NS-1 -

REVIEW OF NUCLEAR POWER GENERATION

Prepared By

B. H. Hamilton
Saskatchewan Power Corporation
Generation Design Division
July 21, 1972

Those Listed Below.

E. R. Smith,
Electric System,
July 26, 1972.

Attached is a copy of Bert Hamilton's report, "Review of Nuclear Power Generation".

The report presents the fundamentals of nuclear power generation and may be useful to those of us whose knowledge of nuclear power is minimal.

Chief Engineer, Electric System.

ERS/dyj
Attach.

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A. INTRODUCTION

This report is a summary of information obtained through the reading of a variety of articles on nuclear reactors and power plants. The report is meant to give the reader a general knowledge of nuclear power plants, beginning with basic principles and dealing with types of reactors, fuels, economics, pollution, availability, and finally a typical turbine cycle.

B. SALIENT POINTS

1. Principles of Nuclear Power

- Fission is the splitting of a nucleus of an atom to form two new nuclei.
- Fusion is the fusing together the nuclei of two atoms to form the nucleus of a new atom.
- Fissile material is material capable of a chain reaction. The three known fissile materials are U_{235}, U_{233}, and P_{U239}. Only U_{235} occurs naturally.
- Fertile material is material which can be converted to fissile material. The two known fertile materials are U_{238} and Th_{232}.
- Natural uranium is 0.7% U_{235} and 99.3% U_{238}. Only the U_{235} is capable of a chain reaction. The U_{238} can be converted to a material capable of a chain reaction (PU_{239}) in a reactor by bombardment with excess neutrons. Reactors which convert U_{238} to PU 235 are known as converters or breeders, depending on the amount of U_{238} converted.
- Thorium (Th_{232}) another fertile material can be converted to U_{233} in the same way as U_{238} is converted to PU_{239}.
- Breeder reactors convert more fertile material to fissile material than they consume.
- Thermal or slow reactors utilize a moderator to slow down the neutrons.
- Good moderators should absorb as few neutrons as possible and have low mass number.
- Fast reactors operate without slowing down the neutrons.
- Generally breeder reactors operate in the fast spectrum and converter reactors in the slow or thermal spectrum although this need not necessarily be so.
- Control rods control the rate of reaction by absorbing neutrons. Reducing the number of neutrons present reduces the rate of reaction.
- The major components of a reactor are:

  (i) core
  (ii) collant
  (iii) moderator
  (iv) control system

  The core contains an amount of fuel somewhat in excess of the "critical size" ie. the size required to sustain a chain reaction. The collant carries the heat from the core.

- Common collants are:

  (i) Light water
  (ii) Heavy water
  (iii) Carbon dioxide
  (iv) Helium

- Other collants in experimental use are:
  (i) Organies
  (ii) Liquid sodium

- The moderator is used to slow down the neutrons making a chain reaction possible. (Fast reactors operate without a moderator.) Common moderators are:

  (i) Heavy water
  (ii) Light water
  (iii) Carbon

- The control system controls the rate of reaction. Control rods, usually boron, are used to absorb neutrons. Insertion of the control rods into the core absorbs neutrons, slowing down or stopping the chain reaction.

2. Candu Reactors

- Utilize fuel efficiently due to the low neutron absorbing characteristics of the moderator.

- Are handicapped by low turbine efficiency due to low steam temperature.

- Successful use of organic cooling would increase turbine efficiency.

- Use natural uranium but also capable of using a variety of fuels.

- Low fuel cost - 0.68 mills/Kwh *

- Fuel burn up 9,300 Mw days (thermal) per ton uranium pellets.

- High capital costs (see Table No. 4.)

- Reports from Pickering are encouraging.

  (i) No. 1 Unit start up five and one half years after construction began.
  (ii) 1.5 to 2 pounds per day heavy water loss.
  (iii) On-load refuelling achieved on No. 1 Unit.
  (iv) Pertinent dates:

Phase	Dates No. 1	No. 2
Criticality	Feb. 25/71	Sept. 15/71
First steam	Mar. 16/71	Sept. 28/71
First electricity	April 30/71	Oct. 6/71
Full load	May 30/71	Nov. 7/71
Commercial operation	July 29/71	Dec. 30/71

  (v) Net Capacity Factor - No. 1 Unit 79% (July 29 to Dec. 30)
  No. 2 Unit 88% (Nov. 7 to Dec. 30)

* Reference #1

3. Light Water Reactors

- U. S. nuclear power plants almost exclusively light water.
- Use approximately 3% enriched uranium.
- Excess capacity of gaseous diffusion plants, developed for military purposes, used to enrich the uranium.
- Fuel costs 1.8 mills/Kwh, approximately 3 times that of heavy water plants. *
- Burn up 27,000 Mw days (thermal per ton uranium.
- Lower capital costs than heavy water plants (See Table No. 4)

4. Gas Cooled Reactors

- Recent developments seem to be towards high temperature gas cooled reactors.
- Allows the use of high temperature, high pressure turbines hence better cycle efficiencies.
- Are potentially "near breeders."
- Opens the door to utilization of an inert gas, closed cycle turbine and atmospheric heat rejection.
- The U. S. and Britain are building commercial sized high temperature gas cooled reactors. None are in service as yet.

5. Fuel

- Uranium dioxide is the most commonly used fuel. It is a compromise fuel as its fissile concentration and thermal conductivity is lower than some other fuels, however, it has a high melting point, (2800°C) and is dimensionally stable up to temperatures near its melting point.
- Natural uranium costs $10.66 per pound or 4¢ per million BTU **
- 3.0% enriched uranium costs $115.59 per pound of 11¢ per million BTU. **
- Spent fuel contains sufficient plutonium and unused uranium that reprocessing is economically and technically feasible.

6. Economics of Nuclear Plants

- 1969 Canadian Capital Cost Comparison ***
  (For 4 Unit, 2,000 MW Plant)

Type	/KW (Net)
Nuclear	302 (Based on Pickering - up to date cost $345/Kw) ****
Coal	146

* Reference #1
** Reference #3
*** Reference #5
**** Reference #6

6. Economics of Nuclear Plants (Cont'd.)

Type	/Kw (Net)
Oil	142

- 1978 Capital Cost Comparison *

Coolant Type	$/Kw
Heavy Water	477
Light Water	368
Gas Cooled	405

- Fuelling cost for heavy water plant - 0.71 mills/Kwh *

- Fuelling cost for light water plant - 1.8 mills/Kwh *

- A 1969 Canadian total unit energy cost was nuclear - 4.85 mills/Kwh, Coal, 5.17 mills/Kwh, and Oil 5.02 mills/Kwh. (Based on 80% capacity factor, 35¢ coal and 34¢ oil.)

- The break even point between a light water nuclear plant and a conventional plant in the United States is 50¢ gas, 45¢ oil and 30¢ coal. **

- A.E.C.L. have estimated a 600 Mw Candu - Phw plant on Vancouver Island would have a total unit energy cost of 6.75 mills/Kwh. An equivalent cost for a gas fired plant on 65¢ gas would be 9.1 mills/Kwh. *** This amounts to a break even point between a nuclear and gas fired plant at about 40¢/10^6BTU gas.

7. Pollution

- There are basically four types of pollution from a nuclear reactor.

  (i) Emission of radiation at the facility
  (ii) Thermal discharge
  (iii) Radioactive wastes
  (iv) Radiation bearing clouds due to accidents

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* Reference #7
** Reference #1
*** Reference #5
**** Reference #8

C. PRINCIPLES OF NUCLEAR POWER

1. Fission and Fusion

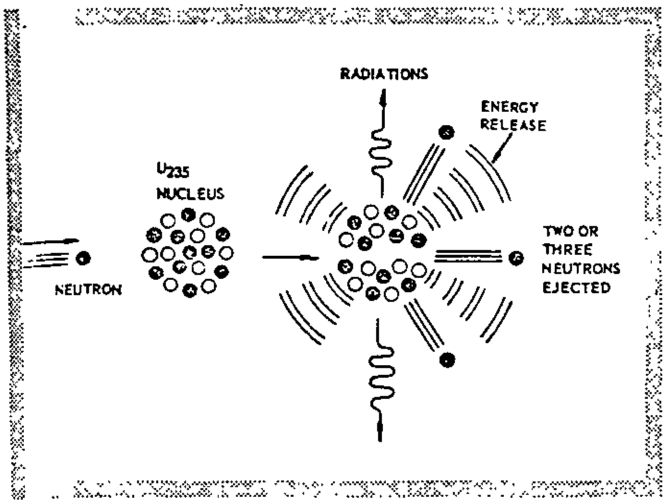
In 1939, Hahn and Strassnan were subjecting various elements to neutron bombardment with the object of producing isotopes of those elements. They discovered that when the nucleus of a U_{235} atom was hit by a neutron two elements, krypton and barium, were formed, a quantity of energy was released, and two or three neutrons were also released from the nucleus. Figure 1 illustrates this reaction diagramatically. The U_{235} nucleus hit by a neutron, fissions or splits into two smaller nuclei. These smaller nuclei are generally termed "fission products", since they are the direct result of a fission of the nucleus. In addition, energy, two or three neutrons and radiation is released when the nucleus is split. The splitting of a nucleus as described above has not been experienced for any naturally occurring element other than uranium. Note: even natural uranium contains only 0.71% of the fissionable isotope U_{235}. The remainder is the isotope U_{238}, which is not fissionable.

The most significant fact arising from the fission of the U_{235}, apart from the release of binding energy, is that one neutron hitting the nucleus not only releases energy, but also provides a source of two or three new neutrons which, in favourable circumstances, could cause fission reaction with other U_{235} nuclei. If such a continuous reaction could be controlled, it would result in a continuous release of energy at a steady rate, the rate depending on the number of fissions occurring in a particular time. A reaction of this kind is known as a "chain reaction".

The fusion of the nuclei of a light element to form a heavy element cannot be achieved as easily, in a relative sense, as the fission U_{235}. Work in this field is still progressing. The basic principle of nuclear

Fig No. 1

Fission of a Nucleus



1. Fission and Fusion (Cont'd.)

fusion is illustrated in Figure 2. Two heavy hydrogen nuclei containing one proton and one neutron each, are fused to form a helium nucleus and a neutron. The average binding energy per nucleon of heavy hydrogen is less than that associated with the helium isotope.

The continuous release of energy by nuclear fusion has not yet been achieved. Two atoms of heavy hydrogen must travel at enormous speeds to enable their nucleii to fuse together and form helium. One method of speeding up the atoms is to raise their temperature, but this requires temperatures of several million degrees (far hotter than the sun). The passing of a large electrical current through heavy hydrogen gas contained in a tube seems to be the most promising way of achieving these conditions. The main difficulty in this method is that of maintaining the temperature for a sufficient time for a fusion reaction to take place. A practical difficulty is the containment of the very high temperature gas.

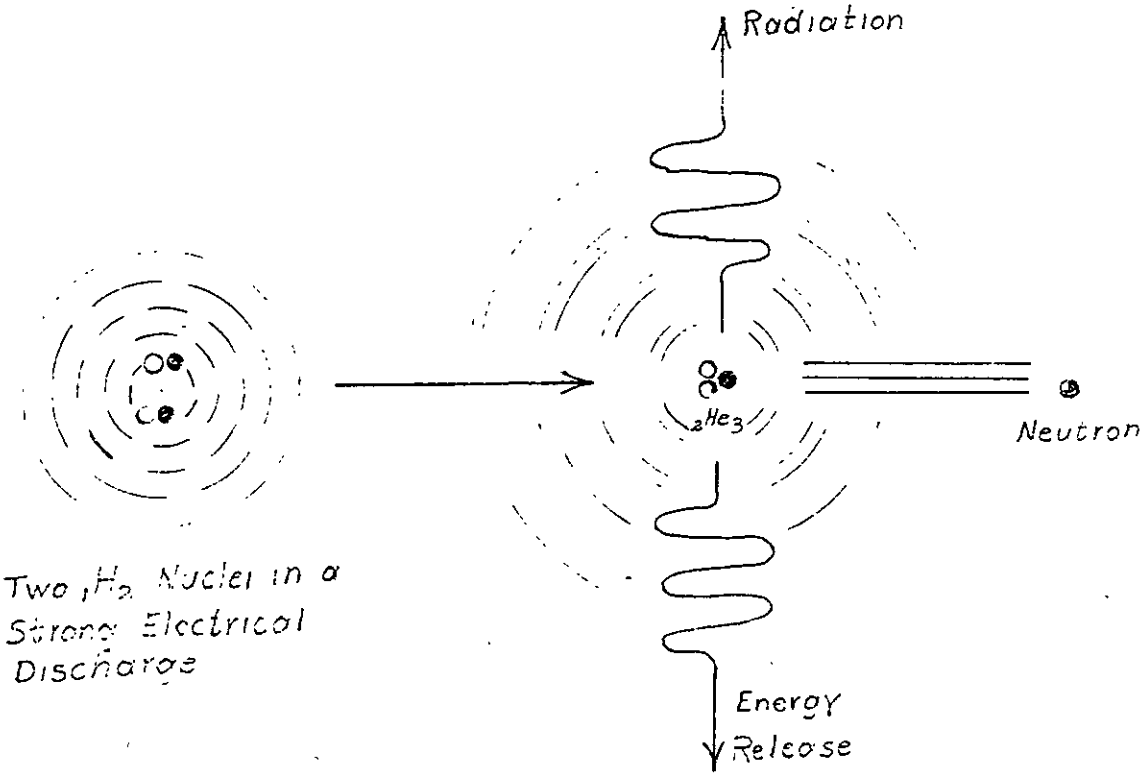
The advantage of the fusion reaction as a source of energy, and one which justifies elaborate and costly research program, is that the fuel that is used comes from ordinary water. Heavy hydrogen is an isotope of hydrogen and the isotope is found in proportions of about one in every 6,000 hydrogen atoms. Heavy hydrogen can be separated at relatively low cost per gram and is available in almost inexhaustible quantity.

2. Fast and Thermal Neutrons

The neutrons emitted as a result of the fission emerge at a very high speed and have a corresponding high kenetic energy. These neutrons are called fast neutrons. Only three elements are known which will undergo a fission reaction with fast neutrons and maintain a chain reaction. They

Fig. No. 3

Fusion of Deuterium



are U_{235}, U_{233}, and Pu_{239} (plutonium 239). U_{233} and Pu_{239} do not occur naturally but are produced as the result of neutron capture in a reactor.

U_{238} atoms, which represent the greatest portion of natural uranium, unfortunately absorb fairly fast neutrons to such an extent that those produced by a fission reaction would be absorbed before reaching a U_{235} nucleus and so producing another fission. Thus, a reactor depending on fast neutrons for the fission of U_{235} would have to be fueled with almost 100% U_{235}. Separation of the U_{235} isotope from the natural uranium is achieved by gaseous diffusion, a very costly process.

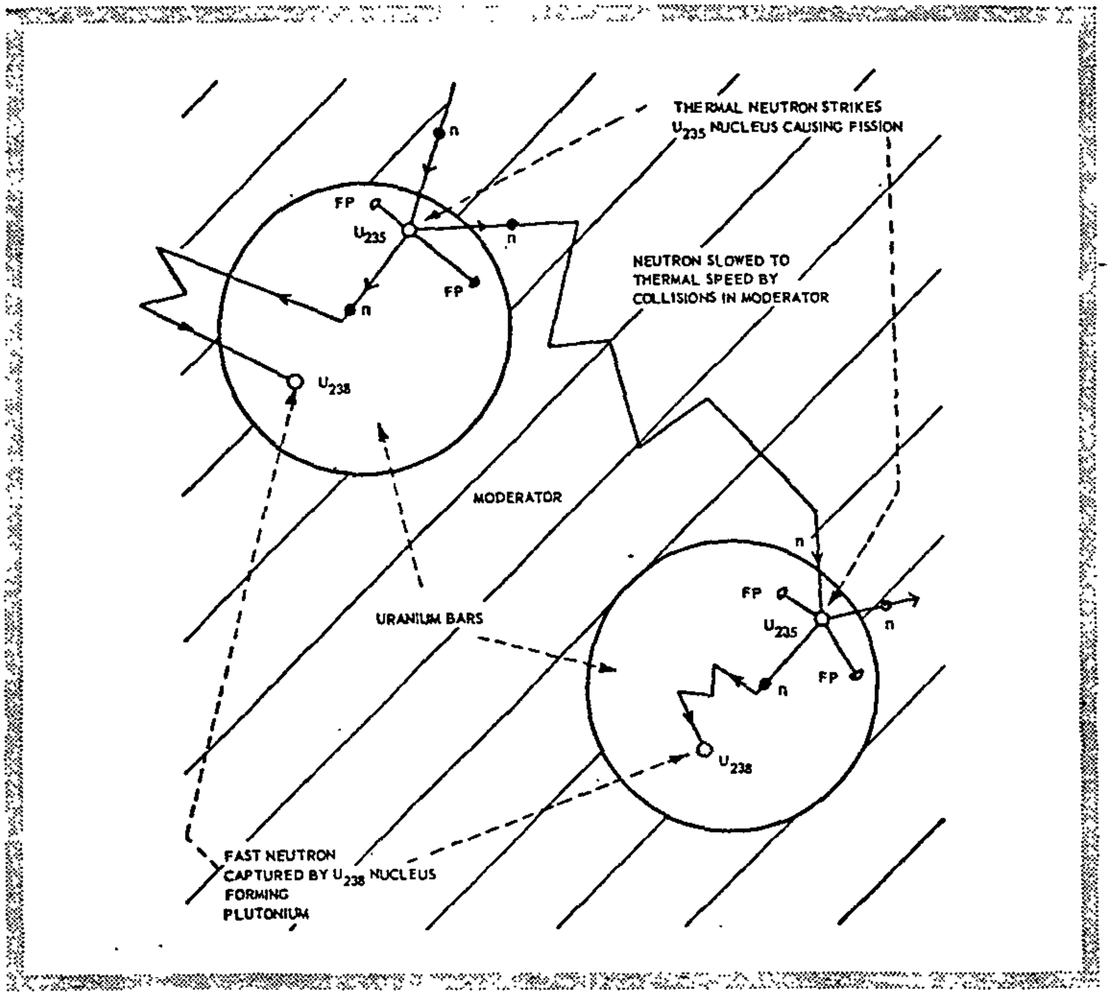
The nucleus of the U_{235} atom, however, can be fissioned by a neutron with a much lower energy than that of the fast neutron. Also, the absorption properties of U_{238} are much reduced where slow or "thermal neutrons" are used. Hence, if natural uranium is bombarded by thermal neutrons, the U_{235} can undergo a fission reaction without incurring cost of separation of the U_{235} isotope. A reactor dependant on thermal neutrons for producing a fission reaction is called a thermal reactor.

A thermal neutron is so called because it has been slowed down to about the speed at which gas molecules move when they are in thermal equilibrium with each other. To illustrate how a fast neutron is slowed down to thermal energies the reader should imagine a neutron rushing at the lattice of the atomic structure of the material. As the neutron hits this lattice some of its momentum will be lost. Some of the energy of the neutron will be imparted to the material which has been used to slow down the speed of the neutron. Elements with good slowing down properties are known as "moderators". Figure 3 shows diagramatically the use of the moderator.

A good moderator must have a low atomic number and should absorb as few neutrons as possible. From this it could be concluded that hydrogen

Fig. No. 3

Diag. of the use of a Moderator



2. Fast and Thermal Neutrons (Cont'd.)

should be used for this purpose. Theoretically, this is true, but hydrogen is a gas and the required densities cannot be obtained. Deuterium, also a gas, presents the same problem and is costly to produce. Light water (H_2O) and heavy water (D_2O) are good moderators. Light water unfortunately has an affinity for neutrons and absorbs them much more readily than heavy water which, on the other hand, is far more costly to produce.

Table 1 shows some examples of moderating properties of elements and compounds. Beryllium has good properties as a moderator and has low neutron absorption properties, but it is very costly to produce and difficult to work with, because of its toxidity. Carbon does not possess moderating properties as good as those of hydrogen and deuteim, but since it can be manufactured in solid state as graphite, and also because it has relatively low absorption properties for neutrons, it is considered to be a suitable material as a moderator in thermal reactors.

3. Divergence and Control

To produce a continuous supply of energy from the nuclear fuels such as natural uranium it is necessary to insure that there are always neutrons present which can cause further fission reaction. A single fission reaction produces one or more free neutrons and these neutrons can then cause other fission reactions, so establishing a continuous reaction called a chain reaction. If such a chain reaction occurred at an uncontrolled rate it would produce an atomic bomb. This is known as a divergent reaction and is illustrated in Figure 4. If the reaction is controlled and only one neutron is available for fission as a result of a previous fission reaction then the required system of constant heat output is maintained, and a power reactor is established. The output of the reactor depends on the number of fission reactions which occur simultaneously.

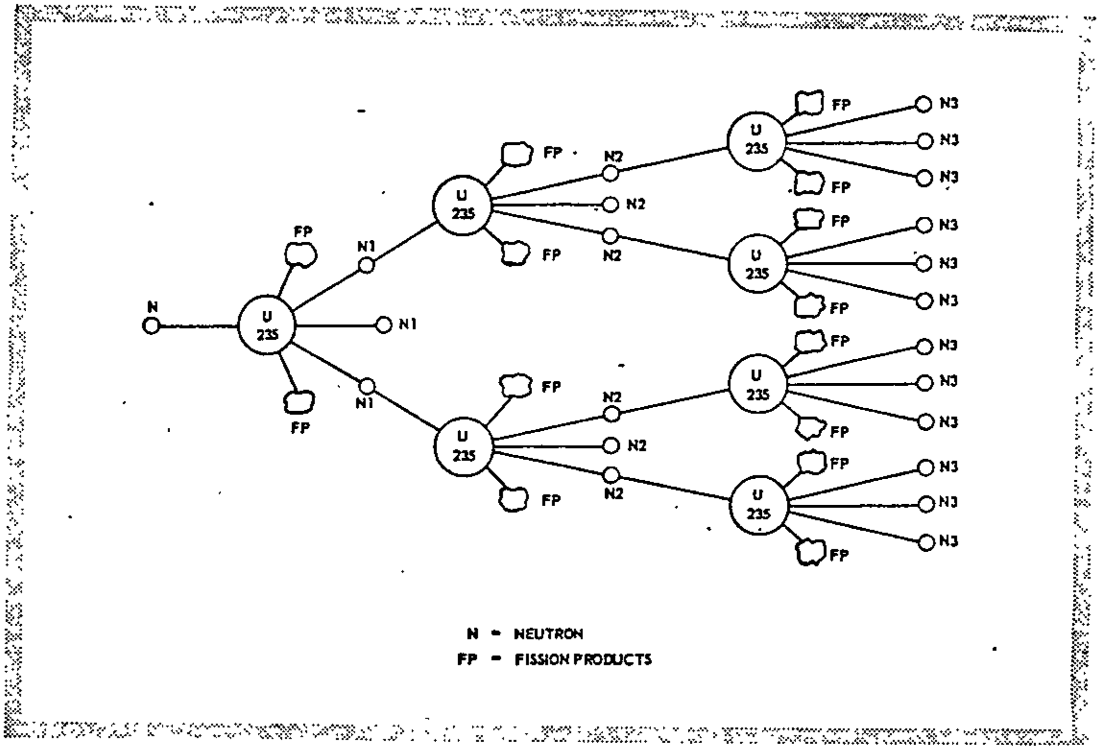
Table No. I

Table of moderating properties of elements and compounds

Element	Atomic or Molecular Weight	Logarithmic Energy Decrement per Collision ξ	Number of Collisions to Thermalise a fission Neutron	Thermal Neutron Absorption Cross-Section in Barns
Hydrogen	1	1	18	0.33
Deuterium	2	0.725	25	0.5×10^{-3}
Helium	4	0.425	43	0
Lithium	7	0.268	68	71
Beryllium	9	0.209	87	10×10^{-3}
Boron	11	0.171	106	755
Carbon	12	0.158	115	3×10^{-3}
Nitrogen	14	0.137	133	1.9
Oxygen	16	0.120	152	Very Small
Light Water	18	0.927	20	0.66
Heavy Water	20	0.510	36	0.92×10^{-3}
Beryllium Oxide	25	0.174	105	9.2×10^{-3}

Fig. No. 4

A Divergent Chain Reaction



3. Divergence and Control (Cont'd.)

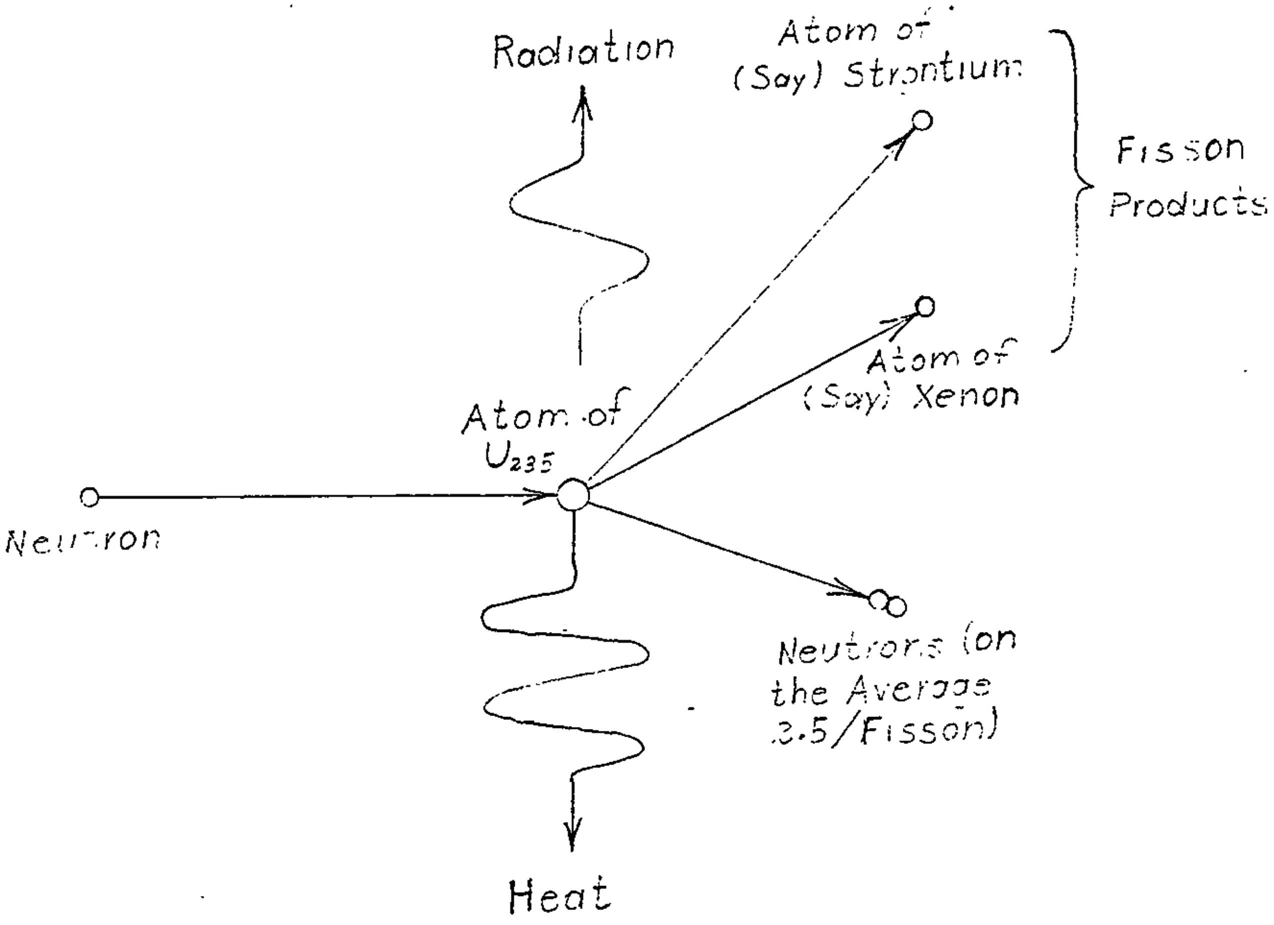
On average, a fission reaction between a neutron and a U_{235} nucleus emits 2.5 neutrons. Figure 5 illustrates this process and names two fission products which may be produced as a result of the reaction. Some of the neutrons are unavoidably absorbed by the various materials, for example a moderator, fuel canning materials, or the U_{238}. But if the reactor is designed in such a way that only one neutron is made available for each fission to sustain the chain reaction, the required conditions will have been achieved.

In a nuclear reactor the starting of a chain reaction for the production of energy in the form of heat depends on the presence of a thermal neutron. This neutron must be able to produce sufficient reaction in the favourable conditions under which a chain reaction can be maintained. It has previously been stated that a fission reaction releases, on average, 2.5 neutrons, and that some of these neutrons may be lost through absorption in the reactor materials or by escaping from the reactor core. To maintain a chain reaction the probability of a thermal neutron causing fission must be a certainty. This can only be realized when there is a certain minimum amount of fuel in the reactor core, and this is termed "critical size". With amounts of fuel less than the critical amount so many neutrons escape that the number of fissions occurring from the second generation of neutrons is very much less than the first, and the reaction dies out. In practice, a reactor is designed so that it contains more than the critical amount of fuel so that the required power level can be obtained and maintained.

A reactor is built up to critical size in stages. Fuel elements are placed in the core, starting at the centre, a close watch being kept on the neutron detecting instrument. Initially, the loading of fuel can be done

Fig. No. 5

Fisson of an Atom of U_{235}



quickly, but as the calculated critical size is approached, the loading is slowed down and the instruments are carefully watched to ascertain whether a growth in neutron population is occurring. The indication that critical size has been reached is when the rate of production of neutron population remains at a constant value or, in other words, a chain reaction is established. When this condition is established the control rods are lowered into the core to absorb the neutrons being produced. This "shuts down" the reactor, and loading continues till final design size or full size, has been completed.

The completed reactor is made critical by withdrawing the control rods, thus enabling the chain reaction to establish again. The movement of the control rods controls the output of the reactor.

4. The Breeder Reaction

There is another characteristic of the fission process, one of upmost significance with respect to extending our fuel supplies and reducing the energy cost. You will recall that when one bombards a U_{235} atom with a neutron, the resulting process produces fission products chemically different from the uranium, abundant amounts of energy, and two or three additional neutrons. These neutrons are essential to maintain the chain reaction by bombarding other U_{235} atoms. However, under proper circumstances, one of the neutrons can be utilized to produce this reaction.

$$U_{238} + \text{Neutron} = U_{239} + \text{Time} = Np_{239} + \text{Time} = Pu_{239}$$

The important things to note are: (a) starting product is U_{238}, different from U_{235} in that it is not readily fissionable but is 140 times more abundant, (b) end product is plutonium (Pu_{239}), a new element, (c) Plutonium is fissionable and like U_{235} produces large amounts of energy upon fissioning.

4. The Breeder Reaction (Cont'd.)

Now, if the fission reaction is conducted in a manner so that one or more of the neutrons can be used in the reaction depicted in the equation, there will be generated one or more atoms of plutonium fuel for each U_{235} atom burned and we have a breeder.

The importance of the breeding reaction is that it extends the supply of fuel by 140 times and reduces costs of heat energy produced. A similar reaction enables one to produce fissionable U_{233} fuel from thorium, which again extends the fuel supply by several hundred times.

5. Putting the Energy to Work

Now let's examine briefly the means of controlling and utilizing the tremendous amount of energy generated through the fission process, and its utilization for the production of electrical energy. At present, the most practical method of utilizing the major portion of energy of fission is as heat. The reactor is basically a nuclear furnace in which a self-sustaining chain reaction takes place under controlled conditions. Such a reactor is schematically illustrated in Figure 6.

This simplified diagram shows major components in a typical water cooled reactor. Its principal parts are:

(a) The reactor core containing some minimum amount of fuel.

(b) A coolant such as water to transfer the heat from the reactor core to the steam boiler.

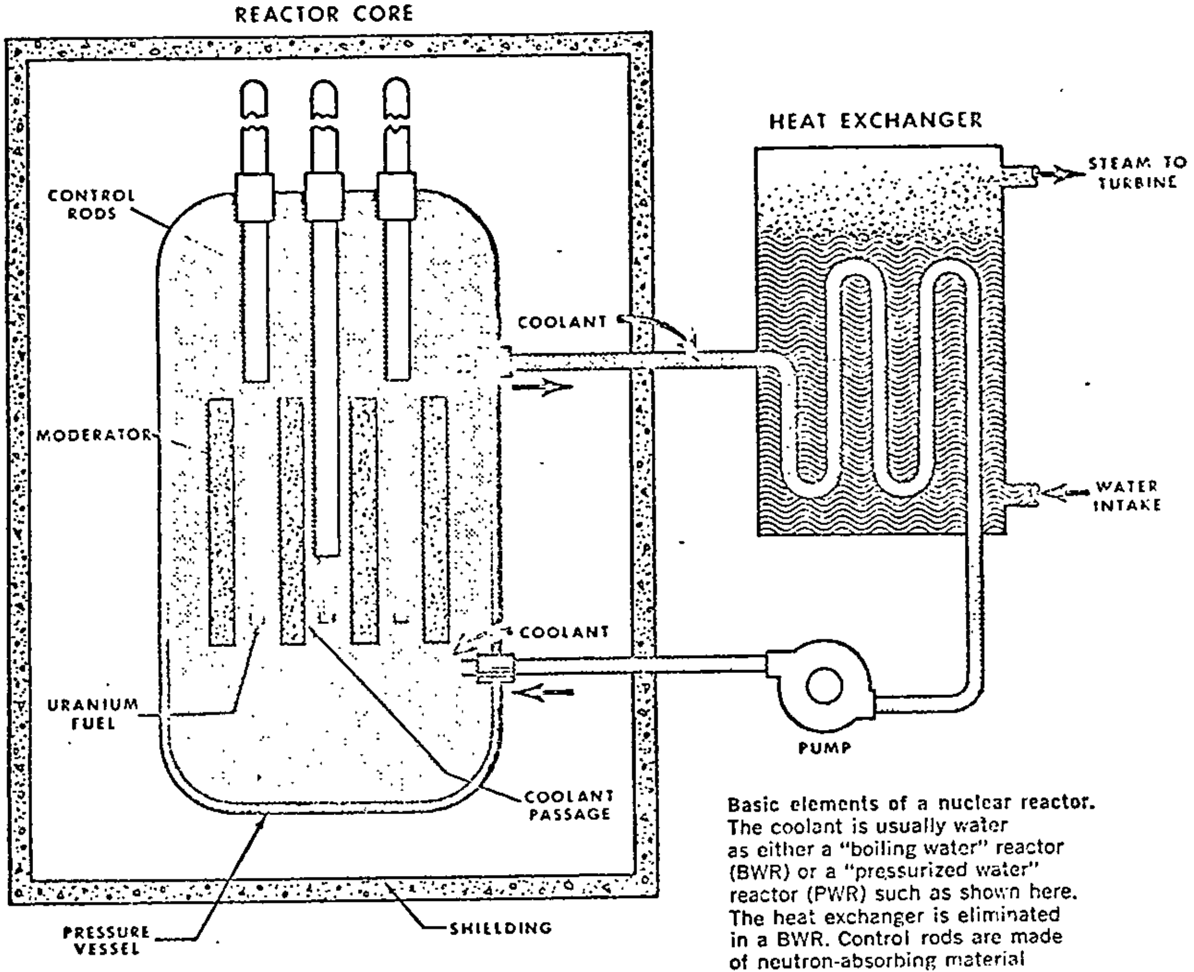
(c) Usually a moderator to slow down the neutrons.

(d) A control system to regulate the heat generation.

Reactors are controlled by moving neutron absorbing material in or out of the core. When in the core, these rods absorb neutrons released during the fissioning process, thus reducing the number to sustain a chain reaction. This reduces the number of fissions and hence the amount of heat generated.

A paper is attached describing the Sequoyah nuclear plant in some

Fig. No. 2



Basic elements of a nuclear reactor. The coolant is usually water as either a "boiling water" reactor (BWR) or a "pressurized water" reactor (PWR) such as shown here. The heat exchanger is eliminated in a BWR. Control rods are made of neutron-absorbing material By their position, they absorb varying numbers of neutrons, varying the sustenance of the chain reactor and, hence, the heat generated.

detail. A pressurized light water reactor is utilized.

D. TYPES OF REACTORS

1. Heavy Water Reactors

The heavy water moderated reactors in use today, because of their low neutron absorption, efficiently utilize natural uranium. In this area, AECL's Candu designs have won recognition. Fuel is natural UO_2 in zircoloy pressure tubes cooled by heavy water.

At design burn up of 9,300 megawatt days (thermal) per ton uranium and 29.1% station efficiency, the fuelling cost is a maximum 0.68 * mills per kilowatt hour. In contrast, U. S. nuclear stations coming on the line will incur fuel costs of at least 1.8 * mills per kilowatt hour. Most of the differential is due to the nature of the beast. Light water moderators and coolants absorb neutrons reducing fuel efficiency and fabricating a 2.9% enriched uranium oxide fuel element to compensate for the loss of reactivity adds more to the cost.

The natural uranium, zirconium alloy clad multi-element fuel that appears to be serving the Candu reactor well today should evolve over the next period of time. In order to obtain more power per channel, the fuel will operate at higher temperature ratings and will be further subdivided. At the same time, Chalk River metallurgists are working with uranium silicide, a fuel with a higher uranium density that could cut costs another 0.05 to 0.10 mills per kilowatt hour.

The silicide in water corrodes and swells, but it seems possible to overcome these problems. Full sized bundle irradiation and burn up in excess of 12 megawatt days per kilogram uranium at adequately high temperature ratings have been experienced. The fuel may be ready for full commercial use in the Gentilly reactor sometime after 1972.

* Reference #1

1. Heavy Water Reactors (Cont'd.)

The versatility of the Candu is such that other fuels can be accepted in the channels. Because of the growing inventory of plutonium in spent fuel, its use as a recycled material is under development. Consideration is being given to both the homogenized and spike type of fuelling. Future booster rods used for overcoming xenon poisoning will probably be made up of plutonim rather than enriched uranium.

The Candu reactor it would seem, will survive the competition from light water reactors because of its edge in fuel costs (an edge that will widen with time) and a greater convergence of capital costs.

One unanswered question is whether the Candu reactor must always suffer the handicap of being a water cooled reactor with an inherently low thermal efficiency. The Bruce station, for instance, will have a net thermal efficiency of 29.8% and the best that AECL can hope for in the early 1980's is the maximum of 32%.

The alternative is to go to a coolant like the organic terphenyls used at Whiteshell. Organics provide high temperature at low pressure and AECL has already postulated a steam cycle in which it is practical to obtain a gross efficiency of 44% from 2,500 psi steam at 750°F. The top temperature of the organic fluid need only be about 770°F provided extra circuits are added to the reheaters.

The Candu boiling light water prototype reactor that AECL built at Gentilly in collaboration with Hydro-Quebec is the first step away from having to worry about heavy water management. The designers have chosen to compromise neutron efficiency (by introducing ordinary water in coolant channels) in order to make possible direct cycle operation, eliminate tritium problems and open the door to superheat.

1. Heavy Water Reactors (Cont'd.)

The development problem associated with boiling light water is that of heat transfer in a two phase regime, (steam and water). Gentilly was designed for an average outlet quality of 16% steam, a conservative rating in view of burn out and dry out tests already conducted.

Gentilly will probably be operated at a 25% steam outlet quality and some channels may be taken to 40%, which is considered an optimum exit quality for large boiling water reactors.

2. Light Water Reactors

The U. S. is well along with a massive expansion program based almost entirely on light water reactors. As of December 23, 1971 the Americans had 118 reactors of 175 megawatts or over either operable, under construction, or on order. Of these 118 reactors 42 were boiling light water, 75 pressurized light water and one high temperature gas reactor. These were a logical choice because of the ample supply of enriched uranium from three gaseous diffusion plants operating at reduced capacity.

The fuel used in the light water reactors requires 2.8 to 2.9% enrichment of UO_2 and is expected to achieve an average burn up of 27,000 megawatt days (thermal) per ton of uranium.

3. Gas Cooled Reactors

In Britain all but a few experimental nuclear plants use the carbon dioxide cooled, graphite moderated cycle with magnox clad natural uranium as a fuel. This cycle was adopted originally as about the only one possible under international trade restrictions of early post war years, not because it promised low cost energy.

Emphasis in Britain is shifting to advanced gas cooled reactors. This design, like the earlier series, uses CO_2 for cooling and a graphite moderator. But fuel will be stainless steel clad 1.4 to 1.67% enriched UO_2

for a burn up of 18,000 megawatt days (thermal) per ton compared with 3,000 to 4,000 megawatt days per ton for the magnox plants. Steam conditions will be 2,300 psig, 1,050°F to drive a conventional turbine generator.

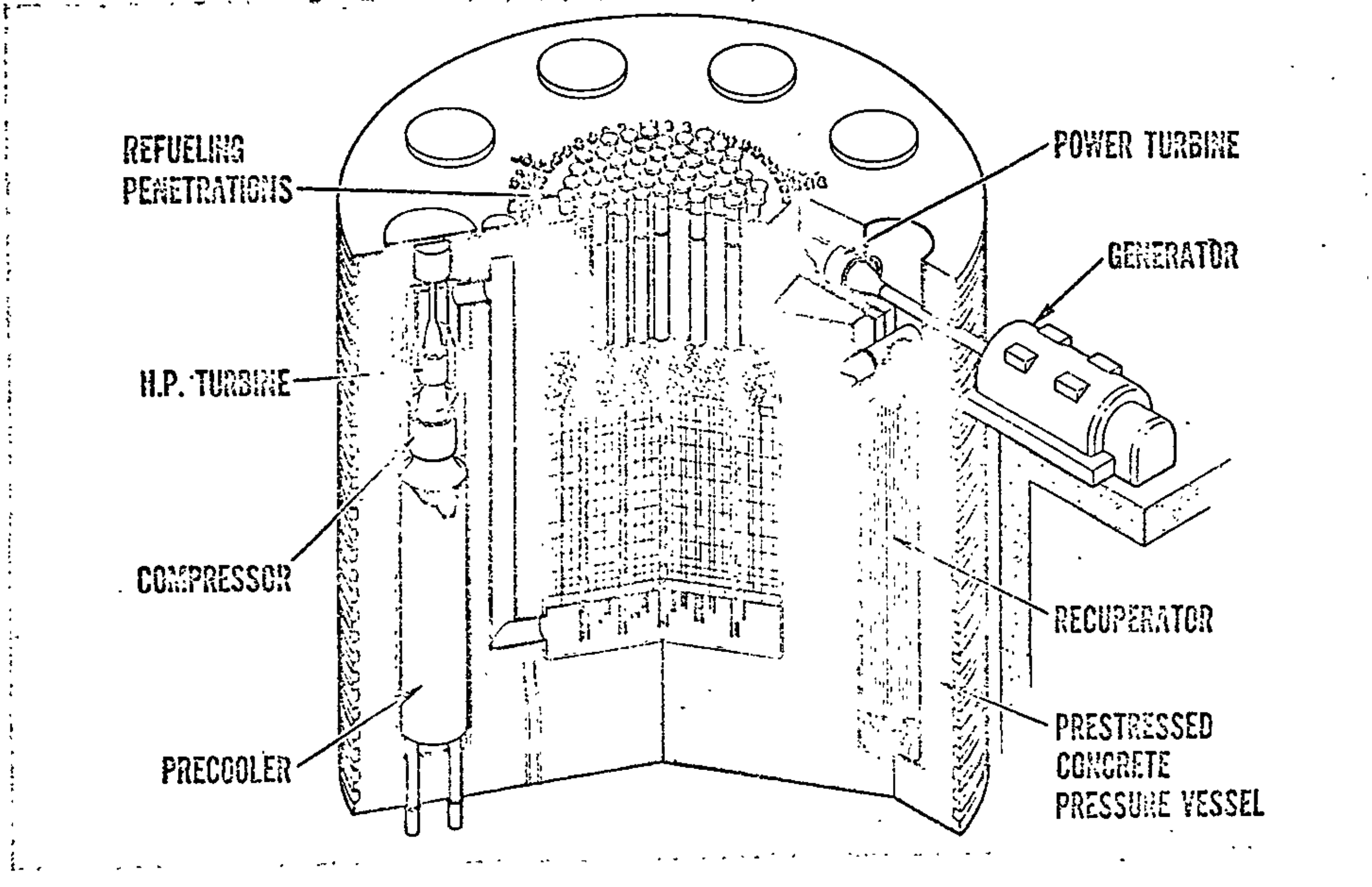
High temperature gas cooled reactors not only offer better thermal efficiencies but are potentially "near breeders". That is they have the capability of producing almost as much fissile material as they consume. This could greatly stretch out the usefulness of available fuel, without however, having to carry the high fissile fuel inventory of the true fast breeders. This later feature arises because the relatively dilute fuel of the high temperature gas reactor can be run at around twice the fissile rating typical of the fast breeder reactors.

There is every liklihood that high temperature gas reactors, particularly in association with closed cycle turbines, operating on inert gas will make much cheaper, more reliable, and certainly more easily operated and repaired power plants, which are also substantially free from sitting restrictions imposed both by safety and environmental restrictions. They could also produce more power from a given total national fissile inventory than could fast breeders alone.

The scope for further high temperature gas reactor plant cost reduction offered by the successful development of an associated inert gas, closed cycle, turbine is already discernible from preliminary studies, which indicate the possibility of quite spectacular reduction in plant bulk and complexity. (See Figure 7.) While it is too early to translate this into precise figures, it can be said that expectations for some further 15% total plant cost reduction initially, together with an attractive reward for later development of higher temperatures, is growing out of these studies.

An additional merit of the inert gas, closed cycle turbine is that, as a result of the high mean temperature of rejected heat, such a plant is readily adaptable to dry air cooling. Preliminary high temperature gas reactor

Fig. No. 7



Cutaway drawing of GGA 1,000-MWe gas turbine reactor

3. Gas Cooled Reactors (Cont'd.)

plant studies indicate that applying dry cooling to gas turbines costs some $25 per kilowatt less than applying it to the equivalent steam plant. Thus as the insistent pressure of environmental considerations and growing scarcity of suitable plant sites increasingly demand atmospheric heat rejection, so they further favor the gas turbine. Such plants, however, can only be effectively realized with the aid of the high temperature and direct heating facility provided by the inert gas coolant of the high temperature gas reactor.

As of December 1971 only one commercial sized high temperature gas reactor was on order in the United States. None were operating. The one unit was a three hundred and thirty megawatt unit for Fort St. Vrain built by Gulf General Atomic. It will operate with a net thermal efficiency of 39% from 2400 psig/1000°F/1000°F steam. The coolant will be helium and the moderator graphite. The expected fuel cost is 1.7 mills/Kwh and the total energy cost 5.9 mills/Kwh * this unit is scheduled to go into operation in 1972. An anouncement has since been made that Gulf received an order from Philadelphia Electric for a two unit station each unit being 1,160 megawatts. The larger units will use essentially the same cycle as employed at Fort St. Vrain. A two-page article dealing with the Philadelphia Electric Units entitled "Persistence Rewarded" is attached.

Recently a rather disturbing article on the British gas cooled reator was headlined "Corrosion Hits HTR's." The article went on to say that the laboratory tests had shown that corrosion might possibly occur in boilers of the advanced gas cooled reactor stations before the design life of 25

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* Reference #2

years was completed. The results could be that the first of the four high temperature gas reactor stations now being built in Britain will be operated at slightly below their normal rating.

4. Breeder Reactors

The breeder reactor as the name implies is capable of producing more fissile material than it consumes. Their use, in the right proportion not only allows fuller use of world fuel resources, but specifically improves the potential of the high temperature gas reactor by uniquely making their desirable starting fuel available.

Two types of breeding cycles are possible - a plutonium and a thorium cycle. Breeding with a plutonium cycle is only possible in a fast neutron spectrum whereas with the thorium cycle breeding is possible for both thermal and fast neutron spectrums. It is interesting to note that both these cycles depend upon the production of either plutonium or U_{233} in a thermal converter reactor in order to provide the initial fuel inventory.

It is convenient to think of the breeder as a fuel factory which, unlike the diffusion plant alternative, is capable of producing electricity as a by-product, instead of consuming it. While the breeder reactor is grossly uneconomic as a fuel producer alone, a breeder power plant can indeed provide a most effective means of industrial fuel production. To supply the whole needs of an expanding industry this way, however, demands at least that fuel doubling time be comparable with that of the industrial growth. (ie. around ten years.) This reemphasizes the need of high conversion breeders and supplies one of several reasons for particular interest in gas cooled fast reactors.

No commercially sized breeder reactors are currently in operation or under construction.

5. Fission Versus Fusion

(a) Fission Advantages

(i) The fuel reserves are large. The fuel used in fission reactors at the present time is obtained from rich ores at a cost of approximately \$5 per pound UO_2, for which the reserve is small - one hundred years at the most. But for weak ores, approximately 10 parts per million UO_2 which would be uneconomic to extract at the present time, the reserve is large. Thus, using the customary large unit of energy the capital $Q = 10^{18}$ Btu the reserves at the 10 ppm level is about 10^6Q. This figure assumes the uranium is used efficiently, ie. breeder fission reactors. The present energy comsumption rate of the world is 1.2 Q per annum, and it has been estimated that for an asymptotic 7×10^9 people world this might rise to 2 to 3 Q per annum. This asymptotic world has then about one million years supply of energy in its reserve of accessible fuel for fission.

(ii) Non breeder reactors are here and producing power competitve with conventional power plants, Breeder fission reactors exist only as prototype as the present time, but are in a state of intense development. They are expected to come into world wide commercial use in the next decade, and be competitive.

(iii) Fission reactors are generally considered less polluting than coal burning power plants of today.

(b) Fission Disadvantages

(i) Fission plants have certain hazards - melt down, power excursions, etc. A major bomb type explosion is probably impossible, and great precautions, with heavy containment vessels and fail safe equipment are taken to prevent escape to the atmosphere from imaginable accidents. But no matter how safe they are made against such malfunctions, they can probably never be made entirely safe from technically informed sabotage. It seems

5. Fission Versus Fusion (Cont'd.)

(b) Fission Disadvantages (Cont'd.)

unlikely, therefore, that they will ever be installed inside cities.

(ii) Plutonium by-product is a basic material for nuclear weapons. In an asymptotic world running on fission, the amount of it in commerce would be enough to make tens of thousands of nuclear bombs per annum.

(iii) Plutonium is valuable, salable, and, therefore, likely to be stolen. If the makings of a bomb became sufficiently widely available mankind's past behavior suggests that sooner or later someone would cobble up a crude fission bomb of a megaton or so strength and fire it in some city centre.

(iv) Fission products are biologically hazardous and probably should not be transported long distances for fear of dispersion by accident.

(c) Fusion Advantages

The first fusion plants will have to operate on the thermonuclearly speaking less difficult lithium cycle. The fuel reserve determining factor will not be deuterium, but lithium. The reserve of this is about 2×10^6Q or enough to last about 10^6 years. Ultimately fusion plants operating on the deuterium cycle may be achieved. Deuterium is present to the extent of one part in 50,000 by weight of the oceans of the earth and constitutes the enormous energy reserve of 10^9Q. This gives an estimatable billion years fuel reserve at the asymptotic Q rate. So we see that the fusion fuel reserves are large and in the worst case about equal to those for fission.

(ii) Fusion reactors are totally incapable of running out of control. It follows that they could be located inside urban complexes should this be desirable.

(iii) They generate no fission products.

5. Fission Versus Fusion (Cont'd.)

(c) Fusion Advantages (Cont'd.)

(iv) The tritium intermediate produce is valuable and subject to theft, but not adaptable to the construction of illicit bombs.

(d) Fusion Disadvantages

(i) Fusion power is not here yet.

(ii) It seems as if the fusion reactors will be more complicated than the basically very simply fission reactor though this may not necessarily always be the case as it is too early to be sure. It suggests, however, that it will take time for fusion power to become competitive with fission.

(iii) Although a fusion reactor produces no long term radioactive fission product, it will produce about ten times as many neutrons per kilowatt hour as fission does. This means that a high level of neutron activity will take place in some components of the reactor and precautions in plant design and hygiene will have to be taken to prevent the creation and escape of biologically hazardous nuclei.

(iv) Tritium will be present and processed in large quantities in a fusion reactor. Although tritium is a biological hazard, it is less dangerous than most radioactive species because of its rapid dissipation in the atmosphere and the low penetrating power of its radiation.

(v) A fusion reactor using the lithium cycle will contain large quantities of fused lithium in a form of a one meter thick layer around the reactor space. Lithium is a chemical fire hazard like the sodium in fission reactors.

E. NUCLEAR FUELS

1. Sources

The uranium isotope U_{235}, a fissile material, is the only natural occurring isotope capable of a chain reaction. Natural uranium is a mixture of U_{235} and U_{238}, 0.7 and 99.3% by weight respectively. The U_{238}, a fertile material, can be converted to plutonium in a reactor through the absorption of neutrons. (An excess of neutrons over that required to sustain a chain reaction must be available.) Plutonium is a fissile material capable of a chain reaction. Thorium a naturally occurring fertile material, can also be converted to a fissile material through the absorption of neutrons. In this case the end product is another uranium isotope U_{233}.

World nuclear fuel resources presently mapped consist of 25 million tons of uranium and 1 million tons of thorim for a total of 26 million tons of which one third can be economically recovered.

2. Types of Fuels

Reactor fuels can be either solid or liquid. Solid fuels consist of metals, alloys, and chemical compounds. Liquid fuels such as molton salts of uranium, and slurries containing uranium, have been used in research reactors, but these liquids are usually highly corrosive and the uranium in the solution of slurries is subject to precipitation. For such applications as small high-powered density cores, liquid fuels may be attractive, but for normal commercial operation the disadvantages of liquid fuels which are difficult to handle out-weigh their advantages. Solid uranium metal fuel has been used extensively to fuel gas-cooled reactors and to fuel the low-power experimental reactors. The metal has a high density and thus a high concentration of fissile atoms. The thermal conductivity is high, but it has a low phase change temperature of 688°C, and for this reason the

2. Types of Fuels (Cont'd.)

pure metal is not dimensionally stable under conditions of radiation and thermal cycling.

Uranium dioxide and uranium carbide are the two most commonly used chemical compounds of fuel. The characteristics of the uranium dioxide are inferior to the metal in the concentration of fissile atom is less. The oxide has a lower thermal conductivity which results in higher fuel temperature. However, this fuel has a high melting point - 2,800°C and it is dimensionally stable up to temperatures near its melting point. Fabrication and handling of the oxide fuel presents no hazards and the oxide is corrosion resistant in hot water. The nuclear and thermal characteristics of uranium carbide are superior to those of uranium dioxide but not as good as those of pure metla. However, it is chemically incompatable with water and to date its use has been restricted to reactors cooled with organic liquids, inert gases, and some liquid metals.

3. Manufacturing

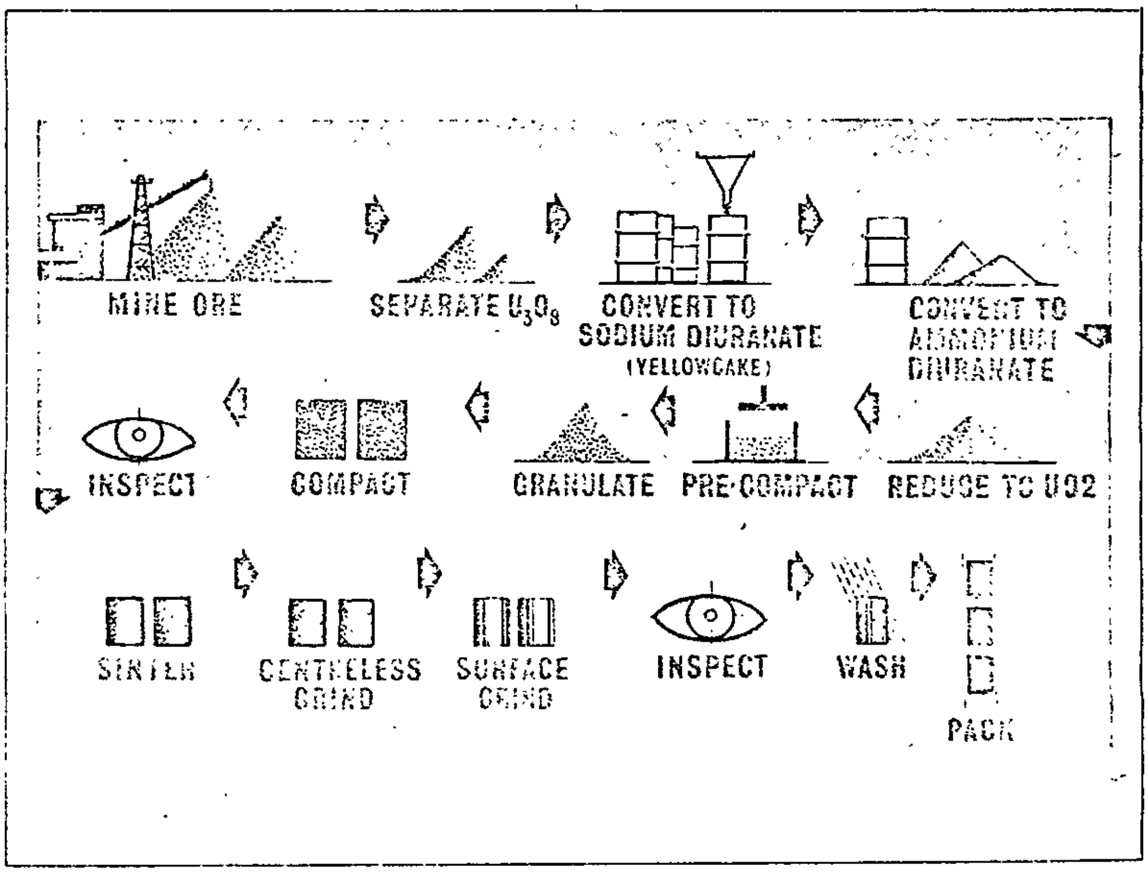
The manufacturing sequence for the uranium dioxide presently used in Canadian reactors (Figure 8) starts with the mining of uranium ore, followed by the refining of this ore to produce concentrate known as yellow cake or sodium diuranate, the further refining of the ore to produce high purety uranyl nitrate solution the precipitation of ammonium diurnate from uranyl nitrate solution and the reduction of this ammonium diuranate to produce ceramic grade uranium dioxide. The uranium dioxide is further prepared by pressing and sintering to produce the high density ceramic pellets.

4. Enrichment

The concentration of U_{235} in U_{238} can be increased by passing the uranium in the form of a gas through a number of diffusion membranes. This method has been used in England, France, U.S.A., and Russia to produce enriched uranium for their military progams. These gaseous diffusion

Fig. No. 8

Uranium Pellet Manufacturing Sequence



4. Enrichment (Cont'd.)

facilities are now being used to make enriched fuel for use in civilian programs, and in these countries there has been an emphasis on building reactors using enriched material. In Canada we do not have gaseous diffusion plants and the effort has here gone in the direction of utilizing natural uranium. Many other countries in the world have a prime interest in natural uranium because they do not have direct access to gaseous diffusion plants.

The gaseous diffusion process is costly and requires large amounts of electrical energy. Other enrichment processes, such as the Separation Nozzle Process and the Gas Centrifuge Technique, are being developed.

5. Fuel Costs

The fabricated fuel costs for Candu units are comprised of three basic coats - the resource cost (uranium) 30% Zirconium alloy and other material 25%, and manufacture assembly and profit 45%. The price of fabricated fuel for Candu reactors has been decreasing. In 1962 the firm price for the first charge of fuel for Douglas Point was $73 per kilogram U. Last year the fabricated fuel for the first core at Pickering was ordered at a price of $44 per kilogram U. In the future refining and fabricating costs should decrease as the production volume increases. Sources show fuel prices decreasing by 30% to 35% in the twenty year period from 1970 to 1990. Declining manufacturing costs should counter any increase in price of the resource. In addition, increases in resource cost will tend to increase the value of spent fuel.

The transportation cost of uranium, on a BTU basis is so small that it can be considered a global fuel. Security of supply, due to political factors, is, however, another consideration

5. Fuel Costs (Cont'd.)

The table below gives costs for natural uranium and 3% enriched uranium on the basis of weight and heat. * Note: This table was taken from a 1967 source. The costs are not likely accurate any longer. The table does show the relative cost between natural and enriched uranium.

Fuel	Cost Per Pound	Cost Per 10^6 BTU	BTU Per Pound
Natural Uranium (0.71% U_{235})	$ 10.66	$.04	245 x 10^6
Enriched Uranium (3.0% U_{235})	$115.59	$.11	1,050 x 10^6

6. Reprocessing

There is an average of almost 3 grams of fissile plutonium in every kilogram of uranium removed as spent fuel from a Candu reactor. The incentive exists to process this spent fuel for the plutonium content.

The price of plutonium is currently high enough to justify the handling, transportation, and reprocessing costs. The unanswered question of the mid 70's is whether the growing inventory of plutonium from light water reactors will depress the price of plutonium to the point that a utility such as Ontario Hydro will not be able to deal off its spent fuel profitably.

There are two other options. The utility can be satisfied with the once through cycle and arrange for permanent burial of the discharged fuel. Or it can have the plutonium extracted for re-cycle in the reactor, the Candu being a more efficient user of plutonium than other thermal reactor systems.

The Candu reactor system has the flexibility of permitting a once-through fuel cycle. By achieving burn-ups in excess of 9,000 megawatt days (thermal)

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* Reference #3

6. Reprocessing (Cont'd.)

per ton uranium the candu reactor operator can bring his fuel costs so low that he need not rely on plutonium credits to make the station economically viable. In contrast, enriched reactors discharge irradiated fuel with enough fissile material remaining to virtually force reprocessing.

If in fact the Canadian utility is able to ask $5 per gram (the current rate) for contained fissile plutonium, it will be netting perhaps $13.50 per kilogram uranium for the spent fuel. This is a third of the original price of the fuel, which has the effect of reducing the fuel cost from about 0.68 mills per kilowatt hour to just over 0.4 mills per kilowatt hour.

7. Utilization

The nuclear characteristics of a reactor may be changed so that the conversion ratio, ie. number of fissile atoms produced vs. number of fissile atoms consumed, can be increased. In fact the conversion ratio is used to catagorize reactor types.

Conversion Ratio	Type
0.5 to 0.75	Converter
0.75 to 1.0	Advanced Converter
1.0 to 1.4	Breeder

Obviously the breeder reactor gives the highest utilization of fuel and in theory 100% of the world fertile elements could be utilized in such a reactor. In practice this is limited by the reprocessing losses. For example, utilization will be limited to 20.5% if reprocessing losses total 2% and to 68% if reprocessing losses total 0.4%. An upper limit of 80% is considered to be a practical limit.

F. ECONOMICS OF NUCLEAR POWER PLANTS

1. Economics of Candu Reactors

Nuclear stations have higher capital costs and lower fuelling costs than coal fired stations. Therefore, the cost of electrical energy is quite dependant upon the capacity factor at which the station is operated. Table 2 compares capital and fuelling components of energy costs for the Pickering nuclear station with two coal fired stations in Ontario. * This table is relatively old but does give an appreciation of the relative costs between nuclear and coal fired stations and shows the influence of capacity factor. Each station is designed with an aggregate output of about 2,000 megawatts from four units. The estimated capital costs includes generation, step-up transformers, and high voltage switching at each site. The nuclear station costs include, in addition, half the cost of the first fuel charge and about $5 per kilowatt for operator training and commissioning of the plant. Interest and depreciation on the estimated costs are based on a 30 year plant life at an annual interest rate of 5½%. The fuelling costs are based on cost at $.32 per 10^6 BTU's and fabricated nuclear fuel at $44 per kilogram uranium. Net station efficiency at 39% and 29% was assumed for the coal fired and nuclear stations.

The unit capital costs, in terms of fixed dollars, should reduce in the future by increasing size, by techinical improvements and by increased experience in engineering and manufacturing nuclear components.

Table 3 entitled, "Estimated Costs for Nuclear, Coal, and Oil Plants in Ontario in 1969, Canadian Dollars", gives a more recent detailed cost comparison between nuclear, coal, and oil fired stations in Ontario Hydro.**

* Reference #4
** Reference #5

Table No. 2

	Station	Cost Item	Annual	Capacity	Factor
			80%	60%	40%
Capital and fuelling component of energy costs in Mill/kWh from 2,000 MWe nuclear and coal-fired stations	Lambton $109/kW[1]	Interest & depreciation	1.07	1.43	2.15
	Commissioned 1968-70	Fuel	2.81	2.81	2.81
		Total	3.88	4.24	5.06
	Nanticoke $121/kW[1]	Interest & depreciation	1.19	1.59	2.38
	Commissioned 1971-72	Fuel	2.81	2.81	2.81
	2 units not scheduled	Total	4.00	4.40	5.19
	Pickering $264/kW[2]	Interest & depreciation	2.60	3.46	5.20
	Commissioned 1970-73	Fuel	.68	.68	.68
		Total	3.28	4.14	5.88

Reference No. 4

Table No. 3

ESTIMATED COSTS FOR NUCLEAR, COAL AND OIL PLANTS IN ONTARIO IN 1969 CANADIAN DOLLARS

(excluding escalation after 1969)

	Nuclear	Coal	Oil
No. of units and capacity, MW(e) (net)	4 x 500	4 x 500	4 x 500
Plant efficiency, %	29.1	37.9	37.3
CAPITAL—DIRECT COSTS, M$			
Site, buildings and equipment (installed)	294	215	197
Nuclear fuel (½ charge)	8	—	—
Heavy water	100	—	—
TOTAL DIRECTS, M$	402	215	197
CAPITAL—INDIRECT COSTS, M$			
Engineering	39	14	14
Construction overheads	43	22	22
Administration, inspection, etc.	15	8	8
Commissioning	11	1	1
Interest during construction	86	28	27
TOTAL INDIRECTS, M$	194	73	72
CONTINGENCIES, M$	8	4	15
TOTAL CAPITAL, M$	604	292	284
Specific capital cost, $/kW(e) (net)	302	146	142
UNIT ENERGY COST, m$/kWh			
Capital	3.63	1.77	1.72
Operations and maintenance	0.38	0.29	0.18
Heavy-water upkeep	0.13	—	—
Fuelling	0.71	3.11	3.12
TOTAL UNIT ENERGY COSTS, m$/kWh	4.85	5.17	5.02

BASIC ASSUMPTIONS FOR CALCULATION OF COSTS FOR TABLE 2

Station net capacity factor	80%
Life	30 years
Interest rate	7.5%
Fixed charge rate on capital	8.47%
Heavy water	
capital cost	$53.5/kg
upkeep cost	$40.0/kg
upkeep rate (per reactor)	1.3 kg/h
Nuclear fuel cost	$46.0/kg U
Nuclear fuel burn-up	223 MWh/kg U
Coal cost (high sulphur)	$ 9.12/ton $ 0.35/MBtu
Oil cost (high sulphur)	$ 2.15/barrel $ 0.34/MBtu

NOTES:

1. Nuclear plant based on 1969 estimate for Pickering (in-service 1971).
2. Coal-fired plant based on 1969 estimates for Lambton and Nanticoke (in-service 1970, 1972).
3. Oil-fired plant based on 1969 estimate for Lennox (in-service 1975).
4. A nine-month strike in mid-construction affected costs for Pickering, Lambton and Nanticoke but not Lennox.
5. Engineering includes development (nuclear only).
6. Nuclear fuelling costs include interest on out-reactor inventory (three-month supply of finished fuel plus some in process and some uranium stock-piled).
7. No credit taken for sale of spent fuel.
8. No credit taken for value of D_2O inventory at end of thirty years.
9. D_2O initial capital investment is high because of unavailability of Canadian supply for Pickering.

1. Economics of Candu Reactors (Cont'd.)

This table was taken from a March 1972 periodical. An up-dated cost for Pickering is $345/Kw(net). *

Table 4 gives estimated investment costs for various reactor types with the same ground rules. The comparison is between gas cooled, light water, and heavy water reactors. **

Repeated analyses are required to determine whether it is still justifiable to take the benefit from the lower capital cost of the conventional thermal station if it means accepting an increasing divergence in cost of fuelling coal fired or nuclear stations.

A high sulphur oil for Lennox was expected to cost 34¢ per 10^6 BTU's. That price has since risen, and if the Canadian public insists on low sulphur fuel the oil could be priced in the $.75 to $1 per 10^6 BTU range.

High sulphur coal has been available for not much more than $.33 per 10^6 BTU's. Again there are both escalation and environmental factors involved in calculating the probable coal price.

In the United States, the so called break even point for steam from a light water reactor is the cost necessary to compete with 50¢ per 10^6 BTU natural gas, 45¢ per 10^6 BTU oil, and 30¢ per 10^6 BTU coal. ***

A.E.C.L. estimated a total unit energy cost of 6.75 mills/Kwh for a 600 Mw Candu - Phw plant on Vancouver Island to be started up in 1976. They estimated on equivalent gas fired plant using 65¢/10^6 BTU gas would have a total unit energy cost of 9.1 mills/Kwh.**** This would result in a break even point at 40¢ per 10^6 BTU gas if the gas fired plant had an overall efficiency of 37%. The 40¢ break even point for a gas fired plant is low compared to the American experience but is in line with Table 3.

* Reference #6
** Reference #7
*** Reference #5
****Reference #8

Table No. 4

Table III
Estimated Investment Cost for Various Reactor Types with Same Ground Rules

1978 Service Date

(In figures of thousands of dollars)

	Gas-Cooled Graphite-Moderated	Light-Water-Moderated		D$_2$O-Moderated	
	United Kingdom (Gibbs)	United States (Davis)	United States (Vann)	Canada (Bates)	India (Meckoni/Surya-Rao)
Direct Cost*	$259,000	$224,000	$224,000	$307,000**	$297,000**
Trends					
Regulatory & Safety	—	5,000	5,000	—	—
Near-Zero Release	—	5,000	5,000	—	—
Cooling Towers	8,000	8,000	8,000	8,000	8,000
Plant Availability	2,000	2,000	2,000	2,000	2,000
Quality Control/Quality Assurance Requirement	1,000	1,000	1,000	1,000	1,000
Aesthetics	800	800	800	800	800
Total Construction Cost	$270,800	$245,800	$245,800	$318,800	$308,800
Escalation (27%)***	72,900	66,300	66,300	85,800	83,200
Interest During Construction (18%)	61,800	56,200	56,200	72,600	70,500
Total	$405,500	$358,300	$368,300	$477,200	$462,500
$/kWe	405	368	368	477	462

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*Based on data as presented but modified to 1,000-MWe plant by .8 factor scaling and updated to 1971 cost levels and removing interest during construction.

**Includes cost of D$_2$O inventory, but omits cost of core.

***Based on approximately 5%/year to represent a better average among countries.

Reference No. 7

1. Economics of Candu Reactors (Cont'd.)

United Engineers and Contractors did a cost analyses for Hydro Quebec in which a light water reactor station compared favourably with power delivered from James Bay, the assumptions being a 10% average interest rate and a 4% annual escalation factor to 1980. A United States light water reactor, however, would pose licensing problems in Canada.

2. Cost of American Nuclear Plants *

(a) 1968 Estimates

Analyses shows that 1968 cost estimates were about $150 per kilowatt lower than will actually be experienced. The largest increase can be contributed to an increase in the scope of the project and a stretch out of the project schedule beyond what was contemplated in the 1968 estimates.

The $150 per kilowatt increase in cost can be attributed as follows:

Increase in scope	$65 per kilowatt
Schedule stretch out	$45 per kilowatt
Lower Labour productivity	$20 per kilowatt
Added inflation	$10 per kilowatt
Miscellaneous	$10 per kilowatt
Total	$150 per kilowatt

(b) 19~~6~~71 Cost Estimates

In order to forecast nuclear plant costs, it is necessary to establish a base cost for a new plant under today's conditions. The basic cost assumed for purposes of this presentation is $250 per kilowatt without interest during construction and without escalation. This represents the cost of a typical 2 unit, 2,200 megawatt plant in the northeastern region of United States. It includes up-to-date safety requirements, and cooling towers contained in the original design. However, it does not include cost for the implementation of studies and analyses of the new

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* Reference #9

2. Cost of American Nuclear Plants (Cont'd.)

(b) 1961 Cost Estimates (Cont'd.)

environmental legislation or plant costs that will be necessary to meet qualification of the "low as possible" criteria. Reactor safeguards and environmental considerations may be expected to add a total of about $6 per kilowatt to the base plant cost. The composition of the base plant cost is presented in Table 5.

(c) Cost Trends

Two step increases in cost can be anticipated. The first is with us now. It is the $6 per kilowatt increase as mentioned already. The second step increase is an assumed $4 per kilowatt increase in the price of the nuclear steam supply system package in 1972.

The total expected cost trend for nuclear plants, excluding the effects of inflation or escalation, as indicated in Table 6, will amount to 8/10's of 1% of the total base plant cost expressed in 1971 dollars without interest during construction.

(d) Forecasts

Figure 9 represents forecast cost for future plants, without escalation, expressed in 1971 dollars. The lower line is without interest during construction, the upper line is with interest during construction calculated at 7½% per annum on a year by year investment during an assumed seven year construction period.

(e) Costs With Escalation

The magnitude of the impact of escalation is evident when plotted for various rates shown on Figure 10.

Most current estimates of plant costs include escalation at 8% per year. If this escalation rate is actually realized for the project period

Table No. 5

Reference No. 9

Typical 1971 Nuclear Plant Cost Estimates

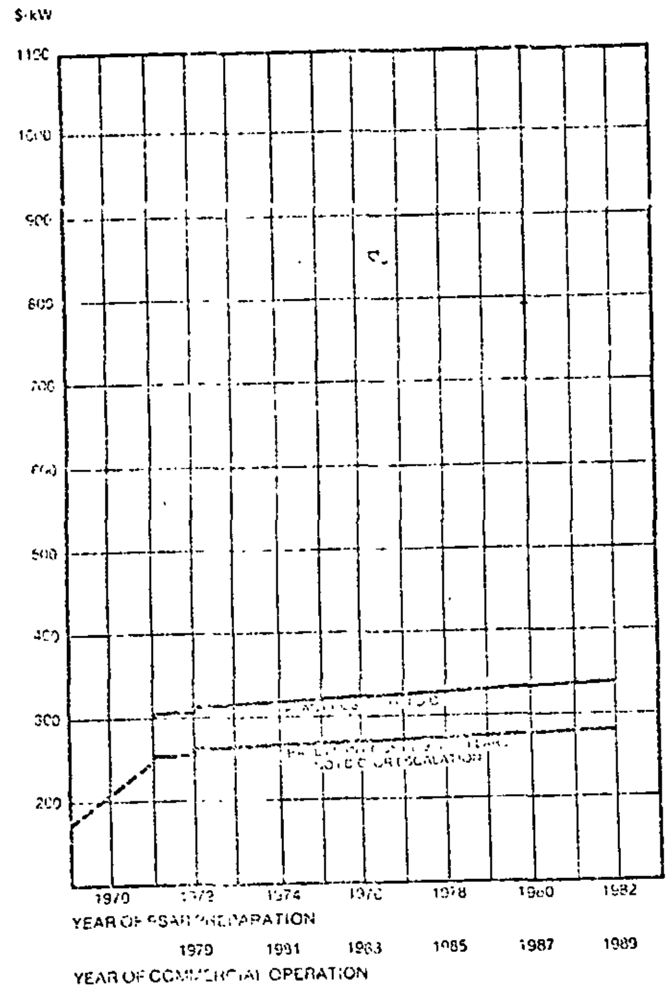
	$/kW
Site Preparation	2.3
Structures and Improvements	43.2
Nuclear Steam Supply System	36.4
Turbine-Generator	35.4
Balance of Reactor Plant and Turbine	57.3
Electrical and Miscellaneous Plant Equipment	19.5
Engineering, Construction Equipment and Spares	37.7
Contingency Interest During Const.	18.2
Base Plant (No IDC or Escalation)	250.0

Table No. 6

Expected Cost Trends for Nuclear Plants (Based on constant 1971 dollars)

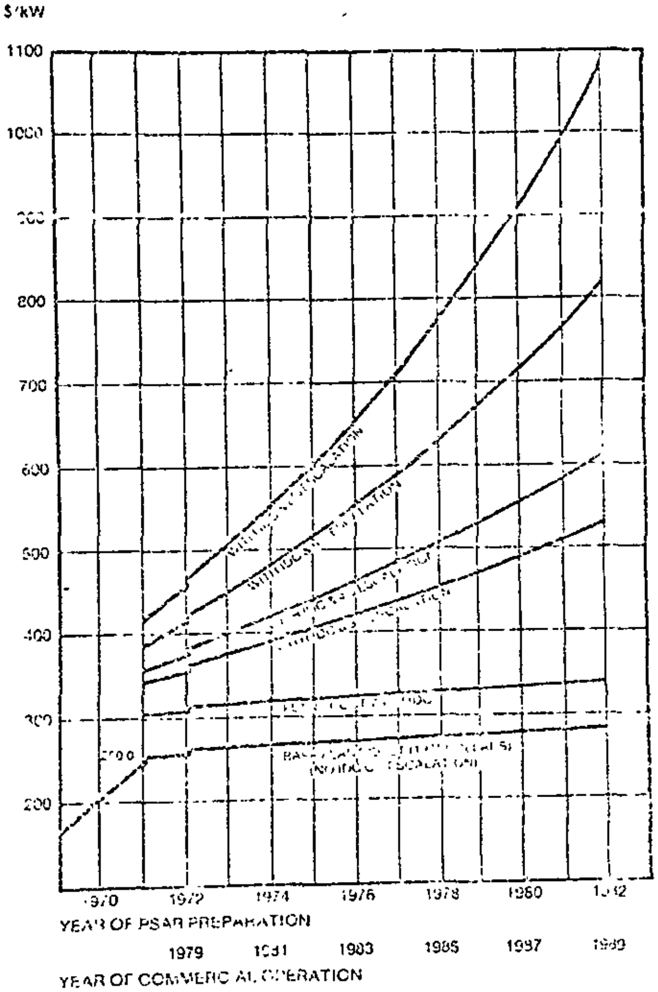
	Annual Impact on Total Base Plant (%/Yr)
Safeguards and Environmental Facilities	+1.0
Field Labor (productivity)	−0.4
Nuclear Steam Supply System	0.0
Other Plant Equipment	+0.1
Engineering and Construction Management	+0.1
T-G Equipment	0.0
Net Effect on Base Plant	+0.8

Fig. No. 9



Forecast of nuclear plant capital costs without escalation (expressed in 1971 dollars)

Fig. No. 10



Forecast of nuclear plant capital costs with escalation

Reference No. 9

2. Cost of American Nuclear Plants (Cont'd.)

in Figure 10, utilities will be placing nuclear plants on their books at over $500 per kilowatt in 1980 and over $1,150 per kilowatt in 1990. A comparable development of costs for a typical coal plant with particulate and SO_2 removal facilities would produce costs of over $450 per kilowatt for 1980 plant and above $950 per kilowatt for a 1990 plant.

G. POLLUTION

Nuclear reactors create four pollution problems: radiation hazards, ie. emission of radiation at the facility, thermal discharge in the form of waste heat, production or radioactive waste and associated disposal processes, radiation bearing clouds as a result of reactor accidents.

The radioactive release from nuclear reactors in both the liquid and gaseous form is very small and certainly does not constitute a health hazard. The amount of radiation received from a chest X-ray, well within the stringently policed radiation protection limitations, is much greater than that received by spending a man's life in the immediate vicinity of a reactor.

The thermal discharge from nuclear generating stations exceed those from fossil fired stations. Tremendous efforts are being directed to increase nuclear thermal efficiencies both by increasing present cycle efficiencies and by designing new reactor concepts in which the thermal efficiency would be inherently greater.

The disposal of radioactive waste has been solved to the satisfaction of most people. Reactor accidents leading to the formation of high-level radiation bearing clouds are very remote. Reactor run-away accidents cannot be related in severity and method to the explosion of nuclear weapons.

H. AVAILABILITY

1. Europe 1971

The mean utilization factor for the European communities' nuclear power plants rose significantly in 1971, reaching about 5,400 hours. Electrical energy production by nuclear means increased by 25%. Light water reactors, using enriched uranium, (both BWR and PWR) chalked up the best availability factors with 60% to 90% as compared to 40% to 60% for natural uranium, gas-cooled reactors.

2. Pickering

Reactor No. 1 achieved criticality on February 25, 1971 and supplied first steam to the turbine on March 16. First electricity was fed to the grid April 30, 1971 full electrical output achieved May 30, 1971, and on July 29, 1971 the unit was declared commercially in service.

The unit operated with a net capacity factor (ratio of net output to perfect net output) from commercial operation to the year end of 79%.

The significant dates for Unit 2 were:

Criticality September 15, 1971

First steam to turbine September 28, 1971

First electricity October 6, 1971

Full electrical output November 7, 1971

Commercially in service December 30, 1971

The net capacity factor from November 7 to December 30, 1971 was 88%.

On the first unit the capability of one power fuelling has been demonstrated, and in both operating units heavy water losses have been held to an insignificant amount (1.5 to 2 pounds per day).

3. Gentilly

The Gentilly nuclear power station is continuing to operate at 50% power while preparations are being made to install additional shut-down

3. Gentilly (Cont'd.)

initiating devices, prior to commissioning the reactor to 100% power. The Gentilly reactor, a natural uranium fuelled boiling light water reactor came into first operating in November 1970. The reactor reached 50% electrical output in October 1971. The period of commissioning to 50% power was prolonged by difficulties with equipment, and by the need to measure physical and control parameters at various power levels and operating conditions. The measurements confirmed the additional shutdown initiating devices were required, and these were to be installed during February 1972. When the installation is completed, the reactor will be commissioned from 50% to 100% power.

I. TURBINES

While a few advance designed reactors supply steam at conventional thermal plant temperature and pressure the majority provide saturated steam at a pressure of 600 to 1,200 psi. Consequently, the heat drop that is available is only about 65% of that used by modern re-heat turbines. The steam consumption can, therefore, be 60% to 90% higher than in conventional plants, depending on specific conditions. The nuclear power plant can only be justified economically if unit ratings are made large. These factors lead to the problems of handling large steam volumes, especially at the low pressure end of the turbine.

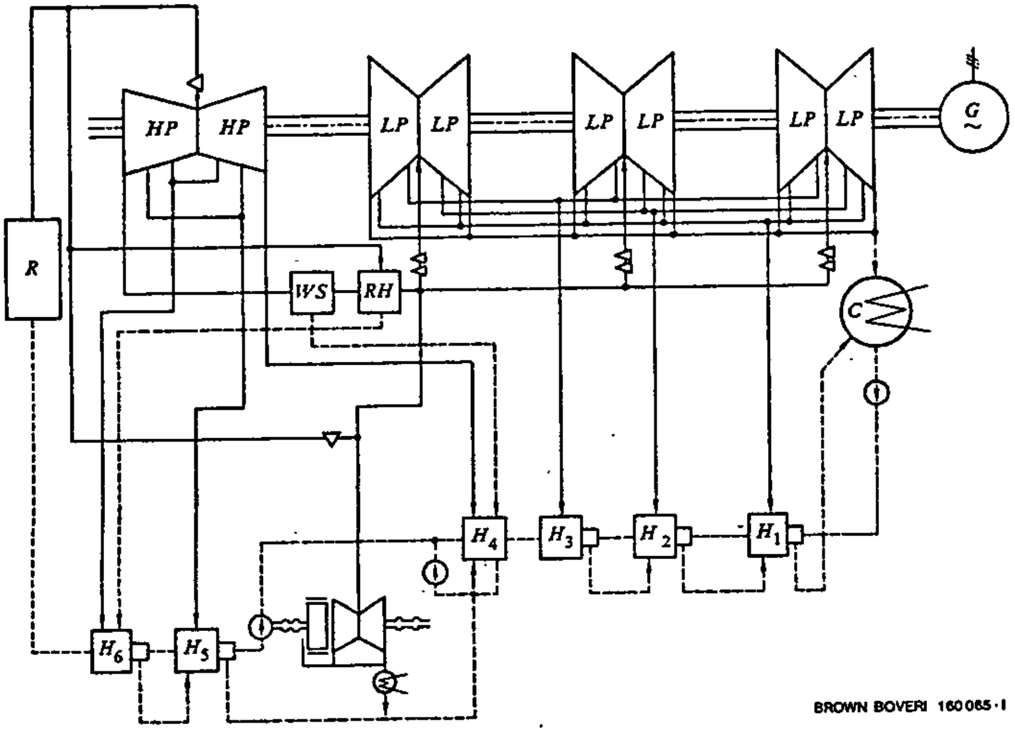
A typical 1,200 megawatt turbine for a nuclear station is described below with emphasis on those portions that differ from a conventional unit. The flow diagram is shown in Figure 11.

The saturated steam at 770 psi and 515^{o}F enters the turbine through four combined valves. These valves resemble the intercept valves supplied for a similar sized re-heat turbine. However, the much lower temperature allows the use of ordinary, low-alloy cast steel.

From the HP Section the steam passes into the combined water separaters re-heaters. There the steam is first dried in the matts of wire mesh, following which it is superheated by flowing through nests of tubes heated with live steam. The re-heating part can be designed in two stages, the lower stage being heated by bled steam from the HP turbine and the upper by live steam.

Re-heat stop and intercept valves are incorporated in the cross over lines, their task in the event of shut-down being to block the large amount of energy in the steam stored in the separator/re-heater tanks and thus prevent the turbine from over speeding.

Fig. No. 11



Schematic layout of the "Donald C. Cook" plant

R = Reactor
HP = High-pressure turbine
LP = Low-pressure turbine
G = Generator
C = Condenser
H = Feed-heaters
WS = Water separator
RH = Reheater
——— = Steam
– – – – = Water

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The rotor blades of the final LP stage are 52" long. To enable these rotors to be transported the last two rows of blades have to be removed.

In the HP Section the expansion of the steam continues well into the wet steam region. To protect it against erosion caused by the film of water that condenses inside the turbine casing, the inner surface is lined with stainless steel. In the final stage of blading, slots insure that this film is drained off.

The blades of the last LP stage are protected against erosion by having their leading edge hardened by an induction process.

In the LP Section the same criteria applies as to the conventional machines because with the arrangement adopted, the expansion line yields the same steam condition as in re-heat turbines. As additional safeguards, special draining facilities are incorporated in the cross over lines to the LP Section which, in the event of failure of the re-heaters, remove the film of condensate that forms on the walls of the pipes and thus prevents the formation of dangerous water streaks at the inlet to the LP blading.

Saturated steam turbines in nuclear power plants are particularly prone to over speeding in the event of shut-down, because the large amounts of steam trapped in the piping and vessels still contain a considerable amount of energy, and because the film of condensate on the walls of all casings and pipes flashes due to the sudden drop in pressure. However, in contrast to earlier assumptions this evergy is released relatively slowly. Therefore, the rise in speed is fairly steep to begin with, ie. at the customary rate, and then after about 1 second, it reaches the level known for conventional plants. Due to the residual energy in the slowly evaporating films and deposits of moisture, there follows a second though slower rise in speed, which does not reach its considerably higher culminating point for about thirty to forty seconds. This "creeping" rise in speed is countered by incorporating valves in the cross over pipes.

The special conditions under which nuclear power plants operate necessitate a special safety analyses be undertaken, in which the most improbable incidents have to be taken into account. All components are examined, firstly in respect of their own inherent safety and secondly with regard to the result of a possible incident.

J. GLOSSARY

Chain Reaction - A nuclear reaction that causes further reactions of the same kind and so becoming self-sustaining.

Critical Size - That size of a nuclear core at which the probability of a thermal neutron causing fission is a certainty, or at which a chain reaction will be sustained.

Fertile Material - Materials that can be converted to a fissionable material.

Fissile Material - Material that will undergo a fission-reaction with a neutron.

Fission Reaction - The splitting of the nucleus of an atom into two smaller nuclei by bombardment with a neutron.

Fusion Reaction - The fusion of the nuclei of a light element to form a heavier element (eg.) two heavy hydrogen nuclei, each containing one proton and one neutron, can be fused together to form a nucleus of helium and a neutron.

Moderator - A material used in a reactor to slow down the neutrons.

Neutrons (Fast) - High speed neutrons emitted as a result of a fission reaction.
(Thermal or Slow) - Neutrons which have been slowed down by a moderator to about the speed at which gas molecules move when they are in equilibrium with each other.

Reactors (Breeder) - Reactors which produce more fissile material than they use.
(Converter) - Reactors which produce some fissile material but use more fissile material than they convert. (A reactor is not considered a converter unless it produces at least half as much fissile material as it uses.)
(Thermal) - A reactor operating with slow or thermal neutrons. (May be non converting, converting or breeding.)
(Fast) - A reactor operating with fast neutrons. (Used mainly in conjunction with breeder applications.)

Tritium - An isotope of hydrogen with atoms of three times the mass of ordinary hydrogen atoms.

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