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INEVITABILITY OF ATOMIC ENERGY IN INDIA'S POWER PROGRAMME

by

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1. INTRODUCTION

Atomic energy is going through the third phase of its existence. The first was its discovery and the demonstration of the feasibility of using it to generate electricity. The second stage was the development of nuclear power technology with due emphasis on the standardization of nuclear power reactor design, suitable material of construction both on the basis of economics and safety. The third stage is its widespread use, with reference to its economic competitiveness, environmental consequences particularly with respect to other sources of energy and the problems of its utilization till towards the end of the century and beyond.

It is clear that atomic power has come to stay but a dispassionate study of its advantages has yet to be made. I say a dispassionate study because in many countries of the world, there has been much public debate on the hazards of nuclear power, some of which not quite connected with either the economics or the safety aspects of the technology. I would also like to make it quite clear that though I have been associated with atomic energy matters for nearly thirty years, the case I present here is put forth not as one belonging to the profession, because any suggestion that I make in this paper with respect to future plans will come into fruition long after I have passed the age of retirement, and I will thus have nothing personal to benefit by it. But looking at it with the experience of the past and the terrifying energy problems of the future, I can think of no other source of energy that has been discovered todate except nuclear energy, which can solve the energy problems of this country during the next 25 years and beyond. If I do not make the case now and point out to the urgency of accepting its inevitability, I will have done a great disservice. I make this presentation in the same spirit in which Jagdish Chandra Bose took up the case of modern scientific research in India. This can at best be a small memorial to the great pioneer.

2. CONVENTIONAL SOURCES OF ENERGY

The sources of energy for the generation of electricity in India are oil, hydel potentials, coal and nuclear fission. Among these, oil fired power stations contribute much less than 1% of the total installed capacity. Since a significant part of the oil that is consumed in India is still being imported, there is very little propsect of any oil fired power station coming on line. Petroleum as a source of energy is irreplaceable in the transportation sector and a considerable part of the petroleum consumption is required as a chemical in many petro-chemical industries viz. fertilizers etc. Hence, increased use of oil for electricity generation can be practically ruled out.

a) Hydro Electric Potential

No one questions that hydrostations are the best from many points of view. These include simplicity of design, easy maintenance, absence of pollution and a zero fuelling cost, as the source is a perpetual one and goes to waste if not exploited. It is clear that every possible sources of hydel energy must be fully exploited whereever it is. We have however to face the fact that the total hydroelectric potential available in India is limited. A detailed survey carried out by the erstwhile Central Water & Power Commission between 1953 and 1960 estimated that the total hydroelectric potential available in India amounts to about 41,000 MWe[1]. But the energy available from these sites will only amount to 221 million Kwh/year, which is equivalent to an installed capacity of 25,000 MWe[2]. The state-wise distribution of the hydroelectric potentials is shown in Table I. From the table it can be seen that the total potential of 41,000 MWe is expected to yield an average capacity factor of 60%. These capacity factors are estimated on the basis of average rainfall in the catchment areas during the year. Out of the total available hydel potential, nearly 16% has been already exploited[2]. Today, hydroelectricity constitutes about 38% of the total installed capacity and produces about the same percentage of total electricity generated.

The capital cost of a hydroelectric station depends on the location chosen. The capital costsof some of the recently completed hydroelectric stations and projects likely to be completed in the near future range from Rs. 1,900/Kwe for the Koyna extension, Rs. 2,800/Kwe for Chibro and Rs. 4,900/Kwe for the Dehar Power Stations[3]. Apart from the high capital investment required, some of the hydel projects have taken a long time for completion - 9 years in the case of Koyna Extension and Idikki, and 11 years in the case of Dehar[3]. There is also the usual socio-political problem of sharing of water between the various states and between the sectors of agriculture and power generation. I am afraid this problem is an emotional one and will remain with us. Despite all these, hydroelectric potential should be exploited wherever possible. Unfortunately even if all the hydroelectric potential in India is developed, it will not be sufficient to meet the growing energy demands even under the most pessimistic assumptions about the rate of growth of energy consumption.

b) Coal

It is true we have coal deposits of considerable magnitude in different parts of India. The major coal fired thermal stations are listed in Table 2. It is known that the total reserves of coal in India is well above 80 billion tonnes, but of this only 21 billion tons is in the form of proved reserves, the rest being almost equally divided between indicated reserves and inferred reserves. Of the 21 billion proved reserves, about 80% is with an ash content of more than 20%.

The current annual production of coal in India is about 90 million tonnes per year. About one third of this is used to produce electricity. Electricity produced from coal fired power stations constitutes about 58% of all the electricity generation in India. More than half of the coal deposits are located in the States of Bengal and Bihar. This uneven distribution of the coal deposits necessitates the transportation of coal over long distances from the mines to the various points of consumption, implying heavy investment in transportation facilities. If the power station is situated at the pit head, the transmission of electricity to centres of consumption is necessary. This requires investment in transmission lines and other electrical equipment and in the development of the technology of extra high voltage power transmission. Assuming that we plan for a per capita energy consumption eventually levelling off by the end of the century to about only half of the present per capita energy consumption in Europe, we will have to increase the coal output by nearly a factor of 10 besides planning for its transportation. If one considers this carefully, it looks like an almost impossible task. Even if the transportation problems can be solved, one can question the possibility of increasing the annual production rate ten times.

We, therefore, cannot entirely depend on coal for the production of all the electricity we need; we have to consider other possibilities. We note that nuclear fuel is a concentrated form of energy and the transportation required for nuclear fuel is almost non-existent because compared to 30, 000 rail wagons of coal required per year for a 500 MWe coal fired plant, a nuclear power station of the same size would require only 5 truck loads of nuclear fuel per year.

3. NUCLEAR FUEL RESOURCES IN INDIA

The latest estimate of the total uranium resources in India is about 52, 000 tonnes of uranium and about 320, 000 tonnes of thorium(4). Though the amount of uranium available in India is relatively small, the energy potentially available from the nuclear fuels is much more than from the coal deposits. Unlike in the case of coal, the energy that can be extracted from a given quantity of nuclear fuel depends on the type of nuclear reactor that is used to burn the fuel. As is known, uranium occuring in nature contains two isotopes, viz. U^{235} and U^{238}. The presently commercially available nuclear power plants working with slow neutrons, normally called thermal reactors, can burn only U^{235} which constitutes just a meagre 0.7% of the total uranium. Fortunately, in nuclear fission reactions, a part of the neutrons which is released can be used to convert the more abundant and non-fissile U^{233} into plutonium i.e. Pu^{239}. This material turns out to be an excellent fissile material. However, in thermal reactors the conversion of the fertile material U^{238} into fissile plutonium is small and the overall fuel utilization in thermal reactors is just about 1%. That is, out of the 7 million Kwh of electricity potentially available per kg of natural uranium, thermal reactors are capable of extracting only 70,000 Kwh of electricity per kg. But we note that compared to the 2 Kwh of electricity that can be obtained from 1 kg of coal, this is substantial. In Fast Breeder systems, the conversion of the fertile material is extremely efficient, where for every fissile atom destroyed in power production, about 1.2 to 1.5 new fissile atoms are produced from the fertile material. This implies that practically all the uranium can be burnt to produce electricity and one can theoretically extract as much as 7×10^6 Kwh of electricity from 1 kg of uranium. In breeder systems, thorium can also be used efficiently as a fertile material to breed U^{233} which is a good nuclear fuel. In practice, the use of $Uranium^{238}$ or thorium in fast breeders involve chemical reprocessing of the irradiated fuel to reprocess and refabricate the plutonium or U^{233} produced respectively. This chemical reprocessing and fabrication of the fuel result in small losses of the material which could restrict the total energy that can be extracted from the fuel to about 50-60% and it is possible to expect 4×10^6 Kwh from

1 kg of uranium in Fast Breeder Reactors. The energy potential from the coal deposits and from the uranium and thorium deposits in India are compared in Table 3.

Thus the energy potential taking breeding into consideration turns out to be enormous and this energy is made available from uranium or thorium, which are materials that have practically no other large scale use unlike fossil fuels. They are ideal materials for burning away.

4. ECONOMICS OF NUCLEAR POWER

There is a widespread belief that nuclear power stations require more capital investment than coal fired plants. It is already a fully established fact that the generation cost of nuclear power in India away from coal fields is not greater than the generation cost from thermal power plants. In fact in the case of many thermal power stations, the cost of electricity generation is significantly higher than that in the Tarapur and Rajasthan Atomic Power Stations. Despite the lower or comparable generation cost, the apparent higher capital investment needed in a nuclear power plant is sometimes held against it. In a nuclear power programme, capital investment is required in certain associated sectors like production of heavy water and setting up of the facilities required in the fuel cycle activities. These facilities and heavy water plants are exclusively required for the nuclear power programme and consequently the capital outlay needed for these plants are considered to be a part of the outlay for nuclear power programme.

On the other hand, in the case of a coal fired power station, the investments needed in developing the coal mines and transportation facilities required to transport huge quantities of coal from the mine to the power station are not considered to be a part of the investment needed in the thermal power programme. This is partly due to the fact that coal production and setting up of railway lines or acquiring wagons and locomotives are not exclusively past of producing and transporting coal to thermal power stations. The point usually overlooked is that for each coal fired power station replaced by a nuclear power station, the need to develop coal mines and to organize transportation facilities will be proportionately reduced, and thus the capital outlay required for these purposes would be significantly reduced. In these calculation, one has to take into account the fact that much of the existing mining and transportation industry is tied down in the operation of coal fired stations. This existing transportation capacity is therefore not avoidable for other economic activities.

A comparison of the capital outlay required for a nuclear power programme and for a thermal power programme is made relatively difficult by many factors. Even the capital cost of nuclear power plants and of thermal power plants are often estimated on different bases. As an example, interest during construction and provision for contingency are integral components in the estimated project costs of nuclear power plants, whereas these are not often included in the preparation of project costs of thermal power plants. Estimates on investment required in in the laying of new railway lines, locomotives and wagons is not easy, as this can be done only with respect to a particular coal mine and a particular thermal power station.

Recently, Balakrishnan[5] has made an analysis on the comparative capital investments needed in a coal fired power programme and a nuclear power programme. The capital cost of the thermal power plants was estimated based on the capital costs of some of the super thermal power stations compiled by the Federation of Indian Chambers of Commerce and Industry[6]. The capital investment needed to develop the mines to support a coal fired power station was estimated based on the data available in the Report of the Fuel Policy Committee[1a]. Estimation of the capital investment required to transport the coal from the pit head to the power station is not easy. It depends on the existing railway lines and on how much of the investment made by the Railways should be appointed to the actual transportation of coal. An estimate of the investments by the Railways to transport a million tonnes of coal per year from Singrauli coal fields of Obra power station, a distance of about 50 Kms, reveals[3] that the capital investment on transportation would be about Rs. 500/Kwe. Extrapolating the different components of this investment for a distance of 500 kms from the coal mine to the power station, the investment in transportation of coal was worked to be 1,000/Kwe.

On a long term plan based on certain assumptions, the investments required in the various sectors of a nuclear power programme and in a coal fired power programme are shown in Table 4[5].

5. SAFETY AND ECOLOGICAL ASPECTS

No field of human endeavour has received as much attention as nuclear power developments from the point of view of safety. Starting from the mining of uranium to the management of radioactive effluents, safety has been the primary concern in the development of this technology. Since the main competition to nuclear power is from coal fired thermal power plants, we compare the safety records of coal fired thermal power stations and nuclear power plants. The first step in the power programme is the mining of the fuel resources. Even though uranium ore is of very low concentration like 0.05%, the amount of coal to be mined per Kwh of electricity is about 100 times as high as the amount of uranium ore to be mined. Coal miners get afflicted with penumoconiosis-popularly known as Black Lung-whereas uranium miners have a slightly higher incidence of cancer. Apart from these occupational diseases, the fatality due to accidents in coal mines is much more than in uranium mines. I have not seen any statistics about the fatalities in coal mines in India. Uranium mining is a very small scale operation in India and there is no point in trying to correlate the deaths of uranium miners in India to the actual mining occupation. It has been estimated[7] that in the United States, the number of coal miners dying of Black Lung is 1000 per 10^{12} Kwh of electricity generated, whereas the fatality rate of uranium miners due to lung cancer is only 20 per 10^{12} Kwh i.e. less by a factor of 50. The number of deaths due to fatal accidents has been estimated to be 189 per 10^{12} Kwh of electricity generated in coal mining and 2 deaths in uranium mining. These are the results of analysis carried out in the USA where coal mining is more mechanized than in India. The fatalities in coal mining in India are not likely to be less than these figures. Thus one can see that from the view point of safety of mining nuclear power is much superior to coal fired power plants.

It is generally not known that the coal that is used in a coal fired power station and the residual flyash that is left in the open are both radioactive. Both contain Radium 226 which is an emitter of beta rays. Radium 226 is a long lived radioisotope with a half life of 1,620 years. This is certainly a health hazard. Each 500 MWe coal fired plant produces about 18,000 truck loads of ash, whereas the total amount of fuel discharged from a nuclear power station of similar size would be about 30 truck loads including the shipping casks, or half a truck load without the casks. More than 95% of the material in the fuel discharged from the nuclear plant will be recovered for successive use as nuclear fuel, and the amount of radioactive waste that has to be managed on a long term basis is small. The concentrated and solidified nuclear wastes are fixed in a special type of glass and stored in underground depositories. There has been some fear expressed about the possibility of underground radioactive waste materials getting into water streams and thus contaminate the environment. Apart from the fact that management of radioactive waste materials is a sophisticated chemical technology backed up by a lot of research and development work, there is a clear evidence in nature itself that such an eventuality is not possible. At Oklo in Gabon, a natural reactor functioned for a period of 100,000 to 500,000 years about 1,800 million years ago. It has been estimated that 6,000 kgs of fission products and about 2,000 kgs of plutonium were produced due to this underground natural nuclear reactor. All the fission products and plutonium seems to have remained at the same spot without ever diffusing into a water stream.

If nature could accomplish this without any special effort, mankind can certainly accomplish it with the help of all the available technology.

In the times we live in, there is need to conserve every inch of land. A study of the comparative use of land by nuclear power plants and coal fired powr plants by organizations primarily interested in environmental quality has estimated that the annual environmental impact on land use for a 1000 MWe coal fired plant is 3,680 hectares if the coal is deep mined and 5,650 hectares if it is surface mined. Besides this 65 hectares is required for processing, 895 hectares for transport and 390 hectares for conversion, including 46 hectares for ash storage and 5 hectares for coal storage. On the other hand, for a similar nuclear power plant the annual average land used is 318 hectares for mining, 127 hectares for conversion, 3.7 hectares for processing and almost zero for transport.

One of the objections to nuclear power made in recent times is based neither on economic nor safety considerations. If concerns the possibility of terrorist getting possession of plutonium and spreading it into the atmosphere. It is true that plutonium is a toxic material, but some of the materials that are commonly used like certain compounds of lead and mercury are much more so. When there are many conventional chemicals which are much more dangerous, one wonders why a terrorist would choose a very rare man made material like plutonium for his activities. Any way, a recent report from Harwell announces[8] that a remedy is being perfected for the treatment of poisoning by plutonium. A chelating agent, Calcium diethylene Triamine Penta Acetic Acid, commonly known as CaDTPA has been found to be capable of picking up plutonium from the blood and cells, that eventually all the Pu is excreted out.

A view that is sometimes held against the widespread use of plutonium is that terrorists might take possession of separated plutonium and make a bomb out of it. This, to me, seems to be a highly improbable event. To begin with, in the nuclear fuel cycle pure plutonium remains as such only during a very short period of time. When it is formed it is in the fuel rod along with all the fission products and the rest of the uranium which has not been burnt. In the fuel reprocessing plant, the plutonium and uranium are separated and the fission products are removed. The separated plutonium is again mixed with the appropriate quantity of uranium and the nuclear fuel assemblies are be fabricated. Once plutonium is mixed with uranium it is unacceptable as bomb material. Plutonium can be used as abomb material only after it is separated in a chemical reprocessing plant. The chemical separation of uranium and plutonium is a highly sophisticated and complex chemical technology. Thus plutonium can be diverted only during a small time interval after the chemical reprocessing of the discharged fuel and before refabrication. During this stage as well as throughout the fuel cycle plutonium is under strict security surveillence not merely because it is a potentially explosive material, but because it is a very valuable commodity costing more than Rs. 250 per gram. Fortunately the quantities that have to be guarded are also small. I personally do not believe it is that easy to make nuclear devices unless the terrorists are supported by powerful laboratories.

6. OTHER SOURCES OF ENERGY

The hike in the oil price in 1973 and the subsequent widespread analysis of energy resources have brought into focus the fact that energy resources in the crust of the earth are limited in supply. The oil resources are expected to last only for 20 to 50 years. The coal reserves may last for 100 to 200 years. Nuclear fuels will last very much longer, but certainly not for ever. It is with this background that a study of all possible sources of energy that can be exploited and developed to a commercially viable level is necessary.

Among the new sources of energy solar energy seems to be the most promising one. There are many technological difficulties in its exploitation, but I am certain that these will be surmounted with increased research and development effort. The method that is getting the maximum attention is the one using photovoltaic cells. Development work is required to reduce the capital cost of these devices by at least a factor of 100 before commercial electricity generation can be considered. Photovoltaic cells are being used in space applications and for certain special applications in defence in some of the developed countries. Whatever be the future of solar energy as a generator of electricity, every effort must be made to use it for domestic heating and low grade heat for industrial operations.

Another source of energy that merits special attention is geothermal energy. Deep inside the earth the temperature is very high, with a temperature gradient from the centre of the earth to the surface. Tidal power, wind power and fusion reaction are the other concepts that are being discussed as possible sources of energy in the future with varying levels of importance.

Before we discuss the potential roles that these energy resources can play, I would like to bring to your attention an analysis made by the distinguished scientist Academican Peter Kapitza[9]. In this study though the principles involved are well known, Kapitza has presented them in a very succinct way and is of great relevance to energy development. We are essentially interested in transforming one form of energy into another form. This transformation has to be done in accordance with the laws of thermodynamics, which stipulates that in all transformations energy is conserved and the efficiency of conversion from thermal energy to mechanical energy or electric energy is higher if the temperature of the source of the heat energy is higher. In any transformation, the efficiency of conversion also depends on the rate of energy flow and this rate in turn depends on the velocity of propagation of some disturbance in the medium through which the energy is transported. The rate of flow of energy or the energy flux is the product of the velocity of propagation of the disturbance and the density of the disturbance or the energy density. The total power available from a source is equal to the area of the source multiplied by the energy flux. An analysis of this kind shows why many possible sources of energy and many methods of energy transformation are uneconomical. For example a fuel cell has an efficiency of converting the chemical energy into electrical energy of the order of 70% or more, but the low rate of energy flux through the electrolytes limits the power that can be extracted. The capital cost of fabricating a large number of fuel cells will make it impracticable for large scale power production. Conversion of solar energy into electrical energy is another example, where 1 square kilometer of collecting area is required to produce 100 MWe. Though very high temperatures of several hundred degree centigrade are available in the rocks at a depth of 10 to 15 km, to produce high temperature steam, large areas of the rocks will have to be exposed because of the low energy flux through the rocks. Exposing vast areas of rocks to water at such depths can not be economically done using conventional methods. It may become necessary for nuclear explosions to be used to produce large cavities or make the rock porous to make such systems economically feasible. Appendix I gives criteria for determining the figure of merit for various energy sources.[10] It can be seen that fission sources are the best.

A source of energy which may assume great importance in the future, at least in the next century, is nuclear fusion. Since it is still in the process of development and far from the stage where economic studies are possible, I will not deal with it in my lecture. It is, however, to be said that even if one succeeds in producing economic power from fusion, all indications are that the system will be very large and complex. Its maintenance and operation may prove to be a problem. It has all the disadvantages of a fission system especially from tritium activity, without any attendant simplicity of operation.

7. INDIA'S NUCLEAR POWER PROGRAMME

The basic philosophy behind India's nuclear power programme is to make use of the existing limited quantity of natural uranium to install thermal reactors of the heavy water type during the first stage. The plutonium produced in these heavy water reactors will then be used to feed fast breeder reactors which will in turn convert the depleted uranium recovered from the spent fuel discharged from the heavy water reactors or the thorium from our vast reserves. The economics of the two possibilities has yet to be worked out on the basis of experiment. The total installed capacity from thermal reactors could be of the order of 10,000 to 13,000 MWe and the total capacity from breeder reactors can grow to many hundreds of thousands of MWe.

Growth of the installed nuclear capacity is bound to be relatively slow at the beginning especially if it is planned on the basis of self reliance. Nuclear power technology requires a special infra structure since many of the components and equipment have to be manufactured for the first time in India. A programme based on self reliance has been one of our important objectives, but this means that a certain price has to be paid for it. This could be in the form of somewhat higher capital costs and/or considerable delay in project commissioning. The political atmosphere in the world at the moment is against free trade of nuclear components. In spite of all these restraints India has made remarkable progress in getting local industry to fabricate many sophisticated and complex items of nuclear equipment. The development of such capabilities involves a good deal of effort in design, quality control and testing of equipment before they are actually used in a power plant. It is a matter of pride to us that today, special nuclear equipment like fuelling machines, reactor vessels, heat exchangers etc. are entirely made in India and routinely tested at the Bhabha Atomic Research Centre, before they are installed in nuclear power plants.

In conclusion, I can state that a careful analysis indicates that nuclear power is the only answer to the energy problem of the world and in particular India. It has been demonstrated to be a safe and economic way of producing energy from otherwise useless materials. The economics of it seem to get better each day and the safety problems are well understood. It certainly requires a degree of sophistication in the fabrication and maintenance of its various components. But this is well within our capacity. I believe this is the time to invest wholeheartedly in nuclear power. Just on the passing fancies of people elsewhere we should not allow this great gift of nature and man's control of it, to slip from our hands at the most critical time of our economic history.

Thirty-ninth J. C. Bose Memorial Lecture delivered on Nov. 30, 1977 at Calcutta.

Table 1

STATE-WISE DISTRIBUTION OF HYDEL POWER POTENTIAL

Sr. No.	State	Potential MWe Average	Potential MWe Maximum
1.	Andhra Pradesh	1,486	2,476
2.	Assam, Meghalaya, Nagaland and Mizoram	6,960	11,599
3.	Bihar	366	610
4.	Gujarat	406	677
5.	Jammu & Kashmir	2,154	3,590
6.	Kerala	924	1,540
7.	Madhya Pradesh	2,749	4,582
8.	Tamil Nadu	425	708
9.	Maharashtra	1,146	1,910
10.	Karnataka	2,024	3,373
11.	Orissa	1,237	2,062
12.	Punjab & Haryana	188	1,360
13.	Rajasthan	39	149
14.	Uttar Pradesh	2,258	3,764
15.	West Bengal	13	22
16.	Himachal Pradesh	1,748	1,868
17.	Manipur	519	865
18.	Sikkim	564	n. a.
	Total	25,206	41,155

Table 2

LIST OF MAJOR THERMAL POWER PLANTS IN INDIA

(In Operation and Under Construction)

Sr. No.	Thermal Power Station	Capacity (MWe)
1	Badarpur	500
2	Bandel	350
3	Barauni	155
4	Basin Bridge	90
5	Bhatinda	440
6	Bhusaval	62.5
7	Bokaro	400
8	Chandrapura	544.5
9	Dalakola	240
10	Dhuvaran	534
11	Durgapur	290
12	Ennore	340
13	Faridabad	125
14	Gorakpur	200
15	Harduagang	300
16	Indraprastha	284
17	Kalaghat	400
18	Koradi	480
19	Korba	300
20	Kota	330
21	Kothagudam	220

Cont'd....

22	Namrup	30
23	Nasik	280
24	Neyveli	600
25	Obra	1550
26	Panipat	220
27	Panki	220
28	Paras	92.5
29	Ramagundam	500
30	Renukoot	130
31	Sabarmati	217.5
32	Santaldih	480
33	Satpura	312.5
34	Talcher	250
35	Tenughat	400
36	Trombay	250

PRESENTLY SANCTIONED PROJECTS

1.	Bokarao 'B'	210 MWe
2.	Korba East	120 "
3.	Korba West	420 "
4.	Nasik Extension	420 "
5.	Parli	210 "
6.	Satpura Extension	420 "
7.	Singrauli	1510 "
8.	Trombay Extension	500 "
9.	Tuticorin	210 "
10.	Wanakbori	630 "

Table 3

ENERGY POTENTIAL FROM COAL AND NUCLEAR FUELS

FUEL	ENERGY, Kwh(e)
Coal	160×10^{12}
Uranium in Thermal Reactors	7.2×10^{12}
Uranium in Fast Reactors	208×10^{12}
Thorium in Thermal Reactors	0
Thorium in Fast Reactors	1280×10^{12}

Table 4

CAPITAL OUTLAY FOR COAL FIRED POWER PLANTS AND NUCLEAR POWER PLANTS
(1977 Costs)

COAL FIRED

	Cost Component		Investment Rs/Kwe
1.	Power Station		4,500
2.	Coal Mines		750
3.	Coal Transportation		1,000
		Total	6,250

NUCLEAR

	Cost Component		Investment Rs/Kwe
1.	Power Station		5,000
2.	Heavy Water Plants		495
3.	Uranium Exploration		65
4.	Uranium Mining		295
5.	Fuel Fabrication		185
6.	Fuel Reprocessing		135
		Total	6,175

APPENDIX I

FIGURE OF MERIT OF ENERGY SOURCES

Energy sources may be characterised by certain intrinsic figures of merit which describe their potential utility to man. These are its (a) concentration and (b) quality.

Concentration : Can be defined as energy per unit volume or energy per unit mass. For a flowing energy source such as solar or wind energy the relevant measure is energy flux i. e. energy crossing unit area per unit time. Other factors being equal, higher the degree of concentration the "better" the energy source. Extraction, transportation, storage, handling etc. become easier and cheaper.

'Quality' of an energy source may be related to the fraction of the total energy that is available for use based on such thermodynamic considerations as source (T_c) and sink (T_o) temperatures. T_c may be deduced from

$E \simeq kT_c$ where E = energy/bond (chemical energy)

or energy/molecule (thermal energy)

or energy/photon (radiant energy)

and k = Boltzman's constant

T_c may also be referred to as its "Characteristic Temperature" since it is a measure of the "energy per unit entropy" of the system.

Table I summarises the concentration and quality (i. e. characteristic temperature) of several energy sources. It may be noted that both fission and fusion nuclear sources are far superior by several orders of magnitude on both the counts of concentration and quality as compared to all other sources of energy.

Table II gives the limits factors of various energy sources.

Table I

CONCENTRATION AND QUALITY OF ENERGY SOURCES

Sr. No.	Energy Source	Energy Density or Flux	Characteristic Temperature (°K)
1)	Uranium Fission	$\sim 10^{11}$ kwh/m^3	$\sim 10^{11}$
2)	Deuterium Fusion	$\sim 10^{7}$ kwh/m^3	$\sim 10^{10}$
3)	Fossil (coal & oil)	$\sim 10^{4}$ kwh/m^3	$\sim 10^{4}$
4)	Hydro Power (30 m water head)	$\sim$0, 8 kwh/m^3	-
5)	Solar	$\sim$1 kw/m^2	$\sim 6 \times 10^{3}$
6)	Wind	$\sim$0, 5 kw/m^2	-
7)	Geothermal	$\sim 10^{-5}$ kw/m^2	$\sim 5 \times 10^{2}$

Table II

LIMITING COMPONENTS, PHYSICAL PROCESSES AND ENERGY FLUXES IN DIFFERENT TYPES OF POWER GENERATORS

Sr. No.	Primary Energy Device	Energy Transformation	Limiting Component	Limiting Physical Process	Energy Flux (kw/m^2)
1)	Tokamak (Fusion)	Nuclear/Thermal	Plasma density and containment time	Electron to ion energy transfer	3×10^2 kw/m^2
2)	Laser Fusion	Nuclear/Thermal	First wall neutron loading	Radiation damage in first wall	10^3 kw/m^2
3)	Migma Cell	Nuclear/Electric	---	---	---
4)	Fission	Nuclear/Thermal	Fuel Rod Surface Area	Fuel rod conductivity (Melting point)	10^4 kw/m^2 (This explains incentive for carbide fuels in fast reactors)
5)	Fuel Cells	Chemical/Electric	Electrode surface area	Rate of diffusion of electrolytes	0.2 kw/m^2
6)	Solar	Radiation/Thermal or Electric	Collector Area	Incident flux of radiant energy	0.3 kw/m^2
7)	Wind	Mechanical/Mechanical	"Sail" area	Low density of wind power	0.5 kw/m^2
8)	Geothermal	Thermal/Thermal	Heat transfer area of pipes	Thermal condictivity of rocks	

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