and fourth systems. The inventory also includes the fuel needed to bring the system to equilibrium in addition to the reactor start-up requirements. In all cycles it has been assumed that the turnaround time (i.e., fuel out to fuel in) is 1.5 years. In all cases the reactor used in the study has essentially the same core design as that of the Pickering reactors, that is, same length of pressure tubes, same lattice spacing, etc.

Taking these cycles in turn:

(1) Natural U-once-through – This has already been dealt with and requires no further comment. It has been given in this table only as a basis for comparison with the other fuel cycles.

(2) Natural U-Pu Recycle – Uranium utilization is improved in this cycle by a little better than a factor of two

over the natural U-once-through case. The cycle becomes economically competitive if Pu fabrication penalties are kept below \$65/kg h.e.*, reprocessing costs are held to \$80/kg h.e., and yellowcake can be purchased between \$65 and \$75/kg U. We believe the target costs for reprocessing and refabrication can be achieved at a commercial scale of operation. However, we lack verification through demonstrated experience. At the moment we are in the process of commissioning a small Pu fabrication plant to gain fabrication, costing and irradiation experience. We have been working on a laboratory scale on the development of fuel processing methods which we believe hold economic promise. Nevertheless, we expect that we will not have gained sufficient experience to commit a commercial Pu recycle program until the latter half of the 1980s.

(3) & (4) Thorium Cycles — It is possible to design the Th fuel cycle to achieve a broad range of efficiencies in uranium utilization. The two which have been chosen for this presentation are of special interest.

The optimized Pu-Th cycle is based on an economic optimization which assumes a reprocessing cost of \$80/kg h.e., a fuel fabrication penalty of \$65/kg for fuels bearing U^{233}, and \$37/kg h.e. for Pu-bearing fuels. On the assumption that these cost targets can be met, this cycle becomes competitive when the price of yellowcake exceeds \$100/kg U. Uranium utilization is a factor of four lower than that for the once-through natural uranium cycle.

The self-sufficient thorium cycle is important from a strategic viewpoint. On the same cost assumptions I have mentioned for the optimized cycle, the self-sufficient cycle becomes economic when the price of yellowcake exceeds \$200/kg U. The strategic importance of this cycle is that it places an economic ceiling on power cost which is only about 20% higher than present commercially viable systems. Once started, the cycle is self sustaining. It generates enough U^{233} at equilibrium to keep any given capacity going indefinitely on a small feed of thorium. Since thorium is four times as abundant in the earth's crust as uranium, a secure fuel supply is assured for several centuries.

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* heavy element

Both the optimum and self-sufficient cycles require a large start-up inventory which results from the high cross section of thorium. However, this inventory is in the same order of magnitude as that required by fast reactors of the same capacity. In the case of the self-sufficient cycle it needs to be invested only once. The accumulated spent fuel to the year 2000 anticipated from the Canadian program (125,000 tonnes U) would be sufficient to launch over 60,000 MWe of self-sustaining thorium fired capacity, essentially indefinitely.

The comparatively large starting inventory for Th-cycle CANDUs suggested that their introduction and impact would be limited by the rate of system growth. This effect was given a preliminary investigation using a system growth scenario as follows:

(1) System grows to 130,000 MWe by year 2000 and 900,000 MWe by year 2030, after which it stops growing.

(2) Thorium-cycle reactors are introduced in 1995 and their intrusion is limited to expansion and replacement.

It was found that cumulative uranium requirements grew to 1.5 x 10^6 tonnes U by the year 2050 and thereafter no further uranium was required.

Using the same scenario but replacing the Th-cycle CANDU with an LMFBR* characterized by a simple doubling time of 17.4 years gave similar results. Again, uranium requirements stopped growing at year 2050 but at a slightly lower cumulative uranium consumption, i.e., 1.3 million tonnes uranium.

We shall be examining the merit and implications of a convertible core in future studies. Such a development would allow a more rapid introduction of the Th-cycle and would add greatly to the confidence with which utilities can commit uranium fuelled CANDUs.

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* Liquid Metal Fast Breeder Reactor

PLANS FOR DEVELOPMENT OF FUTURE CANDU CYCLES

Clearly there is a good deal of incentive to develop the fuel conserving options which I have described. The key to exploitation lies in the development of reprocessing, active fuel fabrication and waste disposal methods which are economically viable.

It is our plan to develop and demonstrate these technologies in close liaison with both our regulatory authorities and the utilities which own the spent fuel.

The ultimate objective is to demonstrate the full thorium cycle in a CANDU reactor by the early half of the 1990s. The intent is to execute the program in orderly steps which recognize that the simpler plutonium-uranium cycle is the most likely to find earliest application and is required to provide the inventory of fissile material necessary to launch the thorium-cycle program. This approach will also allow us to build on the experience of other nations which are already well into uranium reprocessing and active fuel fabrication.

We are attracted to this program for three important reasons:

(1) It opens the door to a vast untapped new energy resource — thorium.

(2) It builds on an existing and commercially proven reactor technology. The same industrial and regulatory reactor infrastructure developed for the simple once-through uranium cycle is directly applicable to the reactor required for the fuel conserving cycles.

(3) It faces no tests of technological feasibility. As such it offers a highly credible option with which to secure future energy supplies, not only for Canada, but for the rest of the world as well.

REFERENCES

(1) J.S. Foster – "The Canadian Nuclear Power Program" Canadian Electrical Engineering Journal, January 1976, Vol. 1, No. 1, p.3-14.

(2) R.W. Barnes (Ontario Hydro), S.A. Mayman (AECL) – "The Canadian Program for Management of Spent Fuel and High Level Wastes". Proceedings of Joint Topical Meeting on Commercial Fuel Technology Today, American Nuclear Society and Canadian Nuclear Association, April 28-30, 1975, Toronto, Canada.

(3) W.W. Morgan – "Management of Spent CANDU Fuel", Nuclear Technology, Vol. 24, Dec. 1974.

(4) S.A. Mayman – Whiteshell Nuclear Research Establishment – Private communication.

(5) E. Critoph, et al – "Prospects for Self-Sufficient Equilibrium Thorium Cycles in CANDU Reactors". Invited paper ANS 1975 Winter Meeting, San Francisco, November 16-21, 1975.

(6) S.R. Hatcher,et al – "Thorium Cycle in Heavy Water Moderated Pressure Tube (CANDU) Reactors". Invited paper ANS 1975 Winter Meeting, San Francisco. November 16-21, 1975.

(7) J.B. Slater – Chalk River Nuclear Laboratories – Private communication.

Table 1

CANADIAN NUCLEAR POWER STATIONS

Station	Unit	Unit Rating MWe (net)	Power System	First Operation
NPD	1	22	O.H.[1]	1962
Douglas Point	1	208	O.H.	1966
Pickering 'A'	4 x	514	O.H.	1971-73
Gentilly-1	1	250	H.Q.[2]	1971
Bruce 'A'	4 x	745	O.H.	1976-79
Gentilly-2	1	600	H.Q.	1980
Lepreau	1	600	NBEPC[3]	1980
Pickering 'B'	4 x	514	O.H.	1981-83
Bruce 'B'	4 x	750	O.H.	1983-86
Darlington	4 x	800	O.H.	1986-88
X	1	600	M.H.[4]	1985+

1. O.H. - Ontario Hydro
2. H.Q. - Hydro-Québec
3. NBEPC - New Brunswick Electric Power Commission
4. M.H. - Manitoba Hydro

Table 2

CANADIAN HEAVY WATER PRODUCTION PLANTS

Plant	Plant Rating t D_2O/a	Owner	First Production
Port Hawkesbury	400	AECL[1]	1970
Bruce A	800	O.H.[2]	1973
Glace Bay	400	AECL	1976
Bruce B	800	O.H.	1979
Bruce D	800	O.H.	1981
La Prade	800	AECL	1981

1. O.H. - Ontario Hydro
2. AECL - Atomic Energy of Canada Limited

Table 3

TYPICAL NATURAL URANIUM REQUIREMENTS OF CANDU-PHW

Reactor Inventory	0.14 t U/MWe
Utilization at Equilibrium	174 ± 10% g/kWe. a

1000 MWe at 80% load factor requires 140 t natural uranium per year.

Table 4

SPENT FUEL CHARACTERISTICS

Burnup		7500 MWd/t
U^{235}	-	0.22%
Total Pu	-	0.38%
Fissile Pu	-	0.27%

Table 5[2]

AREA REQUIRED FOR STORING SPENT FUEL FROM CANADIAN REACTORS TO YEAR 2000 (125,000 t U*)

	Storage Area km^2	Total Site Area† km^2
Pool	0.11	2.36
Canister	1.4	5.76
Convection	0.21	2.79

* Based on installed capacity of 133,000 MWe at year 2000.

† Includes 600 m exclusion boundary.

Table 6

COMPARISON OF RETRIEVABLE STORAGE CONCEPTS*

	Capital $/kg U	Operating $/kg U	Shipping $/kg	Total	
				$/kg	mills/kWh†
Pools (Water)	1.95	2.34	3.19	7.48	0.12
Canisters (Air Cooled)	0.78	2.95	3.19	6.92	0.11
Convection Vaults (Air Cooled	0.87	1.76	3.19	5.82	0.09

* All costs in 1975 dollars.
† Electrical capacity.

Table 7

NATURAL URANIUM REQUIREMENTS FOR CANDU FUEL CYCLES

Fuel Cycle	Inventory* as t-Natural Uranium Equivalent†	Equilibrium Fuelling		Burnup per Cycle MWd/t h.e.
		g/kWe.a	t U/a†	
(1) Natural U — Once-Through	140	174	140	7,500
(2) Natural U — Pu Recycle	380-450	70-80	55-63	17,500
(3) Optimized Pu-Th Cycle	1500-1900	40	32	30,000
(4) Self-Sufficient Th Cycle	1600-2000	0	0	12,000

* Includes requirements for approach to equilibrium.
† Assumes 1000 MWe capacity at 80% load factor.

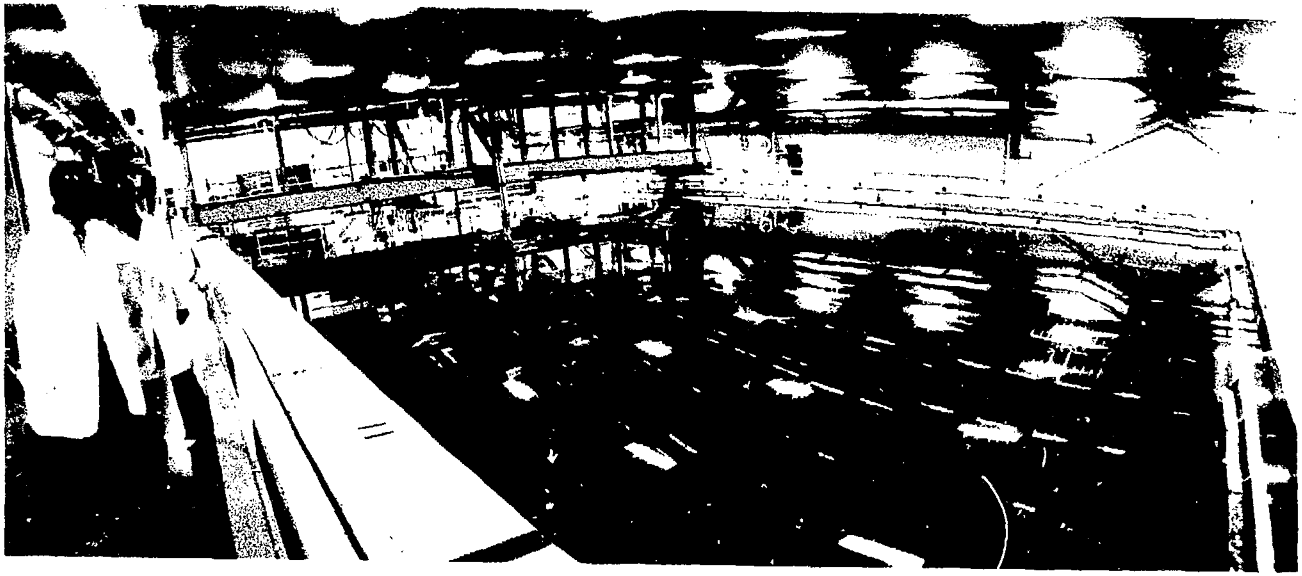


FIGURE 1

SPENT FUEL STORAGE BAY
PICKERING REACTOR

Courtesy T G&M

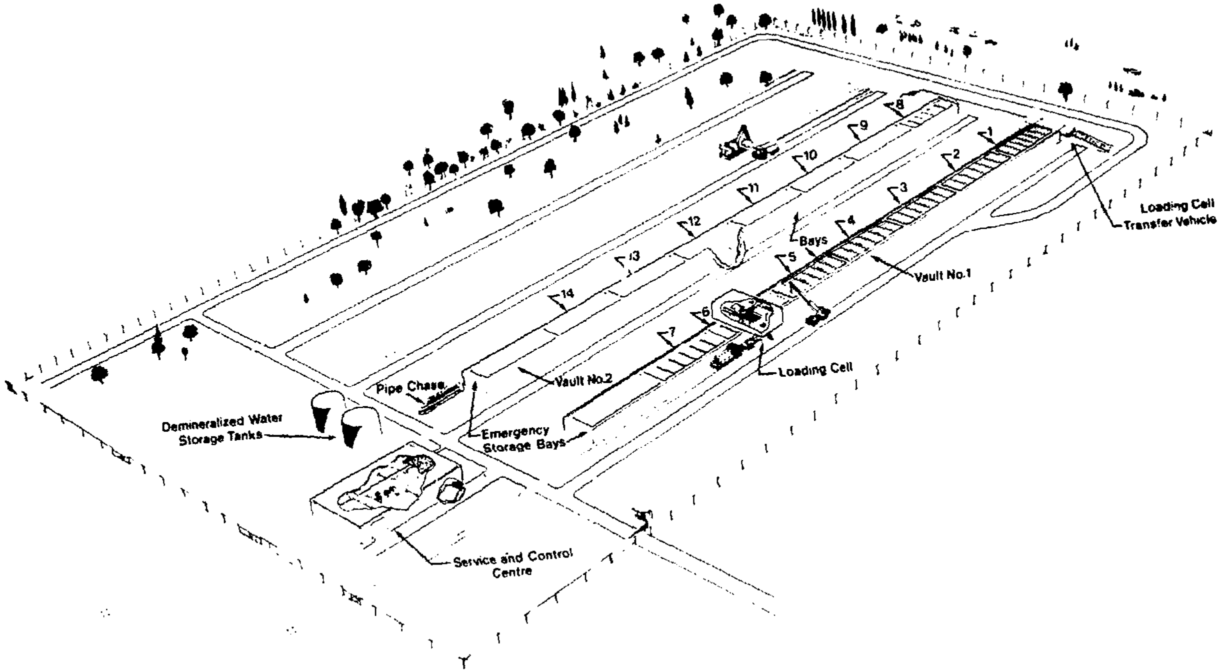
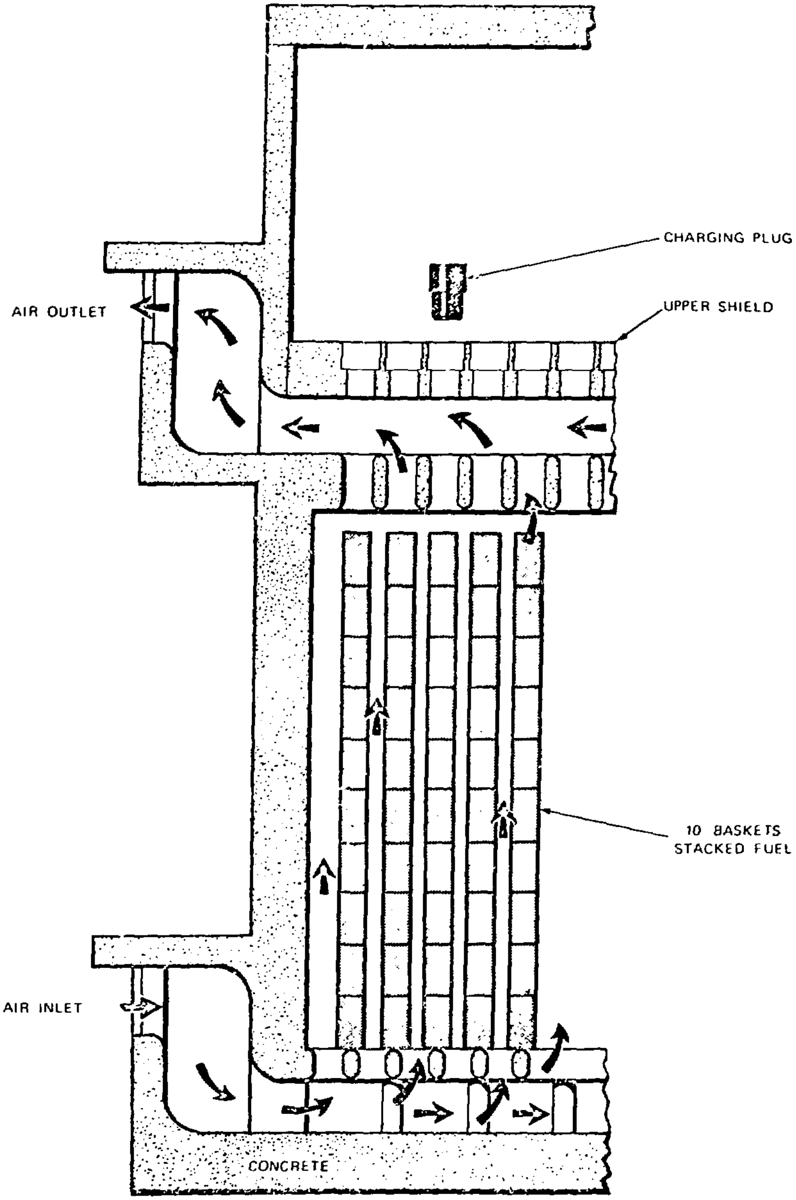


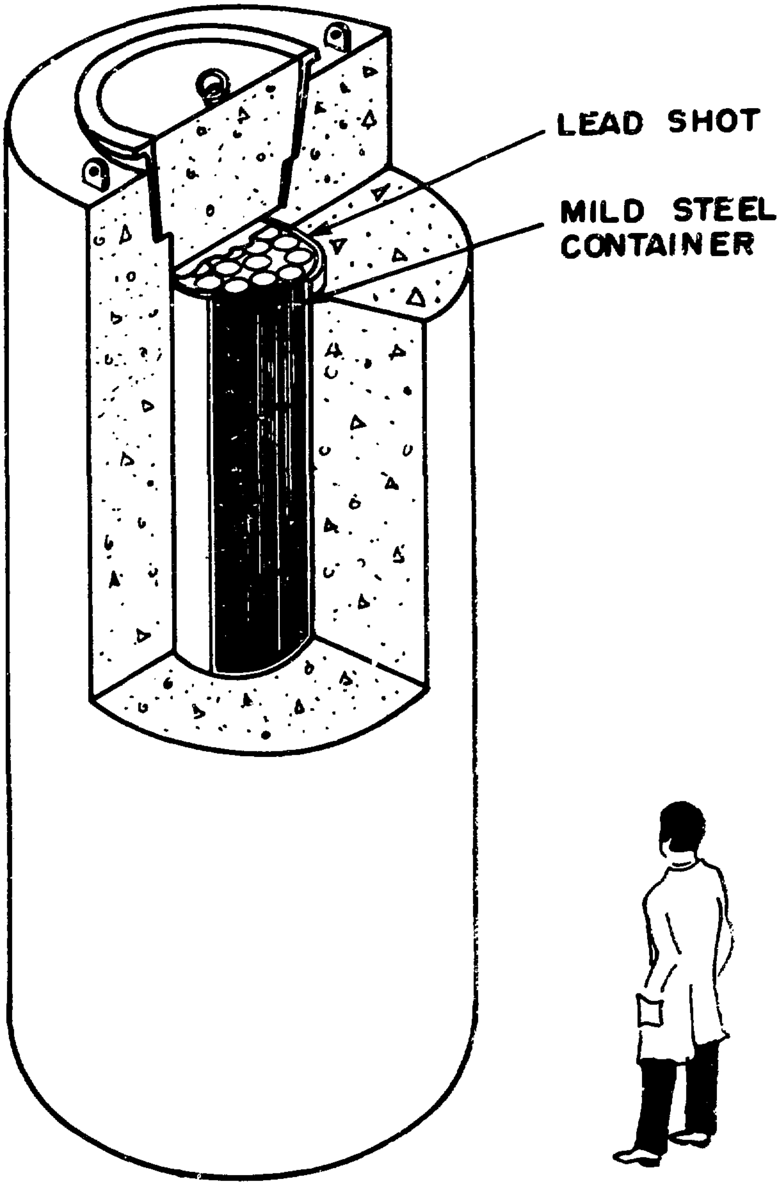
FIGURE 2

SPENT FUEL STORAGE FACILITY



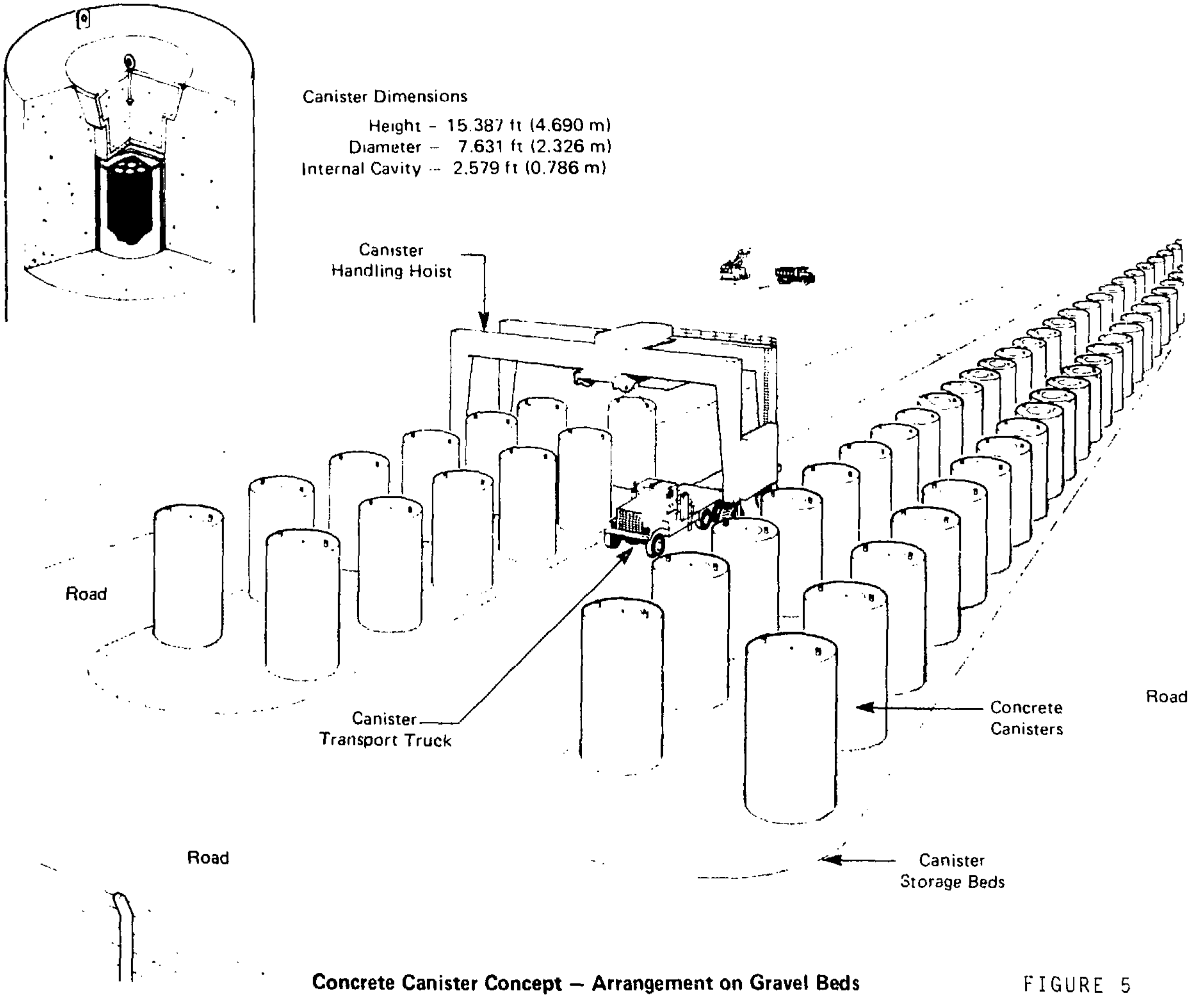
CENTRAL STORAGE FACILITY
CONVECTION VAULT

FIGURE 3



CONCRETE CANISTER

FIGURE 4



Concrete Canister Concept – Arrangement on Gravel Beds

FIGURE 5

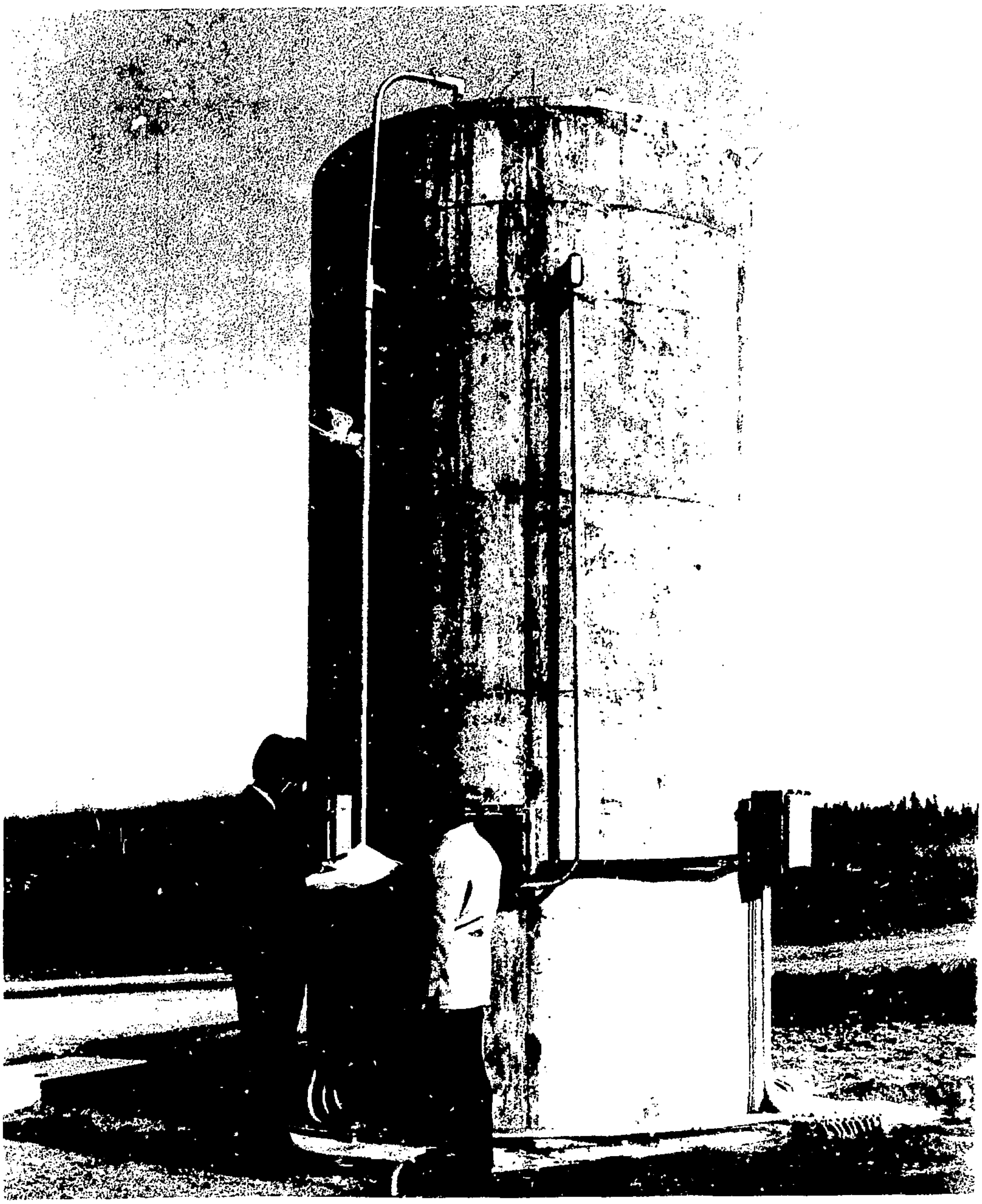


FIGURE 6

CONCRETE CANISTER UNDER TEST

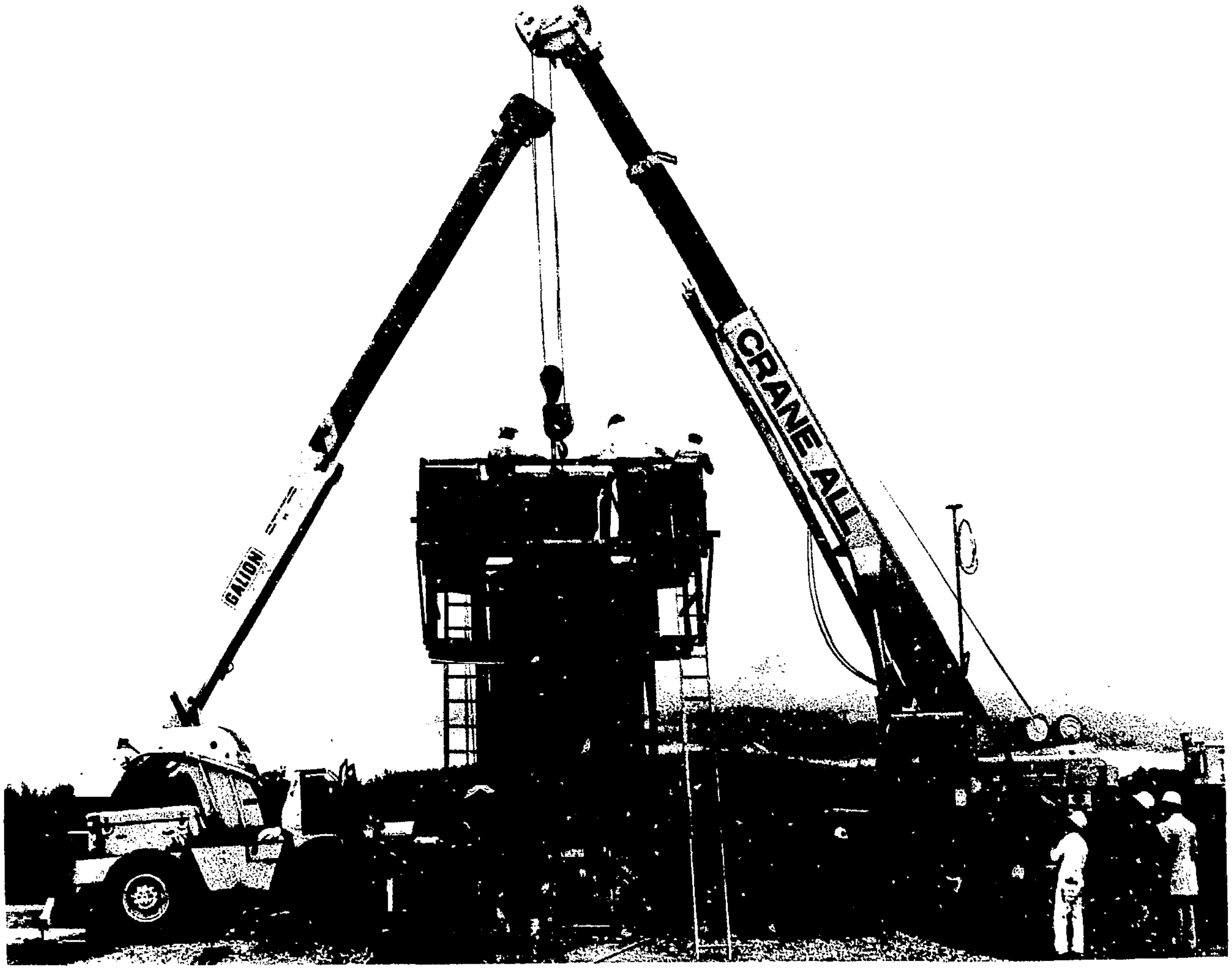


FIGURE 7 LOADING CONCRETE CANISTER WITH SPENT FUEL

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