# ALTERNATIVE NEW ENERGY OPTIONS FOR BRAZIL

James A. Lane

(with assistance of Pedro B. Camargo)

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Nota: A redação, ortografia e conceitos são de responsabilidade dos autores

## FOREWORD

This study was sponsored by Dr. R. Pieroni, Director, Institute of Atomic Energy, São Paulo, Brazil. The English version of the study was prepared by James A. Lane of the Institute for Energy Analysis, Oak Ridge, Tennessee, USA acting as a consultant to the IAE. The Portuguese version was prepared by Pedro Bento de Camargo of the IAE. Typing of both versions of the draft was done by Miss. Célia Maria J. Medeiros of IAE.

Assistance in providing information, was received by other members of IAE including Dr. R. R. Pieroni, Dr. R. R. Franco, Dr. A. Abrão, and Library staff.

The National Balance – 1978 provided most of the historical data on energy consumption and forecasts to the year 1987.

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# ALTERNATIVE NEW ENERGY OPTIONS FOR BRAZIL

## CHAPTER 1, INTRODUCTION

### 1.1 – PURPOSE OF STUDY

The National Energy Balance, base year 1977, was approved by the Minister of Mines and Energy in July 1978. It is to be reviewed annually and is intended to be a basic planning instrument for Brazilian energy policy. Historical data for the years 1967 to 1977 and forecasts for the years 1978 to 1987 are presented. Energy sources covered are (1) water power (2) coal (3) firewood, bagasse and charcoal (4) natural gas (5) alcohol (6) uranium (7) shale oil (8) petroleum and (9) electric energy. Other sources of energy such as solar, eolic, and tidal power are not included in the Energy Balance but will be kept in mind in the light of the domestic energy profile.

Contributors to the National Energy Balance include the Ministry of Mines and Energy, Petrobrás, Eletrobrás, Nuclebrás, and the National Petroleum Council.

In view of this excellent on – going effort, it is not the purpose of this study to either replace or supplement the National Energy Balance but rather to present a brief survey of the technology, state of development and economics of each of the new alternative energy sources which might at some time in the future become a viable energy option for Brazil. Since many of the sources considered are in an early stage of development with respect to commercialization, it has been necessary to look at both "near term" (1986 – 1990) and "longer term" (2000) energy demand in Brazil. Extrapolation of the forecasts given in the National Energy Balance from 1987 to the year 2000 has been done primarily on the basis of judgement. These longer term forecasts are not intended to be definitive but to give some perspective to Brazil's energy situation in the more distant future.

Although most of the technical and economic information presented here is derived from experience in industrialized countries, particularly the United States; wherever possible, the Brazil "scene" is emphasized.

### 1.2 – METHOD OF APPROACH

This study is essentially a literature survey combined with the author's own work and calculations for which he takes full responsibility. Although there is an over abundancy of articles, books and reports on alternative new sources of energy only the latest most up-to-date literature was used. In most cases, this was of late 1977 – early 1978 vintage. The sequence chosen for presentation of the information starts with a brief summary of the important findings. Then follow chapters 4 – 6 covering the three nuclear options, uranium (fission reactors), thorium (thermal breeders or near breeders) and fusion (magnetic and inertial confinement). Chapters 7 – 11 cover the possible new sources of liquid and gaseous fuels (alcohol, shale oil, biomass conversion, synthetic fuels from coal and hydrogen from water). Chapter 12 deals with geothermal energy in Brazil and the final three chapters cover solar energy options (solar radiation, wind, and oceanic energy).

# CHAPTER 2, SUMMARY OF FINDINGS

## 2.1 – OVERALL FINDINGS

The goal of Brazil's National Energy Plan is to minimize dependency on imported oil. This goal is expected to be achieved in two ways: (1) a switch from direct fuel use to electricity wherever possible and (2) the increased use of indigenous resources to produce liquid fuels. Although in 1977 the domestic production of crude oil only amounted to 16% of demand, the oil and gas share of Brazil's total energy consumption was only about 43% compared to about 70% for most industrialized countries. The reason for this was the large contribution of hydropower (25%) and wood, bagasse and charcoal (26%).

In the near term (1987) the contribution of hydropower will increase to 33% of total energy consumption but in the longer term (2000) will drop back to about 28% because of limited resources of economical hydropower sites. The potential gap created by the growing demand for electricity will be met by nuclear power. Other sources of electricity will have only minor imports.

In the fluid fuel sector, the two main hopes for reducing oil imports are alcohol from sugar cane in the near term and shale oil in the longer term. Other sources of liquid and gaseous fuels are not likely to make any significant impact untill well after the year 2000.

Wood, bagasse and charcoal are currently an important source of energy in Brazil and the consumption of these materials will continue to increase. On a relative basis, however, their contribution will decline to about 16% of total energy by 1987 and to about 8% in the year 2000.

## 2.2 – THE LIQUID FUEL SECTOR

The demand for liquid and gaseous fuels in terms of percentage of total consumption will drop from 45% in 1977 to 40% in 1987 and 2000.

The demand for petroleum, which must be supplied domestically or from imports, however, might be expected to decline from 43% of total consumption in 1977 to 36% in 1987 and 29% in the year 2000. The main contributors to this declining demand for petroleum will probably be shale oil and alcohol.

## 2.3 – THE ELECTRICITY SECTOR

In 1977, about 93% of the electricity production came from hydropower, the remainder, mainly from coal-fired plants. Hydro's share of electricity production might decline to about 85% in 1987 and 63% in the year 2000. Fossil-fired power production will drop to about 5% of total electricity in 1987 and remain at that level to the year 2000. The contribution of nuclear LWR's will reach about 10% in 1987 and 32% in the year 2000. The electrical share of total energy consumption which amounted to 27% in 1977 is expected to increase to 38% in 1987 and 46% in the year 2000.

## 2.4 – THE NUCLEAR OPTIONS

**a) Uranium**

Brazilian resources of $U_3O_8$ as of the end of 1977 are estimated at about 67,000 tons compared to a 27,000 tons estimate one year earlier. The increase is primarily a result of new discoveries at Amorinópolis in the State of Goias. Even more recent discoveries at Itatira in the State of Ceará and Caitité in Bahia State promise to extend these reserves considerably.

The present official goal of the Brazil nuclear program as described in a "white paper" published in March 1977 is to have 10 GWe of LWR nuclear capacity in operation by the end of 1990. Some slippage of this program might be anticipated. There is no official long term goal of the nuclear program; however, Nuclebras/Furnas estimates in 1975 indicated a need for as much as 80 GWe of nuclear power by the year 2000. In view of the present high costs of nuclear plants and corresponding electricity costs, a more modest goal of 40 GWe in 2000 would seem to be more realistic.

### b) Thorium

Reserves of thorium in Brazil are about 66,000 tons $ThO_2$ which would be sufficient to supply the fertile material for more than 600 GWe of thorium fuelled reactor capacity. Unfortunately, the development of a nuclear industry of this magnitude does not depend on the availability of fertile material which is in abundant supply, but on the supply of fissile material. Thus an indigenous thorium resource does not justify a thorium reactor program. Although a considerable amount of research and development has been carried out on thorium reactors, there is no commercial supplier of large thorium-fuelled reactors. The development of a thorium based nuclear program in Brazil, therefore, would require several decades and many billions of dollars before commercialization could be achieved. The present Brazil nuclear program based on light water reactors appears to be a much sounder course of action.

### c) Fusion

Both the magnetic confinement and inertial confinement approaches to generating fusion energy are at a stage in technology where commercial plants are not expected to be available until well after the year 2000. This source of energy, therefore, can not make any contribution to Brazil's energy supply within the time frame of interest.

## 2.5 – NEW SOURCES OF FLUID FUELS

### a) Alcohol

The production of alcohol from sugar cane has traditionally been carried out as a by-product of the sugar industry. In 1976, the National Alcohol Plan was inaugurated to encourage the growing of cane exclusively for the production of alcohol. This program is moving successfully and by the early 1980's sufficient alcohol should be produced to replace 20% of the gasoline consumed in the country. Higher percentage mixtures of alcohol and gasoline might be used at a later time, however, this would involved technical changes in automobile engine design and would result in more costly fuel. The feasibility and economics of using mixtures containing more than 20% alcohol then, will depend on future world oil prices and other factors. This study assumes that alcohol production will be held to the 20% mixture limit.

### b) Shale oil

Brazil's reserves shale oil are second in the world only to the USA and constitute an energy resource many times that of Brazil's petroleum and natural gas. The incentive to develop this source of fuel, therefore, is very great. Unfortunately, technical problems, as well as costs, stand in the way of a large scale development. A modest start has been made in Brazil on the extraction of hydrocarbon fuel from oil shale. If this approach in pursued with vigor, as much as 20% of the petroleum demand in the year 2000 might come from shale oil.

**c) Biomass Conversion**

The technology of the conversion of organic solid materials to liquid and gaseous fuels is well understood. The problem here is one of logistics (transporting material to process plants) and costs. In addition to the sugar cane-alcohol conversion program, there are some biomass conversion areas of interest in Brazil; however, it is unlikely that these will become important sources of liquid and gaseous fuels.

**d) Synthetic Fuels from Coal**

Brazil's coal resources are quite small and would be inadequate to support a large synthetic fuel program. No contribution is expected from this source.

**e) Hydrogen From Water**

With the exception of electrolysis, the technology of producing hydrogen by splitting water is in relatively low stage of development. In the case of electrolysis, costs are too high to make this a competitive source of hydrogen unless very low cost electricity (less than 5 mills/kWh) is available. Although there may be some hydro power sites in Brazil which could generate such low cost electricity, this approach would require considerable more study to determine its feasibility.

## 2.6 – GEOTHERMAL

Although the overall geology of Brazil is not conducive to the development of geothermal, there is one area, Poços de Caldas, that shows evidence of past volcanic activity and magmatic activity in the form of hot springs. The chemical composition and other characteristics of the water from these springs should be studied to determine whether further exploration is warranted.

## 2.7 – SOLAR ENERGY OPTIONS

These options (solar radiation, wind, oceanic energy) are in a very early stage of development, but they are being taken very seriously in some industrialized countries such as the United States. Large research and development programs are underway, which if successful, could lead to commercially viable systems within the next two decades. Ultimately, this technology could also be used in Brazil. Because of the time lag associated with technology transfer, however, the solar energy options are unlikely to make any impact within this century.

# CHAPTER 3, THE IMPORTANCE OF PETROLEUM AND NATURAL GAS

## 3.1 – WORLD OIL SITUATION

From an oil supply and demand standpoint, the important areas of the world to consider are those outside of the Communist Blóc (CMEA) and Mainland China. The reason is that most experts believe that CMEA countries and Chir~ will be either self-sufficient with respect to oil supplies or slight exporters of oil. In addition, not much is known about the oil resources of these countries. Thus it is convenient to consider only the so-called WOCA (World Outside Communist Areas) countries[1].

An important factor in evaluating the future oil supply and demand situation is the estimated oil resource in WOCA. These are shown in Table 1 taken from the WAES report. In should be pointed out that these are "proven" reserves. According to Moody and Geiger[2] ultimate recoverable reserves in WOCA may be of the order of 1500 billion barrels or about three times the proven reserves.

TABLE 1

**WOCA Reserves and Cumulative Production to End of 1975**

| Region | Cumulative Production to End 1975 (billion barrels) | Remaining Proven Reserves (billion barrels) |
|---|---|---|
| North America | 133 | 40 |
| Western Europe | 2 | 25 |
| OPEC | 139 | 450 |
| Rest of WOCA | 17 | 40 |
| Total WOCA | 291 | 555 |

WAES forecast of WOCA oil demand to the year 2000 in millions of barrels of oil per day (MBD) is given in Table 2 (based on their C-1 scenario). It is seen that oil demand will just about double in the period from 1975 to the year 2000.

TABLE 2

**WOCA Oil Demand Forecast, MBD[1]**

| Region | 1975 | 1985 | 2000 |
|---|---|---|---|
| North America | 18,2 | 20,0 | 22,7 |
| Western Europe | 12,6 | 14,8 | 20,0 |
| Japan | 5,3 | 8,6 | 15,6 |
| OPEC | 1,5 | 3,1 | 7,0 |
| Rest of WOCA | 5,5 | 11,1 | 20,3 |
| | 43,1 | 57,6 | 85,7 |

[1] 1 MBD = 50 million metric tons/year

(1) C.L. Wilson, Energy: Global Prospects 1985-2000. Report of the Workshop on Alternative Energy Strategies (WAES Report), 1977

(2) J.D. Moody and R.E. Geiger, Techonology Review, Mar/Apr, 1975.

With this rate of consumption all of the presently known proven reserves would be exhausted by the year 2000. However, recent exploration activities show that future oil discoveries might be expected to add from 10 to 20 billion barrels per year to the year 2000 (250 – 500 billion barrels of new oil). Thus the remaining recoverable oil in the year 2000 would be of the same order of magnitude as at the end of 1975.

It can be seen from Tables 1 and 2 that most of the oil reserves and very litle of the demand is in the OPEC countries. Thus these countries will be the future main suppliers of oil to the rest of WOCA. Table 3 shows WOCA oil production forecasts made by WAES. Comparing production rates with demand rates shows that oil supply and demand in WOCA will be in balance through 1985 but by year 2000 there will be a 13,7 MBD shortfall. The 45 MBD of oil production by OPEC in the year 2000 is the upper limit assumed by WAES. It represents a 50% increase over OPEC production in 1977 (30 MBD).

TABLE 3

WOCA Oil Production Forecasts, MBD

| Region | 1975 | 1985 | 2000 |
|---|---|---|---|
| North America | 11,7 | 14,1 | 12,1 |
| Western Europe | 0,6 | 4,5 | 3,1 |
| OPEC | 26,8 | 32,4 | 45,0 |
| Rest of WOCA | 4,0 | 6,6 | 11,7 |
| Total | 43,1 | 57,6 | 71,9 |

The desired net import requirements of WOCA are shown in Table 4. Here it is seen that required imports from OPEC increase from 25,3 MBD in 1975 to 51,7 MBD in the year 2000.

TABLE 4

WOCA Desired Net Import Requirements, MBD

| Region | 1975 | 1985 | 2000 |
|---|---|---|---|
| North America | 5,5 | 5,9 | 10,6 |
| Western Europe | 12,0 | 10,3 | 16,9 |
| Japan | 5,3 | 8,6 | 15,6 |
| Non OPEC Dev. Countries | 1,5 | 4,5 | 8,6 |
| Total | 25,3 | 29,3 | 51,7 |

## 3.2 – THE OIL SITUATION IN BRAZIL

An excellent review of the oil situation in Brazil is given in the National Energy Balance-1978[1] (NEB 1978) and need not be repeated in detail here. Briefly, it shows that domestic production rates

(1) The National Energy Balance 1978. Report of the Ministry of Mines and Energy, Sept. 1978

have fallen from $8{,}65 \times 10^6$ tons (0,178 MBD) in 1974 to $7{,}56 \times 10^6$ tons (0,155 MBD) in 1977. Forecasted production rates, according to scenario (I) of the NEB 1978 show a peaking out of oil production in 1983 at $15{,}2 \times 10^6$ tons and subsequent reduction to $8{,}4 \times 10^6$ tons in 1987. Petroleum consumption, on the other hand, was $46{,}2 \times 10^6$ tons (including non-energetic uses) in 1977. Thus imports in 1977 amounted to $38{,}6 \times 10^6$ tons (0,794 MBD). The historical growth in demand for petroleum products is shown in Figure 3.1 (taken from NEB 1978). It is seen that the consumption of gasoline declined from 1976 to 1977, presumably because of the high prices to the consumers.

At the end of 1977, Brazil's recoverable reserves of oil amounted to $177 \times 10^6$ $m^3$ ($1113 \times 10^6$ barrels). At the forecasted production rates of Scenario I, 75% of the present proven reserves would be exhausted by 1987. Fortunately, fairly extensive exploration activities are underway both on land and offshore Brazil which are rapidly increasing the amount of proven reserves. Petrobras estimates that the 1977 figure may be increased by 20% by the end of 1978. If this exploration continues to be as successful, there is no reason why production rates of about $8 \times 10^6$ tons per year should not be maintainable to the year 2000.

The project demand for oil in 1987 according to NEB 1978 is $72.17 \times 10^6$ tons (1,48 MBD) corresponding to an average growth rate from 1977 of 4,6%/year. Assuming that this growth rate levels off at 4% from 1987 to 2000, the demand in the year 2000 would be 2,5 MBD resulting in an import requirement of 2.3 MBD or three times the 1977 figure. These imports represent about 4% of the total required imports from OPEC in the year 2000

## 3.3 – THE NATURAL GAS SITUATION OF WOCA

Natural gas is a clean desirable fuel and a valuable raw material for the petrochemical industry. Table 5 shows estimated reserves (from Moody and Geiger) and Table 6, present and forecasted consumption rates takes from the WAES report. It can be calculated from the data in these tables that only about 25% of the estimated ultimate recoverable WOCA reserves of gas will be consumed by the year 2000. Thus the availability of natural gas will not likely limit production within the time frame of interest here.

The future role of gas as an energy source will be determined not so much by supply but by the problem of transporting and distributing gas from the wells to the consumer. Because of such problems, intercontinental trade in gas was only 0,3 MBDOE in 1975. Plans to expand this trade by pipelining more gas from the USSR to Western Europe, by LNG (liquified natural gas) exports from OPEC and by pipeline exports from OPEC countries in the Middle East and North Africa.

Import requirements of the US of 1.2 MBDOE in 1985 and 2.8 MBDOE in the year 2000 will probably be met by pipeline gas from Mexico and Canada and LNG from OPEC. Japan's import requirements of 0,9 and 1,6 MBDOE in 1985 and 2000 respectively will also be met by LNG.

## 3.4 – THE NATURAL GAS SITUATION IN BRAZIL

At the end of 1977, estimated reserves of natural gas in Brazil amounted to $39{,}5 \times 10^9$ $m^3$ (253 MBOE). Consumption in 1977 was $1{,}81 \times 10^9$ $m^3$ and was met by domestic production. Thus the 1977 reserve/production ratio was 21.8. The consumption of gas as a source of energy in 1977 amounted to $0{,}56 \times 10^9$ $m^3$ (31% of total) the remainder is used for non-energetic purposes such as re-injection into oil wells and the production of nitrogenous fertilizers.

Natural gas consumed for energy purposes is estimated in NEB 1978 to increase at a rate of 9,6% per year from 1977 to 1987 resulting in a gas energy demand of $1.39 \times 10^9$ $m^3$ ($1.26 \times 10^6$ tEP). If

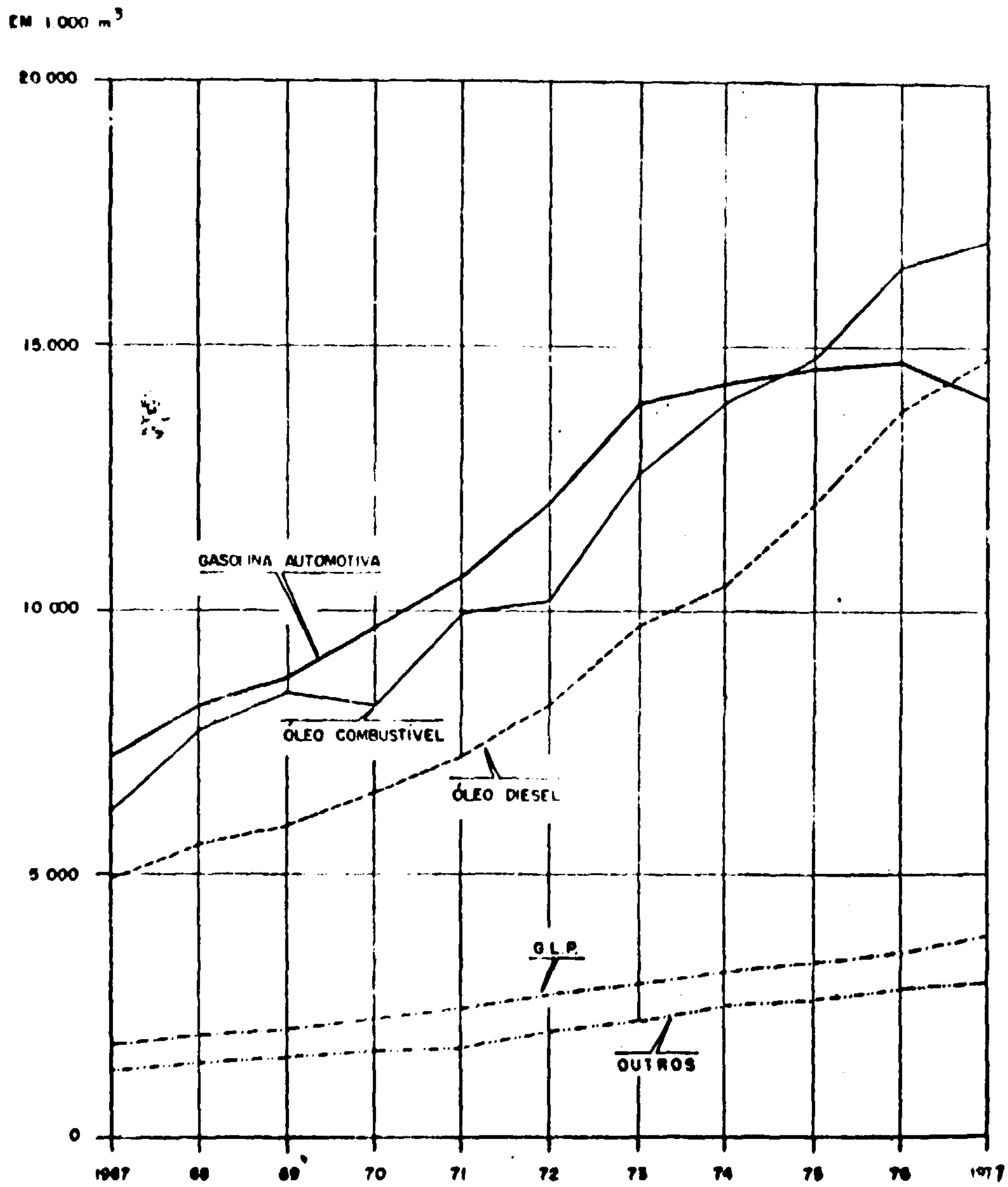


**Figure 3.1 – Historical Consumption of Petroleum Products in Brazil**

## TABLE 5

### Ultimate Recoverable Natural Gas Reserves in WOCA, BBOE[1]

| Region | Total Recoverable | Produced to End of 1975 | Remaining to be Recovered |
|---|---|---|---|
| North America | 284 | 88 | 196 |
| Western Europe | 77 | 12 | 65 |
| Middle East | 270 | 14 | 256 |
| Rest of WOCA | 348 | 20 | 328 |
| Total | 979 | 134 | 845 |

(1)BBOE = Billion Barrels Oil Equivalent

## TABLE 6

### Natural Gas Consumption in WOCA, MBDOE[1]

| Region | 1975 | 1985 | 2000 |
|---|---|---|---|
| North America | 11,3 | 11,3 | 10,8 |
| Western Europe | 3,1 | 5,0 | 6,1 |
| Japan | 0 | ,9 | 1,6 |
| Rest of WOCA | 2,1 | 4,5 | 9,0 |
| Total | 16,5 | 21,7 | 27,5 |

(1)MBDOE = Million Barrels/Day Oil Equivalent
1MBDOE = 0,365 BBOE/year = 57 billion $m^3$/year

non-energetic uses of gas increase similarly, total gas consumption in 1987 would amount to $4.5 \times 10^9$ $m^3$ ($28.3 \times 10^6$ BOE). It is expected that this would come from domestic sources.

## 3.5 – THE OVERALL IMPORTANCE OF OIL AND NATURAL GAS IN WOCA

During the past two decades oil and gas increased their share of energy consumption in WOCA from 35% to 70%. Table 7 shows the percentage share of oil and natural gas by regions based on the WAES study. It is seen in this table that both North America and Western Europe are decreasing their dependence on oil and gas, whereas the rest of WOCA is not.

## 3.6 – IMPORTANCE OF OIL AND GAS IN BRAZIL

Table 8 shows the consumption of fuels and electricity in Brazil in 1977 and forecasts for 1987 taken from NEB 1978. It is seen here that in 1977 the consumption of oil and gas accounted for $47{,}8 \times 10^6$ tEP or about 44% of the total. In 1987, the expected oil and gas share will drop to about 38%. This is considerably below the WOCA average because of the large amounts of hydropower available and relatively high consumption of wood, bagasse and vegetable carbon. Table 8 also shows the emerging importance of alternative fuels such as shale oil, alcohol and uranium.

Crude estimates of the growth in electricity and fuel consumption over the longer term (1988 to 2000) result in a total consumption of $440 \times 10^6$ tEP in the year 2000 (including non-energetic consumption of petroleum and natural gas). This consumption might be distributed as follows: hydropower (29%), nuclear (15%), petroleum (27%), natural gas (3%), coal (8%), wood, bagasse, charcoal (9%), alcohol (2%), shale oil (7%).

TABLE 7

Percentage Share of Oil and Gas in WOCA Total Energy Consumption

| Region | 1975 | 1985 | 2000 |
|---|---|---|---|
| North America | 72 | 61 | 43 |
| Western Europe | 66 | 64 | 57 |
| Japan | 72 | 73 | 72 |
| non-OPEC Dev. Countries | 65 | 65 | 63 |
| OPEC | 84 | 80 | 88 |
| Total for WOCA | 70 | 65 | 57 |

TABLE 8

Fuel and Electricity Consumption in Brazil ($tEP \times 10^6$)

| Source | | 1977 | 1987 | Growth Rate, %/yr |
|---|---|---|---|---|
| Hydropower | | 27,0 | 65,5 | 9,3 |
| Coal | | 4,1 | 11,2 | 10,6 |
| Wood, Bagasse Charcoal | | 28,1 | 31,7 | 1,2 |
| Petroleum | a) Energy | 43,1 | 64,5 | 4,1 |
| | b) Non-energy | 3,1 | 7,7 | 9,5 |
| Natural Gas | a) Energy | 0,5 | 1,3 | 9,6 |
| | b) Non-energy | 1,1 | 2,8 | 9,6 |
| Shale Oil | | – | – | – |
| Alcohol | | 0,5 | 3,9 | 22,8 |
| Uranium | | – | 7,8 | – |
| Total | | 107,5 | 198,7 | 6,3 |
| Electricity, TWh | | 99,9 | 263,2 | 10,2 |

# CHAPTER 4, URANIUM

## 4.1 – DESCRIPTION

### a) LWR and its fuel cycle

The fission of the uranium nucleus, U-235, as a result of neutron capture yields large quantities of heat which can be converted to electrical energy. Nuclear fission is not really a new source of electrical energy because commercial power reactors have been in operation for more than 20 years. Although there are at least 12 different types of nuclear plants in operation at the present time, the predominant type is the light water reactor (LWR) which comprises 87% of the existing or planned capacity of nuclear plants throughout the world.

The LWR uses ordinary water both as the coolant to transport the heat released in fission and as a moderator to slow down the fast neutrons produced in fission thus increasing the probability of neutron capture by the U-235 atoms. In contrast to natural uranium which contains 0,7% U-235 atoms, the fuel for LWR's consists of uranium enriched to about 3% U-235. This fuel is in the form of $UO_2$ pellets inside Zircaloy tubes.

There are two types of LWR's, the Pressurized Water Reactor (PWR) and the Boiling Water Reactor (BWR) which differ primarily in the way the water is used as the coolant. In the PWR, the water is maintained under sufficient pressure so that it passes through the reactor core inside of a pressure vessel without boiling and transfers the fission heat to a steam generator outside of the pressure vessel. Steam from the generator is sent to a turbine driving an electricity generator. In the BWR system, on the other hand, the water inside of the reactor vessel is allowed to boil and the resulting steam after passing through water separators and driers (also inside of the pressure vessel) is sent directly to the turbine.

These two methods of heat removal lead to physical differences in PWR's and BWR's. The PWR pressure vessel, for example, is smaller than that for the BWR but requires greater wall thicknesses. The PWR also requires large steam generators which are absent in the BWR. The turbine of this latter reactor type, however, must be shielded because of the slight radioactivity of the steam.

Despite these physical differences; however, the cost of generating eletricity in PWR's and BWR's is approximately the same. Nevertheless, more than 70% of the planned nuclear capacity of the United States is in the form of PWR's where as on a world-wide basis the ratio of PWR's to BWR's is about 2.5 to 1. Brazil's nuclear program also centers on PWR's.

The reasons why PWR's appear to dominate the world nuclear industry are not clear; however, they may include the following: (1) there are about twice as many major suppliers or PWR's as BWR's (2) the performance of PWR's (at least in the United State) has been slightly better than that of BWR's and (3) some people claim that offers of "packaged deals", in which guarantees of future uranium supplies were tied to reactor purchases have led to unwarranted sales of PWR's.

Both the PWR and BWR use the same basic fuel cycle in which slightly enriched ( ~ 3% U-235) uranium is loaded into the reactor and allowed to remain there about 3 years. During this time, excess neutrons are captured by non- fissionable U-238 to generate plutonium. Some of this plutonium also fissions while in the reactor; however, at the time it is discharged, the spent fuel contains about 6 grams fissile plutonium and 10 grams U-235 per kilogram heavy metal. It also contains large amounts of radioactive fission products which must be separated from the Pu and U-235 before these fissile isotopes can be re-used. Since the cost of shipping and reprocessing spent fuel elaments just about equals the value of the recovered isotopes, there is no great economic incentive for their recovery. Thus at the present time, most nuclear plant operators plan to store spent fuel (this is requirement in the United States) rather than send it to a reprocessing plant. In the long run, however, reprocessing may be necessary as a means of alleviating the spent fuel storage problem and to provide plutonium for future breeder reactors.

**b) Other reactor types**

Of the reactor types in operation throughout the world such as the, pressurized heavy water reactor (PHWR), gas-cooled reactor (GCR), advanced gas reactor (AGR), high temperature gas reactor (HTGR), light water cooled, heavy water moderated (LWC HW), liquid. metal fast breeder reactor (LMFBR) and light water cooled, graphite moderated reactor (LGR), only the PHWR can be considered comercially awailable. The remaining reactor types are either in an experimental stage or available only within a country (UK, India) or a group of countries (CMEA). In any event the PHWR represents only 4,5% of existing and ordered nuclear capacity and all of the other types, 8,4% of the capacity.

Most of the PHWR's sold commercially are of the CANDU type developed by AECL of Canada. This reactor uses heavy water as the coolant and moderator and operates on natural uranium instead of slightly enriched uranium. In contrast to LWR's which use large pressure vessels, CANDU reactors are based on the pressure tube concept. Here, the heavy water coolant flows through pressure tubes containing the uranium fuel elements and generates light water steam in an external heat exchanger. The pressure tubes are located inside a callandria (thin walled tank) containing the heavy water moderator at essentially atmospheric pressure. Since CANDU reactors use natural uranium, fuel exposure times are only 25% of those for LWR's.

In this case, fuel cycle economics dictate the use of spent fuel storage than reprocessing.

## 4.2 – APPLICATIONS OF NUCLEAR FISSION

Numerous applications of fission reactors have been studied such as the use of the primary heat for industrial processes, the use of waste heat for desalination of sea water or the use of power reactor for ship propulsion; however, for technical and economic reasons non of these applications is likely to become very important within this century. Thus when discussing nuclear fission as a source of energy one is really refering to its use for the production of eletricity in central station power plants.

## 4.3 – STATUS OF THE TECHNOLOGY OF COMMERCIAL NUCLEAR PLANTS

**a) World plans for LWR's and other reactor types**

As shown in Table 1, by June 30, 1978 there were 525 nuclear power units in operation, under construction, or on order (1). These represent an installed net capacity of 408,285 MWe. Of this capacity, 87%, or 355,094 MWe is distributed among 405 LWR units.

Table 2 shows how LWR and other types of nuclear plants are distributed among the 34 countries with nuclear programs. Here it is seen that in terms of GWe of existing or ordered nuclear capacity, the 10 countries with the largest programs are USA (195.7 GW), France (41.8), FRG (26.9), USSR (20.9), Japan (17.6), Canada (15.3), Spain (15.2), U.K. (11.8), Sweden (9.4) and Belgium (5.5). These 10 countries represent more than 88% of the nuclear capacity ordered up to mid 1978.

**b) The Brazilian Nuclear Program**

Brazil's nuclear program is thus for based entirely on PWR's. The first plant of this type, ANGRA-I, with a net capacity of 626 MWe is expected to come into operation by mid 1979. The next two plants (ANGRA II and III) each with a net capacity of 1245 MWe will come on stream in accordance with the Brazilian – German agreement. With ANGRA I, they will form a nuclear Central Unit named Almirante Alvaro Alberto. Expected operating dates are of the order of 1984 and 1986.

(1) Nuclear News, August 1978.

## TABLE 1

### WORLD DISTRIBUTION OF REACTORS BY TYPE[1]

| REACTOR TYPE[2] | MWe (net) | NUMBER OF UNITS | % of CAPACITY |
|---|---|---|---|
| PWR | 257,746 | 286 | 63.1 |
| BWR | 97,348 | 119 | 23.8 |
| PHWR | 18,029 | 34 | 4.4 |
| GCR | 15,062 | 49 | 3.7 |
| LGR | 15,760 | 23 | 3.9 |
| MISC | 4,340 | 14 | 1.1 |
| | 408,285 | 525 | 100.0 |

(1) In operation, under construction or on order as of June 30, 1978

(2) PWR = Pressurized Water Reactor
BWR = BOILING Water Reactor
PHWR = Pressurized Heavy Water Reactor (CANDU)
GCR = Gas Cooled Reactor
LGR = Light Water Graphite Moderated
MISC = LMFBR etc.

# TABLE 2

## WORLD DISTRIBUTION OF REACTORS BY COUNTRY

| COUNTRY | LWR's MWe | LWR's Nº Units | OTHER TYPES MWe | OTHER TYPES Nº Units |
|---|---|---|---|---|
| Argentina | | | 919 | 2 |
| Austria | 692 | 1 | | |
| Belgium | 5475 | 7 | | |
| Brazil | 3116 | 3 | | |
| Bulgaria | 1760 | 4 | | |
| Canada | | | 15270 | 24 |
| Czechoslovakia | 1760 | 4 | 110 | 1 |
| Egypt | 622 | 1 | | |
| Finland | 2160 | 4 | | |
| France | 38110 | 39 | 3708 | 10 |
| Germany (DR) | 2710 | 7 | | |
| Germany (FR) | 26276 | 26 | 647 | 3 |
| Hungary | 1760 | 4 | | |
| India | 400 | 2 | 1284 | 6 |
| Iran | 4200 | 4 | | |
| Italy | 5105 | 7 | | |
| Japan | 16980 | 24 | 659 | 3 |
| Korea | 3157 | 4 | 629 | 1 |
| Luxemburg | 1250 | 1 | | |
| Mexico | 1308 | 2 | | |
| Netherlands | 493 | 2 | | |
| Pakistan | | | 125 | 1 |
| Philippines | 1252 | 2 | | |
| Poland | 440 | 1 | | |
| Rumania | 440 | 1 | | |
| South Africa | 1844 | 2 | | |
| Spain | 14703 | 17 | 480 | 1 |
| Sweden | 9397 | 12 | | |
| Switzerland | 4960 | 7 | | |
| Taiwan | 4924 | 6 | | |
| United Kingdom | | | 11780 | 39 |
| United States | 194138 | 198 | 1540 | 3 |
| USSR | 5065 | 12 | 15850 | 24 |
| Yugoslavia | 615 | 1 | | |
| | 355095 | 405 | 531J1 | 120 |

In operation, under construction or on order as of June 30, 1978

In continuation of the program, units similar to ANGRA II and III will be put into operation under the Brazil-German agreement. The location and operating data of these plants has not yet been specified; however, the goal of the present nuclear program is to have approximately 10000 MWe of nuclear capacity in operation by 1990. Longer range goals call for as much as 80 GWe (80000 MWe) by the year 2000.

In 1977 the Federal Government of Brazil published a "White paper" outlining official policy on the Brazilian Nuclear Program. Subjects covered in this paper included (1) The Need for The Nuclear Option (2) The Agreement for Cooperation between the FRG and Brazil (3) The Application of International Safeguards and (4) Brazil and the Non-Proliferation of Nuclear Weapons.

A major element of this policy is that Brazil can no longer plan its economic development on the basis of imported oil which has become expensive and the future availability of which is uncertain. Thus there will be an increasing shift toward the use of electricity based on indigenous energy sources. It is estimated that by the year 2000, an installed electrical capacity of 180 GWe to 200 GWe will be required. This level of demand in any case exceeds the hydroelectrical potential existing in Brazil even if the latter were entirely usable from the economic and technical points of view. The balance, therefore, has to be made up by an alternative energy source. The Government of Brazil considers nuclear energy to be the only viable alternative, especially because the country has reasonably large resources of natural uranium (about 67.000 tons $U_3O_8$). The possibility exists that considerably greater amounts will be discovered. A second important element of Brazilian policy is that the Government considers that it makes no sense to shift from dependency on foreign oil to dependency on foreign nuclear fuel cycle services. This implies the need to transfer to Brazil of all technologies involved in the nuclear fuel cycle. Since Brazil's planned nuclear program involves slightly enriched LWR's, these technologies must include enrichment and reprocessing.

Although some people fear that such an approach can lead to the increased proliferation of nuclear weapons, Brazil has taken step to insure that it will not. The white paper covers these steps in detail. These include an agreement among the Governments of FRG and Brazil with the IAEA on the application of International Safeguards on all nuclear activities in Brazil.

Brazil is also a party to the Treaty for the Prohibition of Nuclear Weapons in Latin America (Treaty of Tlateloco) which prohibits the manufacture or possession of nuclear weapons (including those belonging to weapon states).

Thus Brazil is convinced that it can develop a self-sufficient nuclear industry while at the same time meeting international objectives of non-proliferation.

## 4.4 – CURRENT ECONOMICS OF LWR's

### a) Investment Costs

This section is not intended to give a definitive estimate of the cost of the "next" plant in Brazil's nuclear program because such costs are site specific and are influenced by many factors too complex to cover in this brief study. What will be given here are some impressions of recent trends in costs in order to provide an indication of the current economics of LWR's.

Figure 1 shows how costs for a 1000 MWe LWR built in the United States have increased during the past ten years. Here it is seen that most of the increases can be attributed to indirect costs such as engineering, contingencies, escalation, and interest during construction. The reasons can be traced mainly to increased regulatory requirements, increased scope of supply and longer construction times.

This is the nuclear plant capital cost situation which prevails in the United States. Unfortunately, even

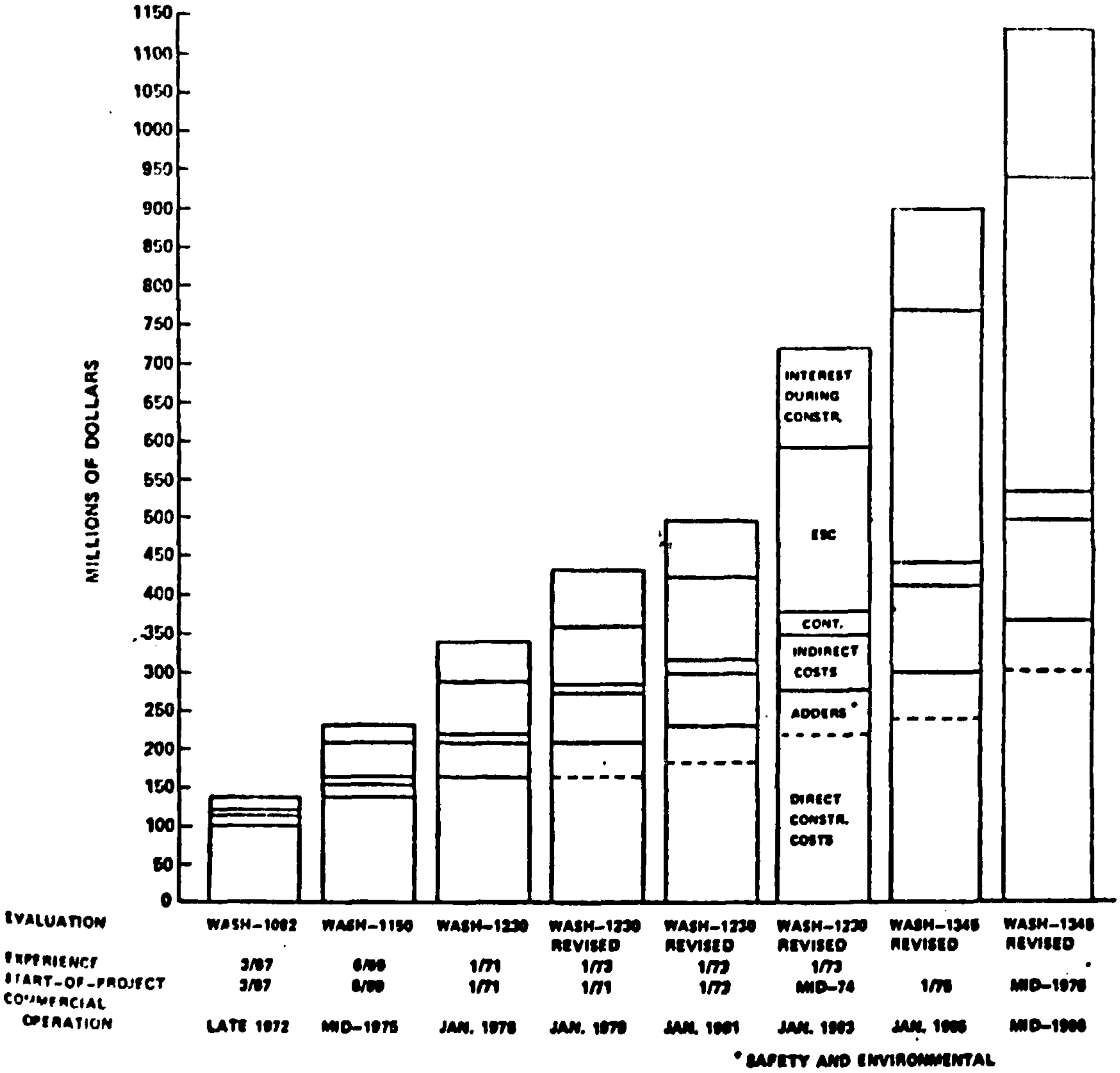


Figure 4.1 – Nuclear Plant Investment Cost Estimates Single 1000 MWE Light Water Moderated Reactor Plant

with lower construction labor cost which might be encountered in a country like Brazil, compensating factors more than offset these lower labor cost. The International Atomic Energy Agency has attempted to keep abreast of nuclear and conventional plant costs both in developed and developing countries and uses a computer code ORCOST, for making such cost studies. Up to date input data for the code are provided by consultants from countries with active nuclear construction programs. Table 3 shows costs developed from the ORCOST code given in terms of Jan 1978 U.S. dollars. Here costs at a hypothetical site, "Intertown" in a developing country have been extrapolated from cost at "Middletown", a hypothetical site in the U.S.A. In making this extrapolation, it was assumed that labor cost for a nuclear plant at Intertown would be 60% of those at Middletown. For this same plant, equipment cost were assumed to be 10% higher and engineering and construction management cost 14% higher than at Middletown. In the case of the oil-fired units, on the other hand, labor cost at Intertown were taken to be 40% of Middletown costs and other costs assumed to be the same.

**TABLE 5**

**Extrapolation of Costs to Developing Countries**

| Plant Type | Capacity MWe (net) | Unit Cost, \$/kW(1) Middletown, USA | Intertown |
|---|---|---|---|
| PWR | 600 | 1260 | 1285 |
| | 900 | 980 | 1000 |
| | 1200 | 820 | 845 |
| Low S. Oil | 600 | 485 | 395 |
| | 900 | 435 | 355 |
| High S. Oil | 600 | 550 | 450 |
| | 900 | 500 | 405 |

(1) Excluding Fuel and Escalation during Construction (jan 1978 U.S.\$)

The net result of these assumption, as seen in Table 3, is that nuclear plant costs at Intertown are slightly higher than at Middletown. Intertown oil-fired plant costs, however, are only 80% of those at Middletown.

**b) Fuel Cycle Costs**

It is axiomatic in the present energy situation that costs of alternative energy sources tend to seek their highest permissible level. This is apparent from Figure 2 which shows the $U_3O_8$ prince trend over the past 10 years. Exchange prices at which uranium would change hands on the specified date, increased from \$ 7/lb $U_3O_8$ at the end of 1973 to \$ 43/lb in early 1978. This trend closely paralleled that of world oil prices indicating that a uranium cartel probably existed similar to the OPEC cartel. Other nuclear fuel cycle cost trends are shown in Table 4.

The IAEA has developed a computer code, FUELCASH, which combines economic data, such as that given in Table 4, with technical data shown in Table 5. The final results are shown in Table 6 for a 626 MWe PWR similar to the ANGRA I nuclear plant. Extrapolation of these results to larger plant sizes as shown in Table 7 shows that fuel cost are not very sensitive to plant size.

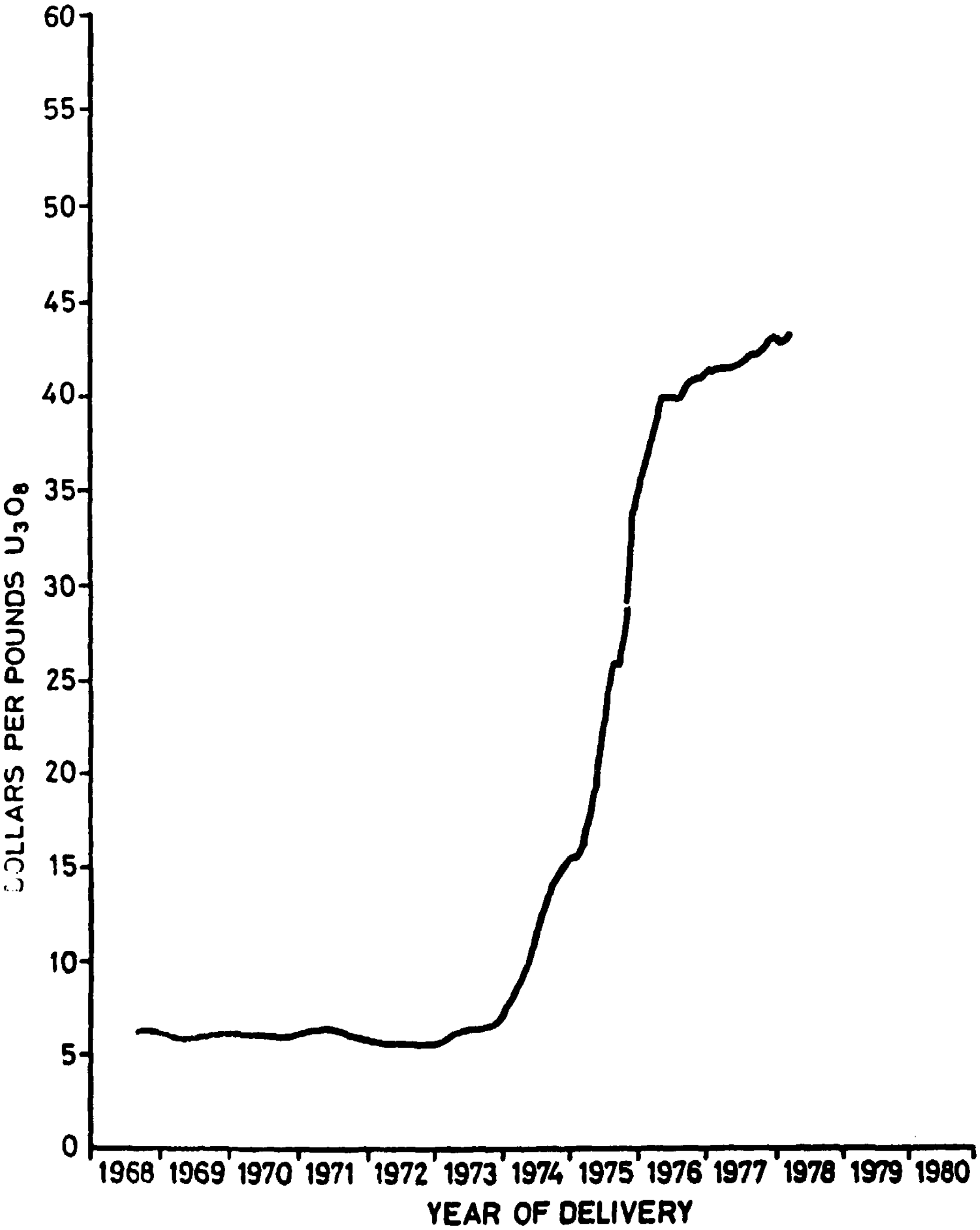


Figure 4.2 – Historical $U_3O_8$ Exchange Value

TABLE 4

Nuclear Fuel Cycle Cost Trends

| Item | | 1973 | 1978 |
|---|---|---|---|
| Natural $U_3O_8$, | \$/lb. | 7 | 40 |
| Conversion to $UF_6$, | \$/kg | 2.6 | 4 |
| Enrichment, | \$/S.W.U. | 32 | 100 |
| Fabrication, | \$/kg | 80 | 170 |
| Shipping, | \$/kg | 4 | 50 |
| Reprocessing, | \$/kg | 36 | 250 |
| Uranium Credit, | \$/kg | -35 | -150 |
| Plutonium Credit, | \$/g. | -10 | - 20 |
| Net Fuel Cycle Costs, | m/kWh | 1.68 | 7.30 |

TABLE 5

Basis for Fuel Cycle Cost Calculation
(Equilibrium Core)

| | |
|---|---|
| Initial Enrichment | 3.4 % U-235 |
| Final Enrichment | 0.95% U-235 |
| Enrichment Plant Tails | 0.25% U-235 |
| Burnup | 33,000 MWD/MT |
| Heat Rate | 10,242 Btu/kWh |
| Present Worth Factor | 0.10 |
| Natural U Lead Time(1) | 2.5 years |
| Enriching Lead Time(1) | 2.0 years |
| Fabrication Lead Time(1) | 1.5 years |
| Shipping Lag Time(2) | 0.75 years |
| Reprocessing Lag Time(2) | 1.00 years |

(1) Prior to charge date
(2) From discharge date

TABLE 6

Current Nuclear Fuel Cycle Costs (626 MWe PWR)
(from FUELCASH)

| Item | Direct (m/kWh) | Indirect (m/kWh) | Total (m/kWh) |
|---|---|---|---|
| Uranium | 2.85 | 0.99 | 3.84 |
| Conversion to $UF_6$ | 0.11 | 0.03 | 0.14 |
| Enrichment | 1.83 | 0.61 | 2.44 |
| Fabrication | 0.70 | 0.22 | 0.92 |
| Shipping | 0.20 | -0.04 | 0.16 |
| Reprocessing | 1.00 | -0.20 | 0.80 |
| U Credit | -0.74 | 0.15 | -0.59 |
| Pu Credit | -0.53 | 0.12 | -0.41 |
| Net Fuel Cycle | 5.42 | 1.88 | 7.30 |

TABLE 7

Fuel Cycle Costs Versus Nuclear Plant Size

| Nuclear Plant Size, MWe | Direct (m/kWh) | Indirect (m/kWh) | Total (m/kWh) |
|---|---|---|---|
| 600 | 5.43 | 1.88 | 7.31 |
| 900 | 5.30 | 1.83 | 7.13 |
| 1000 | 5.25 | 1.81 | 7.06 |
| 1200 | 5.17 | 1.79 | 6.96 |

The fuel cost given in Tables 6 and 7 assume that spent fuel would be shipped and reprocessed. As seen in the last column of Table 6, however, shipping and reprocessing cost are 0,96 mills/kWh, where as, the credit for U and Pu is 1,00 mills/kwh. Thus with a spent fuel storage cycle, fuel cycle costs would be only 0,04 mills/higher, excluding costs of long term storage.

Fuel costs for oil-fired plants can be based on an assumed average world price of US$ 12.70 per barrel.

**c) Operating and Maintenance Costs**

In a nuclear plant, these costs range from about 2.2 mills/kwh in a 600 MWe plant to about 1.8 mills per kwh in a 1200 MWe unit. Corresponding costs in a 600 MWe and 900 MWe oil-fired are 1.4 and 1.2 mills/kwh respectively. The 900 MWe size assumed here for comparison purposes is the average of the largest oil-fired units being built.

**d) Generating Costs**

The above cost data are combined in Table 8 to show electricity generating costs in PWR's (representing LWR's as a class) and low sulfur oil-fired plants. It is seen in this simplified analysis that a 900 MWe PWR has about the same power costs a 600 MWe and 900 MWe oil-fired plants whereas the 1200 MWe PWR has somewhat lower power costs. In this regard, it should be pointed out that a generalized economic analysis such as given here is merely indicative of the prospects for nuclear power and should not be used as a basis for nuclear power planning. Other factors such as diversification of energy supplies and reduction of oil imports must also be considered along with economics.

**TABLE 8**

**Electricity Generating Costs from PWR's and Oil – Fired Plant in Developing Countries, m/kWh Jan, 1978 Basis**

| | PWR | | Low Sulfur Oil – Fired | |
|---|---|---|---|---|
| Plant Capacity MWe | 900 | 1200 | 600 | 900 |
| Investment Costs (12% Interest Rate, 65% PF) | 21,1 | 17,8 | 8,3 | 7,5 |
| Fuel Costs | 7,1 | 7,0 | 20,8 (1) | 20,8 (1) |
| Operating and Maintenance | 2,0 | 1,8 | 1,4 | 1,2 |
| Total | 30,2 | 26,6 | 30,5 | 29,5 |

(1) Based on Jan. 1978 world price of $ 12,7/U.S. barrel

## 4.5 – CONTRIBUTION OF NUCLEAR POWER TO BRAZIL'S ELECTRICITY SUPPLY

**a) Near Term (1990)**

As reported in the previously mentioned "white paper" technical studies carried out in 1973-74 demonstrated the need to have 10 GWe of nuclear power on stream in Brazil by 1990 to complement a hydroelectric capacity of 60 GWe. If this goal is attained, these nuclear plants operating at a 70% plant factor, would generate more than $60 \times 10^9$ kWh in 1990. This would constitute 18% of the electricity demand in that year.

**b) Longer Term (2000)**

There is no "official" nuclear power program beyond the year 1990. Studies by Nuclebras/Furnas indicate, however, that as much as 80 GWe of nuclear electric capacity may be needed by the year 2000.(1) This amount of nuclear capacity would generate $455 \times 10^9$ kWh representing about 60% of the total electrical requirement in the year 2000.

This forecast was made in 1975 at a time when nuclear plant costs had not felt the impact of meeting high environmental and safety standards. In view of the present high costs of nuclear plants it is probable that the nuclear capacity goal for the year 2000 will be considerably more modest, say of the order of 40 GWe. On this basis, and assuming an average growth in electricity requirements of 8% per year from 1987 to 2000, nuclear power would contribute about 32% of the electricity needed in the year 2000, with most of the remaining electricity coming from hydro plants.

## 4.6 – AREAS FOR POSSIBLE RESEARCH AND DEVELOPMENT

With a nuclear program as large as the one planned and the Brazilian goal of achieving complete autonomy in the nuclear field in the next 15 years or so, there are many areas where research and development could contribute to the program. This is particularly true of the nuclear fuel cycle where Brazilian experience and know how of such things as uranium mining and milling conversion to $UF_6$, enrichment, fuel fabrication, spent fuel storage or spent fuel shipping and reprocessing will be required. More emphasis should be given to uranium exploration activities, siting studies, and training of nuclear technologists. Although Nuclebrás and CNEN are responsible for most work in these areas, the Institute of Atomic Energy should be in a position to contribute.

(1) L. C. de Almeida Magalhaes, "O Problema Energetico Brasileiro" Sept. 1975.

# CHAPTER 5, THORIUM

## 5.1 – IMPORTANCE OF THORIUM UTILIZATION

Early in the history of nuclear reactors it was recognized that the long term importance of nuclear fission for power production depended not only upon the ability to use the fissile U-235 provided by nature but also upon using an appreciable part of the much more abundant naturally occurring fertile materials, U-238 and thorium (Th-232) which through neutron capture can be converted into fissionable fuels. In order to achieve such a conversion however, the rate of production of new fissile isotopes in the reactor must be essentially equal to, or greater than, the rate of consumption of isotopes undergoing fission. This conversion ratio (or breeding ratio) provides a measure of the potential of utilizing the large amounts of U-238 and Th-232 available in the world. Figure 1 shows quantitatively the relationship between breeding ratio and resource utilization. Light water reactors, on which the present nuclear industry is based, have conversion (breeding) ratios well below the range shown in the figure. Thus a nuclear power system based solely on LWR's would have to rely essentially on the U-235 that is available, with the more abundant fertile materials going to waste. On this basis, it is generally agreed that the ultimate nuclear power system must have large numbers of reactors with high breeding ratios (breeders) to generate new fissile fuel.

The points at issue concern not whether breeders are needed but when they are needed and also what kind are needed. In regard to the former issue, opinions of experts differ greatly because the timing of breeder introduction depends on estimates of the future rate of growth of the industry, itself, and the amount of low cost uranium (up to $110/kg $U_3O_8$) available in the world. At the lower end of the range of estimates, it is claimed that for prudent planning, one should depend only on the uranium resources which are "reasonably assured". The amount to only about 2 million tons of uranium which is just enough to support 400 GWe of LWR capacity over a 30 year lifetime. This is essentially the same as the world LWR capacity planned for 1990. At the other end of the scale, it is claimed that with vigorous future exploration activities, as much as 10 to 20 million tons of low cost uranium will be discovered. This amount of uranium would be adequate to support from 2000 GWe to 4000 GWe of LWR capacity which will probably be reached sometime during the period 2010 to 2020. In any event, taking the average of this range of estimates as a likely possibility would mean that breeders are not needed in significant quantities before the year 2000.

Concerning the issue of what kind of breeder should be developed, there are two basic systems from which to chose. The first, involving the U-235, U-238, plutonium cycle utilizes a liquid metal cooled fast breeder reactor (LMFBR). Most of the research and development work on breeders has been devoted to this approach. The second possible breeder system involves the U-235, Th-232, U-233 cycle which has the potential of improving the conversion rate of thermal reactors. Several reactor type have been considered for operation on the thorium cycle. These include the high temperature graphite reactors (HTGR), the thorium fueled heavy water reactor (CANDU-Th), the molten salt breeder reactor (MSBR), the light water breeder reactor (LWBR) and the heavy water suspension reactor (HWSR). The development works on these reactors has been relatively small compared to that on fast breeders. The reason for this is that there is no clear incentive for developing thorium breeders in parallel with, or instead of, fast breeders. Although thorium utilization would greatly extend the nuclear resource base, this is a relatively unimportant issue because fertile material is not in short supply, only fissile U-235. Thus the argument for developing thorium reactors must be based on other factors such as possible lower power costs, improved safety features relative to fast breeders, and removal of the public concern over a large "plutonium economy".

The overall impact of these factors can not be assessed at this time.

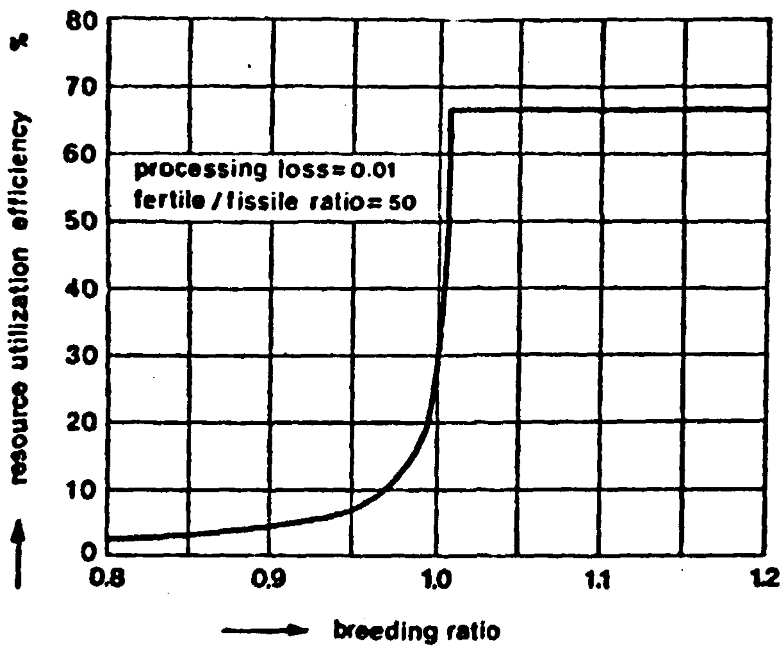


Figure 5.1 -- Resource Utilization Efficiency as a Function of Breeding Ratio

## 5.2 – DESCRIPTION OF THORIUM FUELED REACTORS

### a) HTGR

This reactor type is a thermal reactor, moderated with graphite, and cooled by helium. The core consists of hexagonal shaped graphite elements containing fuel channels packed with microspheres of partially carburized $UO_2$ (UCO) and $ThO_2$ each coated with thin layers of pyrolytic carbon to retain the fission products. The helium passes through coolant holes in the graphite element running parallel to the fuel channels. Because of its unique fuel design, the HTGR can use a wide range of fissile to fertile and heavy metal to moderator ratios without alteration of the basic design. These parameters control to a large extent the conversion ratio of the system and associated fuel cycle costs. Unfortunately minimum fuel cycle costs do not occur at the maximum achievable conversion ratio. Although the current "reference" HTGR is designed to operate with a conversion ratio of 0,66 (not much higher than 0,55 attainable in LWR's) it appears that near minimum fuel cycle costs can be achieved with a conversion ratio of 0,75 to 0,80. Higher conversion ratios are possible, but with greater economic penalty. Thus the HTGR does not qualify as a true thorium breeder or near breeder.

### b) CANDU – Th

The overall basic design of the CANDU-Th reactor is identical to the current commercial CANDU design which uses natural uranium fuel. The CANDU-Th reactor is fueled with thorium and U-235 (or U-233 when available) in the form of oxide pellets. Fuel replacement is on-load, reducing reactor shut down time. A 1000 MWe CANDU-Th requires about 2100 kg fissile material and 126000 kg thorium in the core. Burnups of 10 MWD per kg (Thorium + uranium) are achievable compared to 7.5 MWD/kg U for the natural uranium fueled CANDU. With U-233 as the fissile fuel, breeding ratios of the order of 1.0 are possible. The thermal efficiency of the CANDU-Th is [illegible]% compared to 33% for LWR's.

### c) MSBR

The molten salt breeder reactor is characterized by the use of a fluoride fuel salt containing both fissile material and thorium which is fluid at temperature above about 500°C. The fluid fuel approach allows on-site fuel processing (U-233 and fission product separation) without the necessity for subsequent fuel fabrication operations. The high operating temperature of the fluid fuel (600°C in and 740°C out) permits generation of superheated steam and results in overal thermal efficiencies of about 44%. The MSBR has a breeding ratio of about 1.07 which is low relative to breeding ratios of 1.25 – 1.50 achievable in fast breeders; however, the system fissile inventory (1.5 kg/MWe) is only about 25% to 35% of that required for a fast breeder and is significant lower than that for other thorium fueled reactors. Thorium requirements for the MSBR are only 68 kg/MWe. The low inventories are particularly important in a rapidly expanding breeder industry where the cumulative fissile requirement to reach an equilibrium situation depends more on specific fissile inventory than on breeding ratio (1). The breeding specific inventory performance of the MSBR is obtained without a separate thorium blanket by using a salt volume fraction in the outer region of the graphite core that is three times larger than that in the central core. This produces a well-moderated core and an undermoderated outer region where neutron captures in thorium predominate.

To achieve good breeding in an MSBR, protactinium (Pa-233) which is an intermediate decay product leading to the production of U-233 and some of the salt soluble rare earth fission products must be removed from the salt in cycles of about 10 and 40 days respectively. This is accomplished by passing fuel salt through a chemical treatment plant located adjacent to the reactor. Here the Pa-233 is removed

(1) IAEA report "Status and Prospects of thermal Breeders and Their Effect on Fuel Utilization", May 1978.

and stored until it decays to U-233 which then is returned to the fuel salt. The rare earth and other fission products are removed by a liquid bismuth extration process.

All metal surfaces that contact fuel salt must be made from modified Hastelloy N a nickel base alloy developed especiallv for molten salt reactors. Special, low permeability graphite is also required for the core of the MSBR.

### d) LWBR

The light water breeder reactor, otherwise known as the seed blanket aqueous breeder, is characterized by the presence in the reactor of two distinct regions having very different nuclear characteristics. The first, called the "seed", is the smaller of the two regions and forms the core of each of some 75 to 190 modules comprising the reactor. This seed, containing highly enriched uranium, has a high neutron multiplication factor and is surrounded by a sub-critical "blanket". Despite its relatively smaller size, the seed is large enough so that most neutrons orignating in the seed result in fission there. In many respects, each seed-blanket module acts like a small reactor with the blanket serving as a good reflector for the seed.

Both the seed and blanket are fueled with rods containing pellets of $ThO_2$ plus $UO_2$ (as U-233 or U-235); however, the rod diameters, the ratio of fissile material to thorium and the volume ratio of heavy metal to water are adjusted in each region to obtain maximum nuclear performance.

Because U-233 does not occur in nature, it must be produced from thorium before one can use it to fuel a light water breeder reactor. For this reason, the LWBR system is envisaged as envolving in two steps. A pre-breeder step to generate the required U-233 and a self-sustaining breeder step simultaneously generating and consuming U-233 and thorium. The pre-breeder seed blanket concept can use highly enriched U-235 and thorium; however designs which use "slightly" enriched (12% – 17% U-235) uranium in the fuel rods and thorium in the blanket rods are also considered.

The light water pre-breeder concept has breeding ratios of the order of 0.7, where as the LWBR fueled with U-233 can achieve breeding ratios up to 1.01.

The steam generating characteristics of the LWBR (pre-breeder and breeder) are similar to those of commercial LWR's.

### e) HWSR

The heavy water suspension reactor uses mixed crystals of thorium oxide and uranium oxide in the form of tiny spheres, 5 microns in diameter (1 micron = 0,001 mm). These particles are dispersed in heavy water which has the combined function of moderator, reflector and coolant. Although the intent of using such small particles is to allow the fission products to leave each particle and be absorbed by the heavy water, under normal operating conditions, some flocculation occurs resulting in more or less loose clusters of particles. Thus some of the fission products leaving one particle come to rest in an adjacent particle with the result that only about 70% of the fission products are found in the heavy water.

The particles have density of about 10 g./cc and their sedimentation velocity is relatively high. Thus care has to be taken in the reactor design to prevent settling of particles in an wanted places such as the walls of the core vessel. heat exchanger etc.

In order to prevent erosive attack on the construction material by the flowing suspension, direct impact on the surfaces or penetration of the laminar boundary layer by fuel particles must be avoided. This can be done by design of piping and vessel shapes necessary to induce the required flow patterms.

The design of a 250 MWE HWSR has been prepared by KEMA (Netherlands). This reactor would be fueled with 1.5% U-233 as $UO_2$ and 98.5% $ThO_2$. Specific fissile inventories between 1.5 and 2.5 kg/MWe corresponding to breeding ratios of 1.02 and 1.07 respectively can be achieved with semi-continuous reprocessing (0.3% of fuel inventory daily). Startup would be with highly enriched U-235 with operation gradually shifting to U-233.

## 5.3 – COMPARISON WITH OTHER REACTOR TYPES

Table 1 gives typical performance characteristics of thorium fueled reactors, LWR's and fast breeders. These alternative reactor types are listed in decreasing order of breeding ratio. Here it should be once again pointed out that in an expanding nuclear industry the other characteristics shown are also important. These performance data, with the exception of fuel cycle costs, were taken from the IAEA, "Thermal Breeder Consultants Group report", May 1978 draft. Fuel cycle costs for the HWSR are not shown; however, this fluid fuel reactor would have integrated reprocessing facilities and fuel cycle costs should be comparable to those for the MSBR. CANDU-Th fuel costs are also shown. Costs for a natural uranium fueled CANDU reactor, including heavy water inventory and makeup costs, are of the order of 6 mills/kwh. Costs for a CANDU-Th fuel cycle should be about 1-2 mills per KWh higher.

One aspect of thorium fueled reactors which may become important in the intermediate term (1990-2000) is that even without going to a breeding cycle, such reactors can generate at least twice as much energy from U-235 as LWR's. This may lead to the use of thorium if shortages of low-cost natural uranium occur before breeders can be deployed in significant numbers.

### TABLE 1

**Typical Performance Characteristics of Alternative Reactors Types (Based on Equilibrium Fuel Cycle)**

| Reactor Type | Breeding Ratio | Core Fissile Inventory Kg/MWe | Total Fissile Inventory Kg/MWe | Fertile Inventory Kg/MWe | Thermal Efficiency % | Fuel[1] Cycle Costs m/Kwh |
|---|---|---|---|---|---|---|
| LMFBR | 1.27 | 2.8 | 4.2 | 62 | 44 | 3.9 |
| MSBR | 1.05 | 1.4 | 1.5 | 68 | 44 | 3.2 |
| HWSR | 1.04 | 2.0 | 2.2 | 126 | 32 | |
| LWBR | 1.01 | 4.3 | 6.4 | 186 | 33 | 13.8 |
| CANDU-Th | 1.00 | 2.1 | 3.1 | 126 | 29 | |
| HTGR | 0.72 | 1.2 | 1.8 | 23 | 40 | 6.4 |
| LWPBR | 0.70 | 3.2 | 4.6 | 99 | 33 | 6.6 |
| LWR | 0.55 | 2.0 | 3.0 | 86 | 33 | 7.6 |

(1) From L.F.C. Reichle, Proceedings of the Salzburg Conf. "Nuclear Power and Its Fuel Cycle" Vol. 1, 531, Sept. 1977 (1985 basis)

## 5.4 – STATUS OF DEVELOPMENT

### a) HTGR

This reactor concept has been under development on the USA, primarily by Gulf General Atomic Co. with the help of the Oak Ridge National Laboratory, since the early 1960's. The 40 MWe Peach Bottom Atomic Power Station, the first HTGR built for commercial power production in the US went into operation in June 1967 and operated successfully until, Oct. 1974. It served to demonstrate many important design features of the HTGR such as the integrity of the graphyte modules, the burnup behavior of coated particle fuels and the performance of system components such as circulators, steam generators, control drive mechanisms, valves and instrumentation.

A larger (330 MWe) HTGR was built by Gulf Atomic for the Public Sevice Co. of Colorado. This plant known as the Fort St. Vrain plant was originally scheduled for operation in 1972; however, because of equipment difficulties, startup was delayed until 1977. Full power operation is expected to be achieved in late 1978. This reactor will demonstrate improvements over the Peach Botton design such as the use of a prestressed concrete reactor vessel (PCRV), an advanced graphite fuel block, steam turbine driven circulators and modular once-through steam generators.

Two larger (770 MWe) HTGR's were sold to the Delmarva Power and Light Co. and four 1160 MWe HTGR's to two other utilities in the United States. All of these plants were scheduled for operation in the early to mid 1980's. With the mutual agreement of Gulf Atomic and the utilities, however, these plants were all cancelled in 1975 and 1976.

A small (13.5 MWe) HTGR fueled with graphite balls containing fuel particles was put into operation in West Germany in mid 1969. This plant, called AVR Juelich, is still in operation. A 300 MWe unit, the THTR is being constructed and should go into operation in 1981.

### b) CANDU-Th

CANDU reactors have been under development for many years by Atomic Energy of Canada Ltd. (AECL) and the first commercial station, the 200 MWe plant at Douglas Point, Canada went into operation in September 1968. Since that time 7 additional units with a total net capacity of about 4.300 MWe have been placed in commercial operation by the Ontario Hydro Power Company. A 319 MWe heavy water reactor plant supplied by the Siemens Co. of Germany has been in operation at Atucha, Argentina since mid 1974. Canadian General Electric has also supplied small CANDU reactors to India and Pakistan. Thus it can be stated that CANDU type reactors are commercially available from Canada or West Germany. Fuelling with U-235 plus thorium, if desired, should present no technical problem.

### c) MSBR

No molten salt breeder reactor has ever been built; however, the technology of molten salt reactors has been studied extensively at the Oak Ridge National Laboratory since 1950. There have been two experimental molten salt reactors, the 2.5 MW (thermal) Aircraft Reactor Experiment in 1954 and the 8 MW (thermal) Molten Salt Reactor Experiment (MSRE) which operated from June 1965 to December 1969. This latter reactor was fueled with a U-235, U-238 mixture during the initial 2 years of operation and with U-233 the final 1 1/2 years. At the time the MSRE completed its operation the following technical problems remained to be solved:

1. Tritium containment

2. Microscopic cracking of Hastelloy N used in primary circuit

3. Graphite integrity

4. Fuel processing

5. Large scale component development

These problems appeared formidable enough to cause postponement of the construction of a large (250 MWe) MSBR demonstration plant. Development work on MSR's, however, continued at ORNL until mid – 1976 when the program was terminated. During this same period, molten salt reactor development and evaluation activities were undertaken in a number of countries, particularly those of Westen Europe. Although no demonstration reactor construction effort has yet been initiated, an industrial group in the USA (the Molten Salt Group headed by Ebasco Services Inc.) has proposed such an effort. After careful evaluation of the results of the MSR development program, the Molten Salt Group believes that the technical problem mentioned above have been, or can be solved and the attractiveness of the MSBR warrants a program leading to a commercial MSBR. Such a program would cost $ 3 – 4 billion (current U.S. dollars). It is doubtful whether such funding will ever be available in the US or elsewhere despite the fact that MSBR's continue to appear to be technically feasible and economically attractive.

**d) LWBR (Seed Blanket Aqueous Reactor)**

The seed blanket concept was originally introduced in the early 1950's as a means of minimizing the separative work (U-235 enrichment) required for the fuel of an LWR.

This concept was employed in the first commercial (60 MWe) PWR plant at Shippingport Pennsylvania, USA which operated with a mixture of highly enriched U-235 (seed) and natural uranium (blanket) from the early 1960's to the present.

After preliminary work in the early 1960's indicated the feasibility of breeding in a light water seed blanket reactor operating on the thorium cycle, the USAEC (Now Dept. of Energy) authorized the demonstration of the LWBR concept in the Shipping part plant. Full power (204 MWth) operation of the demonstration core began in December 1977. The U-233 for the core was produced in the US Savannah River production reactors. Three modules, typical of commercial design of LWBR's will be tested. More than 2 years of operation at 85% plant factor will be required for the modules to achieve their full burnup. Thus the nuclear performance of the LWBR will not be demonstrated until about 1980.

Although the technology of LWBR's appears to be well in hand, even when fully developed, commercial LWBR's would not look promising from the standpoint of either breeding or economics.

**e) HWSR**

The development of the heavy water suspension reactor started in the late 1950's with the investigation of the physical properties of a suspension reactor in a sub-critical experiment. Parallel with this effort, the development and evaluation of Sol-gel processes for microsphere production and studies of the behavior of circulating aqueous uranium – thorium suspensions at elevated temperatures were undertaken. On the basis of encouraging results of this program, the KEMA Suspension Test Reactor (KSTR) was built in the Netherlands and started operation in May 1974. This reactor had a thermal power level of 1 MW, a fuel inventory of 30 kg of 25% $UO_2$ – 75% $ThO_2$ and operated at 250°C. Although its main objective was to test the fuel under the influence of fissioning at a power density of 50 KW/liter (required in commercial HWSR's) the KSTR also demonstrated that problems such as instrumentation, inventory control, erosion and system leak tightness could be solved at least on an experimental scale. The reactor was shut down in May 1977 to permit removal of fuel and inspection of the reactor system. This program is still underway.

Although it is too early to assess the overall performance of the KSTR, it appears that the HWSR concept is still in a very early stage of development. Commercialization would take several decades, at which time, other breeder types will predominate. The lack of a large industrial sponsor and funds for further development of HWSR's are obstacles which are unlikely to be overcome.

## 5.5 – IMPORTANCE OF THORIUM REACTOR FOR BRAZIL

### a) Thorium Reserves

Thorium has been produced as a by-product of the rare earth industry since 1949 with the result that about 2000 tons of $ThO_2$ concentrate have now been stockpiled. Estimated reserves of economically recoverable $ThO_2$ (up to $20/kg) amount to about 66,000 tons, most of which are located in the State of Minas Gerais. Thus there has been considerable interest in Brazil in the development of a reactor type capable of utilizing this large amount of thorium.

### b) Problems of Developing a Thorium Fueled Reactor

The outlook for a commercial supplier of a thorium fuelled power reactor from industrialized countries is not very promising at the present time. Thus if Brazil were to follow the thorium route to nuclear power, the design and construction of a reactor based on thorium would have to be done by Brazilian personnel, although some components of such a plant might be purchased abroad. The development of the local capabilities and industrial infrastruture to manufacture the majority of equipment and components of a thorium reactor would take several decades and cost several billions of current U.S. dollars. This would be a very high risk venture whose outcome is uncertain since such a reactor would have to compete with LWR's and fast breeders. The present nuclear program of Brazil appears to be a much sounder course of action.

## 5.6 – AREAS FOR POSSIBLE RESEARCH AND DEVELOPMENT

A "thorium utilization" program is already in existence at the Institute for Atomic Energy. This program should be continued but not expanded.

# CHAPTER 6, FUSION

## 6.1 – INTRODUCTION

There are a number of reactions of interest in the generation of energy from the fusion of light atoms; however, the two principal ones are:

$$D + T \rightarrow He\text{-}4 + n + 17.6 \text{ MeV} \; ( 25 \text{ KeV}, 275 \times 10^6 \; ^\circ C)$$

$$D + D \rightarrow He\text{-}3 + n + 3.2 \text{ MeV} \; (150 \text{ KeV}, 165 \times 10^7 \; ^\circ C)$$

The numbers in parenthesis are the characteristic temperatures at which the plasma density times the mean confinement time needed for energy break-even are minimized. With some changes in these two parameters, higher and lower temperature can also be used. It is seen that the reaction which is less demanding technically (because of the lower temperature required) is the deuterium-tritium (D-T) reaction. Since tritium is nearly non existent in nature, it must be produced by neutron bombardment of lithium which thus is the limiting fuel resources for D-T fusion. There are however, an estimated 84 million tons of lithium in the word constitutes an essentially inexhaustible supply. Thus the development of the more demanding technology of utilizing the D-D reaction will probably not be necessary from a resource stand point even in the long term.

In order to derive energy from the D-T reaction, it is necessary to heat a sufficiently dense mixture of deuterium and tritium as a plasma to the required temperature and hold it long enough for the reaction to take place. The fraction of the plasma that will react depends on how close one is to the so called Lawson region. In the late 1950's J.D. Lawson, a British physicist, showed with some reasonable assumptions that a D-T fueled fusion reactor would produce net power if the confinement parameter, $n\tau$, exceeded $10^{14}$ sec/cc at an ion temperature of around $10^8\,^\circ C$. Here n is the number of ions per cc and $\tau$ is the mean confinement time in seconds. At ion temperatures lower than $10^8\,^\circ C$, higher values of $n\tau$ are necessary for a net power output. It is generally believed that for a fusion reactor to be of commercial interest values of $n\tau$ at $10^8\,^\circ C$ will have to be between 2 and $5 \times 10^{14}$.

The two basic approaches for achieving the conditions described above are called "magnetic confinement" and "inertial confinement", respectively. The former might achieve the break-even condition with $n = 10^{14}$ ions/cc and $\tau = 1$ sec and the latter with $n = 10^{26}$ ions/cc and $\tau = 10^{12}$ sec. The two approaches are described in the following paragraphs.

## 6.2 – DESCRIPTION OF MAGNETIC CONFINEMENT APPROACHES

This approach which relies powerful magnetic fields to confine the hot fusion fuel (a fully ionized plasma) has been under development in most industrialized nations for the past 25 years. The leading contender among the magnetic confinement schemes is the class of toroidal or doughnut shaped devices called "tokamaks". The primary and secondary backup schemes are "mirror" machines and pulsed high density "pinch" devices. This discussion, however, will be limited to tokamaks since they essentially dominate the field of magnetic confinement.

The first (or second generation) of tokamaks are represented by the Stellerator Tokamak and the Adiabatic Toroidal Compression Experiment both at Princeton and the Doublet II built by General Atomics at San Diego.

These machines operated in 1973 and 1974 and achieved $n\tau$ values in the range of $10^{11} - 10^{12}$

sec.cm$^{-3}$ at temperatures of the order of $8 \times 10^6$ °C. Thus they were about a factor of $10^3$ away from meeting the Lawson criterion.

By 1975 and 1976, the next generation of tokamaks came on line. These were the Alcator at MIT, the Princeton Large Torus (PLT), the Tokamak-10 in the USSR, the Tokamak Fusion Reactor, (TFR) in France and the ORMAK at the Oak Ridge National Laboratories. These machines achieved temperatures in the range of 12 to $25 \times 10^6$ °C and $n\tau$ values in the range of $10^{12}$ to $10^{13}$ sec.cm$^{-3}$. This represented about a factor of 10 improvement over the previous generation tokamaks.

Further improvements in performance of existing tokamaks were made in 1977 and 1978. The PLT reached a temperature of 26 million °C in Dec 1977 at an $n\tau$ of about $10^{13}$ sec.cm$^{-3}$ and a temperature of 60 million °C in August 1978. Expectations are that the PLT can go to $80 \times 10^6$ °C, a "new regime" in plasma physics according to fusion scientists.

These recent experiments with the PLT indicate that tokamaks are within one order of magnitude of achieving break even condition (the boundary of the Lawson region). At least five larger tokamaks are in the design or construction phase which seem capable of approaching or reaching break-even" conditions (if fueled with D+T). These are the Tokamak Fusion Test Reactor (TFTR) at Princeton, the Tokamak-20 in the USSR, the JET (Joint European Tokamak) in the UK, the JT-60 in Japan, and the Doublet III at San Diego. All of these machines, are expected to be in operation during the 1979 to 1982 period. It should be pointed out that even if break-even is demonstrated, this would mean that less than 1% of the D-T fuel would react. Tokamaks even larger than the coming generation machines will, therefore, be necessary to achieve "power reactor" conditions.

There are five basic components of a magnetic confinement device such as a tokamak. These are (a) fuel injection system (b) plasma heating system (c) fuel confinement device (d) power or heat removal system and (e) tritium breeding blanket.

a) The **fuel injection system** faces the problem of injecting cold fuel to refuel the plasma during an extended burn. One promising technique for fuelling is the injection of pellets of frozen fuel at velocities greater than 1000 m/sec. Recent experiments in which hydrogen-ice pellets (0.03 mm in diameter) were injected into ORMAK demonstrated the feasibility of this technique. In these experiments, pellet velocities of 100 m/sec were achieved by means of a hypersonic gas jet. Experiments to obtain the required higher velocity using mechanical acceleration in an advanced centrifuge are underway at ORNL.

b) **Heating of the Plasma** to the required temperature of 100 million °C appears to be achievable using high current neutral hydrogen bean injectors. The $60 \times 10^6$ °C temperature reached in the PLT was obtained by about 2 MW of neutrol bean power but at low plasma densities.

To achieve break-even in the TFTR, 30 MW of neutral beam capacity will be required. Data from experiments at Oak Ridge and Lawrence Berkeley Laboratories indicate that this can be done.

c) **Confinement of the hot plasma** requires precisely shaped, dynamically controlled, magnetic fields with strengths of the order of $10^4$ to $10^5$ gauss. These magnetic fields are produced by superconducting (4°K) or cryogenic (77°K) coils. Coils made of niobium titanium with the potential of operating in the range of 8 to 10 teslas (1 tesla = $10^4$ gauss) and others made of niobium tin with a potential of 10 to 12 teslas are being constructed as part of the Large Coil Program at Oak Ridge.

d) An **energy removal system** is necessary to convert the kinetic energy of 14 MeV neutrons which escape the core into heat. This is achieved by surrounding the core with a blanket where the heat released is removed by a circulating coolant. Coolants, such as a salt consisting of sodium and potassium nitrites and nitrates (which have been used commercially for many years) helium gas and liquid lithium all appear promising.

The energy deposited in the blanket, however, represents only about 80% of the total heat produced. The remaining 20% of the energy produced by the D-T reaction must be absorbed by the core vessel walls or be deposited in a diverter. Some designs of tokamaks provide paths along magnetic field lines for ions diffusing out of the plasma and for unwanted ions that might enter the plasma to be swept out of the reactor vessel to a diverter collector. The design of this collector represents an as yet unsolved problem.

e) **Finally a tritium breeding blanket** is necessary to regenerate the tritium burned. Since only lithium offers any promise for tritium production through neutron interaction, the use of liquid lithium for both the coolant and breeding material seems to be the best choice.

## 6.3 – DESCRIPTION OF INERTIAL CONFINEMENT APPROACHES

The inertial confinement approach is based on the concept of compressing very small pellets of D-T gas liquid or ice to densities of the order of 10000 times that of normal solids by irradiating them symmetrically with short high power pulses from lasers, electron beams or heavy ion beams. The resulting conditions of density and temperature permit a significant fusion reaction to occur before the attendant pressure overcomes the inertia of the pellets constituents and it flies apart. Values of $n\tau$ necessary for commercialization of inertial confinement devices are essentially the same as for magnetic confinement.

The idea for this approach dates to around 1960 but it has been pursued vigorously only since the begining of the 1970's. Critical problems include developing lasers that can deposit on target, pulses of laser light containing $10^5$ to $10^6$ joules in a pulse time of $10^{-9}$ seconds or less. High repetition rates and high efficiencies of conversion of electrical input to laser output are also required. The alternative of developing relativistic electron beams or heavy ion beams is just as demanding. The feasibility of all approaches hinges strongly on the development of target pellet designs and production techniques. These hollow pellets must be extremely small (0,05 mm to 0,5 mm) spherical within 1% and a surface smoothness of $1\text{-}3 \times 10^{-4}$ mm. Four types of targets are being considered: (1) current ICF targets consist of glass or metal microspheres filled with DT gas; (2) compression targets to achieve 100 x liquid density are similar but coated with a teflon ablator; (3) scientific breakeven targets are double shell targets using possibly a beryllium ablator, heavy metal fuel pushers and liquid DT fuel; (4) finally, targets for a fusion power plant would use a Li H ablator and frozen DT fuel. The impinging beams must also be perfectly symmetrical in order to achieve high compression and high ratio of fusion output to input to the pellet.

As in the case of the tokamaks, break-even conditions using inertial confinement might also be demonstrated in the early 1980's but this possibility is difficult to evaluate because much of the pertinent information on pellet design and behavior is classified under the US DOE's defense activities. Information on laser, electron bean and heavy ion bean performance, however, is available in the open literature. Two large laser systems, the 20 bean Shiva laser at Lawrence Livermore Laboratory and the 8 beam $CO_2$ laser at Los Alamos are of particular interest. In November 1977, Shiva produced a pulse of $11.3 \times 10^{12}$ watts (11.3 TW) in $10^{-9}$ secs and in June 1978 increased the output to 26 TW in $10^{-10}$ secs. Although this latter pulse incited about $8 \times 10^9$ fusion reactions, the corresponding fusion energy output amounted to only $10^{-5}$ of the input energy. Future Shiva experiments are expected to raise the output energy to a few percent of the input. The Los Alamos laser produced a pulse of 15 TW in April 1978 demonstrating that both laser devices have comparable performance.

Neither Shiva nor the LASL laser is expected to reach break-even but their proposed succesor systems LASL's Antares and LLL's Nova are expected to have a net output of energy. These will be in operation in the early 1980's.

Sandia Laboratories electron beam accelerator, REHYD, first demonstrated neutron production using this approach in June 1977. It operated at 1 million volts and 250,000 amps and deposited 40,000 MW on the target causing a 1000 fold compression of the pellet. Sandia's next model, Proto II, in July 1978 generated 8 million MW in a $24 \times 10^{-9}$ second pulse and its succesor Proto III is expected to achieve a 40 million MW pulse in late 1979. This is not too far away from the 100 million MW in $10 \times 10^{-9}$ secs necessary for breakeven conditions.

The components of an inertial confinement fusion power plant operating on the D-T reaction are essentially the same as those for magnetic confinement. Figure 3.1 shows what such a power reactor might look like.

## 6.4 – FUSION – FISSION HYBRID REACTORS

Hybrid reactors consist of a fusion core surrounded by a blanket containing both lithium and either U-238 or thorium. The fusion neutrons cause fission reactions in the otherwise subcritical blanket and convert the fertile material to fissile Pu or U-233 for use in fission power reactors elsewhere. Although there are proponents of hybrid reactors everywhere (the Soviets are planning to convert their largest tokamak (T-20) into a hybrid) this approach appears to combine most of the complexities of both fission and fusion in a single device. An analysis of the economics of a hybrid plant producing U-233[1] indicates that such an approach is not likely to be competitive with either a fast or thermal breeder. U-233 costs from a hybrid FFF (Fusion Fuel Factory) were estimated to range from $ 120/gram to $ 450/gram.

## 6.5 – RESEARCH AND DEVELOPMENT PROGRAMS

Major R + D programs on fusion (Mainly on magnetic confinement approaches) are underway in France, Japan, U.K., USA and the USSR. In the United States, funds authorized for magnetic confinement remained relatively constant at about $ 30 million a year during the 1960's and early 1970's. In 1975 they started increasing rapidly, however, reaching $ 330 million in FY 1979. The reason for this increase is due primarily to the increasing cost of the experimental machines. Whereas ORMAK cost about $ 20 million to build, the TFTR at Princeton will cost about $ 200 million.

The inertial confinement budget is in the range of $ 130 million per year in both FY 1978 and FY 1979.

## 6.6 – STATUS OF THE TECHNOLOGY

Some mention has already been made of the remarkable advances in fusion research which have been achieved during the past five years. Whereas in 1973 magnetic confinement devices were a factor of 1000 of achieving energy break even conditions, at the present time this factor is about 10. Tokamaks capable of reaching the boundary of net energy gain systems are being designed and constructed and expectations are that breakeven conditions will be demonstrated in the early 1980's. This is a long way, however, from commercialization of fusion power.

The US program for developing fusion to the point where power plants might be of interest to utilities envisages the construction of a prototype experimental power reactor (PEPR) to follow the Princeton TFTR. This would lead to a Experimental Fusion Power Reactor (EFPR) and finally to a few hundred megawatt (net) commercial scale demonstration plant. Various research strategies have been studied by the USDOE as a means of reaching this goal. The reference strategy calls for the demonstration plant to be on-line about 1998 after a research and development effort costing $ 15 billion in constant 1978

(1) H. Bethe, "The Fusion Hybrid" Nuclear News, May 1978

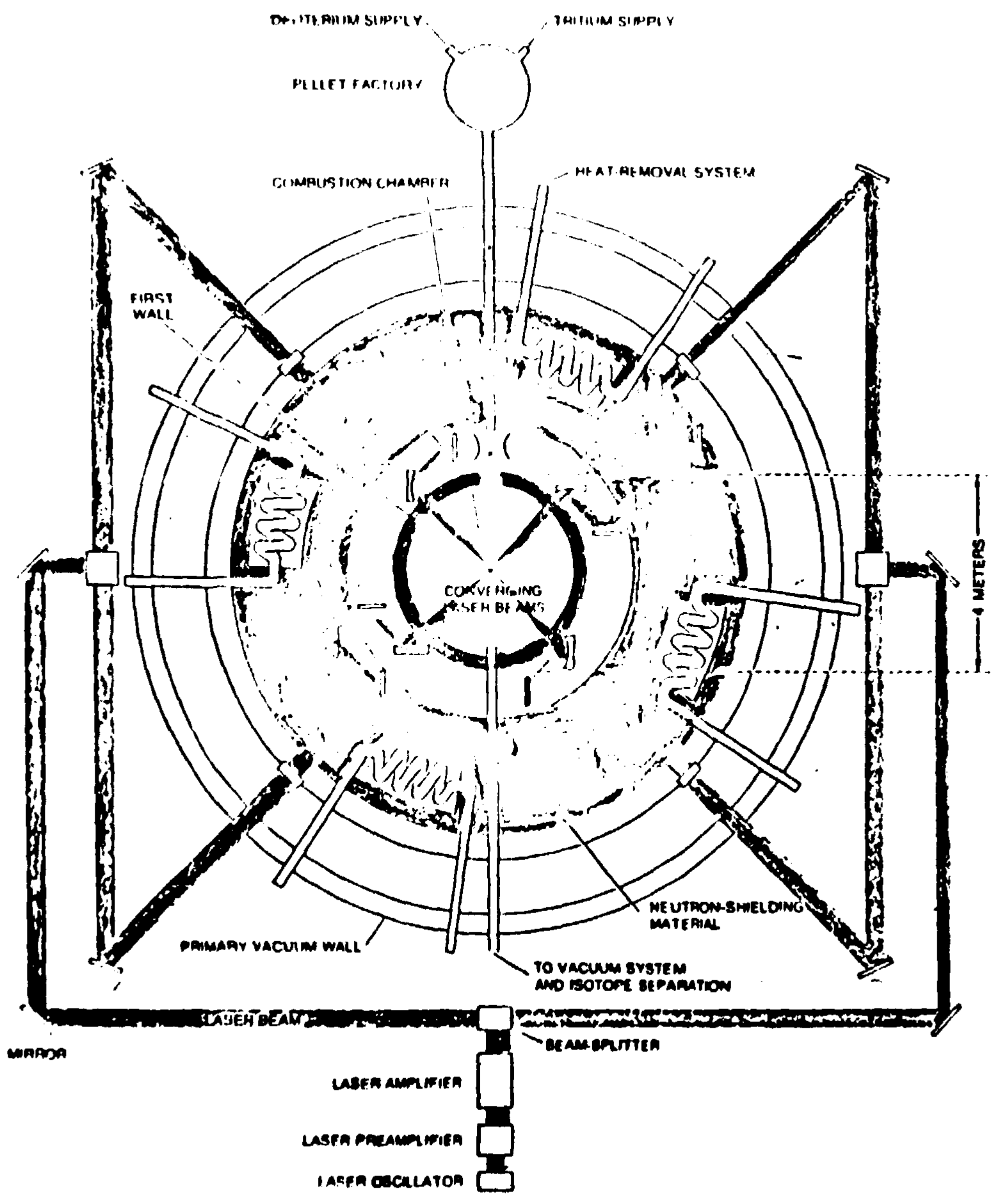


Figure 6.1 – Schematic of Inertial Confinement Fusion Power Plant

dollars. Many people feel this program is too ambitious. Even if is achieved, however, fusion power would by at the same point that fission power was 15 years ago. On this basis, fusion power plants are unlikely to capture more than about 10% of the U.S. or world electricity market by 2013 even under very optimistic assumptions.

## 6.7 – ECONOMICS OF FUSION POWER PLANTS

In contrast to a LWR nuclear plant, where generating costs would be distributed 70% to capital investiment, 20% to the fuel cycle and 10% for operations and maintenance, in a fusion power plant, 90% of generating costs would be for capital expeditures, less than 1% for fuel consumption, and the remainder for operation and maintenance. Thus the economics of fusion power depend essentially on the investment cost of the plant itself.

Predicting what the cost of a tokamak power plant might be in the year 2013 is comparable to attempts to predict the cost of LWR nuclear plant in 1978 based on data available in early 1943. Nevertheless, some serious design studies have been carried out by fusion engineers to define the characteristic of a tokamak power plant and estimate possible costs. One such design study was completed in 1973 at the University of Wisconsin which served more to define the problems of a fusion power plant than to solve them. Because of the large size of the toroidal core of this first plant design, called UWMAK-1, the costs of the stainless steel alone, after fabrication and installation, would have exceeded the total cost of a comparable size LWR. UWMAK-1 emphasized dramatically the need to go to smaller toroids. The design of UWMAK-III, the latest in the series, was completed in 1976 and a cost estimate prepared by the University of Wisconsin group and the Bechtel Corporation. The result was a total estimated cost (in first quarter 1977 dollars) of $ 7780 million for a plant with design output of 1750 MWe. Contingency and interest during construction were included but owner's cost or escalation during construction were not. These costs correspond to a unit cost of 4450/kWe. Unit investiment costs for an LMFBR on the same basis were estimated to cost $ 1820/kWe.

D. Steiner of Oak Ridge presents a much more optimistic outlook for the economics of fusion power (1). He points out that the size of the torus required for a commercial fusion power reactor is a function of the parameter beta (the ratio of plasma pressure to magnetic pressure). The UWMAK-1 design was based on a beta of 3% which required a non-circular toroidal coil 15 m x 21 m in diameter. Recent experiments indicate, however that betas in the range of 5% to 10% may be feasible. A fusion power reactor based on a beta of 8% would require a toroidal coil size of only 7 m x 10 m. Estimated direct costs of the nuclear island (torus, blanket, shield, toroidal field coils, poloidal field coils, ohmic heating system, etc) of a tokamak power plant were $ 450 per kWe (in 1976 dollars) compared to direct costs for the nuclear island of an LMFBR of $ 100/kWe (on the same basis). The tokamak "balance of plant" costs were estimated at 800/kWe compared to $ 700/kWe for the LMFBR. Putting these costs on the same basis as those for UWMAK III gives a unit cost of $ 2850/kWe for the Oak Ridge design.

A schematic of the Oak Ridge design inside of a vacuum building (in this case the NASA Plumbrook facility) is shown in Figure 6.2.

## 6.8 – POSSIBLE CONTRIBUTION TO BRAZIL's ENERGY SUPPLY

Since fusion power production is a very long range energy option it is unlikely to make any contribution to Brazil's energy supply in the time frame of interest.

## 6.9 – AREAS FOR RESEARCH AND DEVELOPMENT

None are suggested

(1) D. Steiner and J.F. Clark, "The Tokamak: Model T Fusion Reactor" Science 199 31 Mar., 1978.

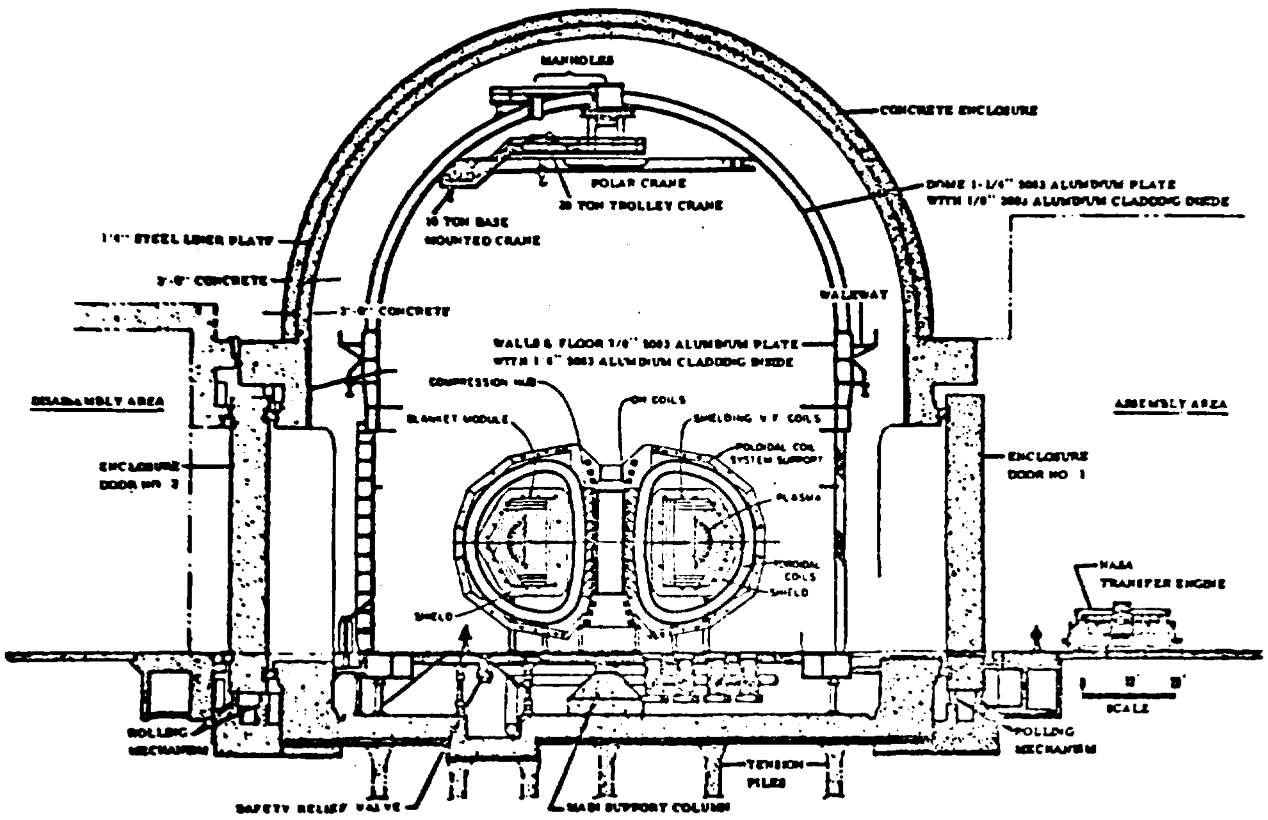


Figure 6.2 – The ORNL Tokamak Design – Superimposed on NASA Plum Brook Vacuum Building

# CHAPTER 7. ALCOHOL

## 7.1 – INTRODUCTION

A large number of grains, root vegetables, plants, wood and coal can be used to produce ethanol (ethyl alcohol) or methanol (methyl alcohol); however, biomass sources of interest for the commercial production of ethyl alcohol as a fuel are sugar cane, cassava, sorghum and corn. This discussion will deal only with sugar cane as the prime contender for the production of alcohol in Brazil. The ratio of energy output to energy input for the growing of sugar cane is 2.4[1] which is the highest amont the sources of alcohol listed.

## 7.2 – DESCRIPTION OF PROCESS

Depending on location, the quality of the soil, and agricultural techniques employed the production of cane can range from 50 tons to 100 tons per hectare. (1 hectare = 2.47 acres) A typical average value for good land in Brazil is 60 tons per hectare (80% of the land would actually produce cane and the remaining 20% awaiting new plantings). For economic reasons, plantings are usually done on a three or four year cycle. The production of cane the first year amounts to about 100 tons/ha with the other years yielding lower values down to about 50 tons/ha.

If the sugar mill is producing crystalized sugar from the cane and using the molasses residue for the production of alcohol, each ton of cane will yield about 100 kg of sugar and 11 liters of alcohol. When the cane is used entirely for alcohol production, each ton will produce about 67 liters of alcohol. This corresponds to an average production of 4000 liters of ethyl alcohol per hectare.

## 7.3 – USE OF ALCOHOL AS AN AUTOMOTIVE FUEL

The use of alcohol (anhydrous ethanol or methanol) is automobiles poses no great technical problem, in fact up to 20% mixtures can and are being used in present engines without any modifications. At higher percentages of alcohol, engine modifications involving mainly a change in the compression ratio are necessary but are technically feasible. Engine performance with a 20% mixture of ethanol and gasoline is comparable to that with pure unleaded gasoline. At velocities of 40 km/h or lower, the mixed alcohol fuel has a slightly better fuel consumption; in the range of 60 to 80 km/h, fuel consumption for both types of fuel is the same but at higher speeds gasoline is slightly better. The use of alcohol also improves the octane number of the fuel and reduces engine emissions.

An engine operating on 100% ethanol has about 18% more power and consumes 10% more fuel than same engine with unleaded gasoline.

Alcohol can also be mixed with diesel fuel. In this case two tanks are required, one containing pure diesel fuel for startup and a second containing up to 60% mixture of alcohol and diesel fuel for driving. The carburation system must be modified to accommodate these two modes of operation.

## 7.4 – THE BRAZILIAN ALCOHOL PROGRAM

During the past ten years or so, alcohol produced as a by-product of the Brazil sugar industry has been mixed with type "A" gasoline for use in automobiles. Almost all of this "mixed fuel" was consumed in the South-Central region (São Paulo and Rio de Janeiro). The percentages of alcohol in the mixture

(1) J. Goldemberg, Brazil: Energy Options etc. Science, 200 Apr. 14 1978.

varied from year to year depending on the amount of surplus alcohol available after meeting industrial requirements. These ranged from less than 1% to more than 6%. In 1976, fuel alcohol consumption was only $270 \times 10^6$ liters; however, by 1978 alcohol availability is expected to exceed $1 \times 10^9$ liters.

In 1976, a National Alcohol Plan was proposed according to which sugar cane would be grown specifically for the production of alcohol in order to reduce dependency on imported oil (so-called autonomous plants). The specific goal of this program is still under consideration, however, possible scenarios for the year 2000 range from adding 20% alcohol to all gasoline consumed in that year plus providing $10^9$ liters of alcohol for industry, to the substitution of 100% alcohol for all gasoline and diesel fuel. In the short term, 4 autonomous plants will go into operation in 1978, an additional 40 in 1979 and about the same number in 1980. The total output from these plants will be of the order of $3\text{-}4 \times 10^6$ $m^3$ alcohol ($3\text{-}4 \times 10^9$ liters) in 1980.[1] [2] If these planned plants come into operation as expected, sufficient alcohol will be produced in 1980 to provide an 18-20% mixture for all gasoline consumed in Brazil in that year. (The estimated gasoline consumption is based on a 7% per year growth in demand to 1980 from $14.1 \times 10^6$ $m^3$ consumed in 1977).

To meet this 20% mixture goal in 1980 (or soon thereafter) will require about 7500 $km^2$ of new land committed to the growing of sugar cane for alcohol. This is about 40% more land than the 1975 figure of 18,800 $km^2$ allotted to sugar cane. These new land requirements do not appear to be a limiting factor in the alcohol production program.

To consider the longer term implications of the National Alcohol Plan, it is necessary to forecast future automotive fuel requirements. Although some experts forecast a 9%/year growth in demand over the next decade, others believe a 7%/year growth rate is more likely in view of the present high cost (8.3 cruzeiros/liter = $ 1.71/U.S. gallon). Based on a 7% growth rate, the demand for automobile fuel in 1986 would be about $28 \times 10^9$ liters. Assuming a 5.5%/year growth in demand from 1986 to the year 2000 would result in a gasoline consumption in that year of $60 \times 10^9$ liters.

If the 20% alcohol-gasoline mixture goal is maintained to the year 2000, fuel alcohol requirements in 1986 would be $5.6 \times 10^9$ liters and in the year 2000, $12 \times 10^9$ liters. On this basis the fuel alcohol program would require a land commitment of about 14000 sq.km. by 1986 and 30,000 $km^2$ by the year 2000. Although this latter requirement is about 1.5 times the present area devoted to sugar cane it does not appear to be unreasonable.

The maximum goal of complete replacement of gasoline and diesel fuel with alcohol by the year 2000 would require the production of about $120 \times 10^9$ liters of alcohol per year and an 18-fold increase in land used for sugar cane. Such a goal appears to be neither attainable nor desirable.

## 7.5 – THE ECONOMICS OF ALCOHOL AS A FUEL

There is a considerable debate underway in the United States over the merits of so-called "gasohol" (a blend of 90% unleaded gasoline and 10% ethanol). Proponents of gasohol claim that a 80 million liters per year ethanol plant using sorghum as feed would cost $ 27 million and production costs would be 20 U.S. ¢/liter. Sale of ethanol at about 29 ¢/liter ($ 1.10/U.S. gallon), by-product animal feed at $ 120 per ton and $CO_2$ at $ 2,00 per ton would result in an annual profit of 22% on the investment. The sale price of 29 ¢ liter to a refiner compared to a gasoline (refinery) cost of 10 ¢ liter is justified on the basis of credits for improved animal feed by-product, higher octane rating of gasohol, and improved fuel economy. Opponents refute these figures and say that it makes no sense for refiners to pay 32 ¢ liter for ethanol when they are selling pure unleaded gasoline for 16 ¢ liter. The consensus of U.S. experts appears to be that gasohol is uneconomic in the US at present oil prices.

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(1) Personal communication, L. Navarro, Destilaria Alcidia, S. A., Sept 1978.
(2) National Energy Balance, 1978

The Brazil situation is, however, quite different from that in the U.S. In Brazil, the fuel used by the distillery would be bagasse rather than coal, oil or gas used in the US. The cost of a 360,000 l/day distillery in Brazil is of the order of 400 million cruzeiros. Because of high inflation rates (36%/year) normal interest rates are above 40%/year.

As part of the National Alcohol Plan, however, loans are available to autonomous distilleries at 17% per year with no adjustment for inflation. Using this interest rate, investment costs for the 360,000 l/day distillery, operating 180 days per year, would be about 1 Cr/liter. Cane production costs of 135 cruzeiros/ton would add another 2 Cr./liter, and other costs and profit would bring the total to about 4,6 Cr./liter. Cane costs are sensitive to land costs; however, and could be 50 cruzeiros/ton higher with land at 40.000 cruzeiros/ha. This would add about 0,7 Cr./liter to the cost of alcohol.

A possible improvement in the economics of alcohol production is being developed. This involves evaporation of part of the sugar solution to a heavy syrup with 80 Brix density (80% sugar by weight). The sugar is then inverted with sulfuric acid to prevent crystalization and the syrup stored for later use as distillery feed. This approach could extend the distillery operation to about 240 days per year, reducing alcohol production costs to about 4,2 Cr./liter ($ 0,80 per U.S. gallon). This is considerably below the $ 1.10/gallon figure for ethanol production in the US.

Despite the lower cost of fuel alcohol in Brazil, it is still higher than the production cost of gasoline based on imported oil. This is about 2.8 Cr./liter at the present time. A 20% alcohol-gasoline mixture would cost about 3.1 Cr./liter which is well below the gasoline consumer price of 8.3 Cr./liter.

Substitution of the higher cost domestic fuel (alcohol) for the lower cost gasoline (based on imported oil) would result in a reduction of oil imports; however, there would be an overall net revenue loss. If the goal of 20% substitution in 1986 is maintained the net revenue loss (in constant 1978 prices) would amount to about 16 billion cruzeiros. Without the National Alcohol Plan, crude oil imports in 1986 would cost about $110 \times 10^9$ cruzeiros. With the planned program, import costs would drop about $8 \times 10^9$ cruzeiros; however, the cost of producing the alcohol would be $24 \times 10^9$ cruzeiros, resulting in the deficit mentioned.

This analysis is based on the assumption that imported oil prices in real terms remain constant. If these prices were to escalate 1.5% per year faster than general inflation, then the above National Alcohol Plan would just break even. It thus might be considered an insurance aganist the possibility of such escalation.

There is one other advantage of the alcohol program, namely, increased employment. The above mentioned 1986 goal would provide about 125 million man hours per year of employment.

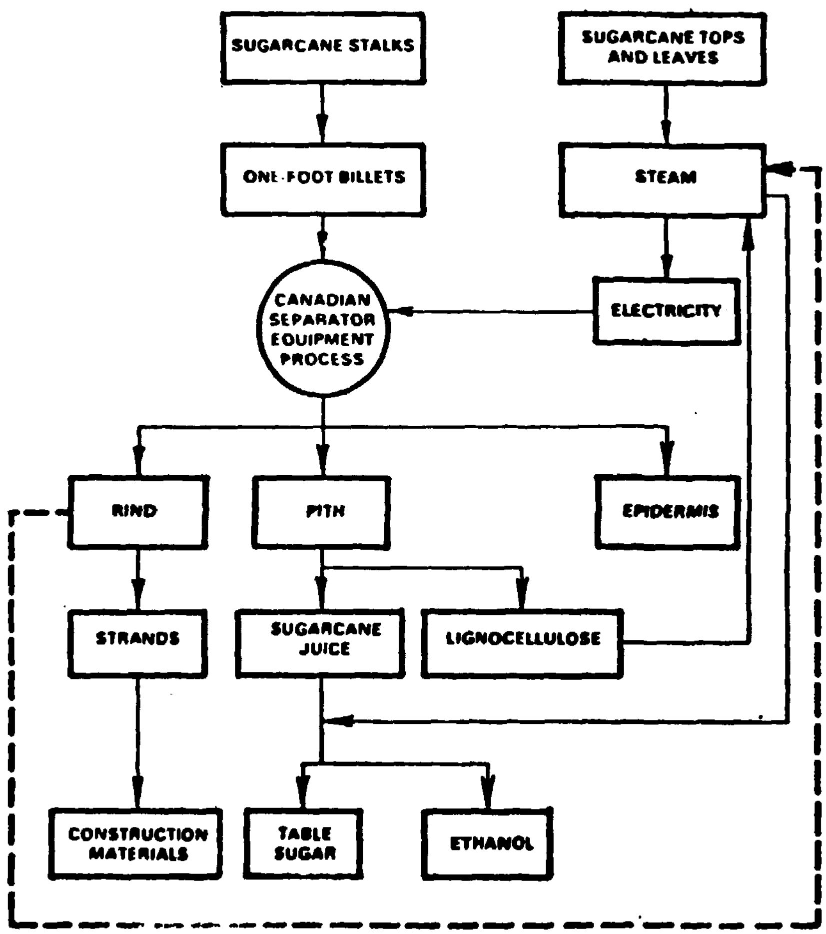
## 7.6 – POSSIBLE AREAS FOR RESEARCH AND DEVELOPMENT

Land costs represent a large fraction of the costs of growing sugar cane. It is therefore, highly important to make yields as high as possible. Research into methods of increasing yields might produce interesting results. Perhaps new high yield strains of sugar cane can be developed as was done in case of rice and wheat.

The most active and promising yield-increasing research now in progress in the US is the use of narrow row spacings (0,6 to 0,7 meters instead of 1.4 to 1.8 meters)[1]. This increases substantially the plant population and achieves canopy closure at an early date.

A second area for R + D is the development of by-products from surplus bagasse. A new method of processing cane is under development in Canada. In this process shown in Figure 7.1 a device removes

(1) J.C. Powell "Dynamic Conversion of Solar Generated Heat to Electricity" NASA/CR 134724-5, vols I and II, Aug. 1974




The Canadian separator equipment process.

**Figure 7.1 – The Canadian Separator Equipment Process**

the pith of the cane (containing essentially all of the sugar) while leaving behind the fibrous rind. Rind fiber produced in this nanner is estimated to have twice the value of conventional bagasse as a source of paper.

A third area for research would be to investigate the possibility of producing high value crops along with the sugar cane using the land that is available between plantings.

A fourth area of research for the Institute would be to investigate the possibility of irradiating a concentrated sugar solution as a means of preventing fermentation. The cane mill could then be sized to produce twice the distillery capacity. During cutting season, half of the mill output could be concentrated irradiated and stored. Thus the distillery could be operated at a high plant factor reducing alcohol costs.

# CHAPTER 8, OIL SHALE

## 8.1 – INTRODUCTION

There are a number of naturally occuring hydrocarbons in the world whose extraction from the earth can not be accomplished by normal petroleum techniques. The two most important sources of such hydrocarbons are tarsands and oil bearing shales, of which the latter are more abundant. In fact, some experts believe that resources of shale oil exceed those of conventional petroleum by factors of 100 to 200. If this is true, oil bearing shales can become a very important source of energy for mankind.

Shales from which oil can be readily obtained are found in a number of countries however, the largest known reserves of recoverable oil are located in the United States ($350 \times 10^9$ $m^3$) and in Brazil ($127 \times 10^9$ $m^3$). All of the rest of the countries in total have $45 \times 10^9$ $m^3$. When it is realized that the total world production of petroleum is $3 \times 10^9$ tons/year at the present time, Brazil's oil shale reserves would be sufficient to supply the entire world for 40 years at current rate of production. This serves to emphasize the potential importance of oil shale in Brazil.

The hydrocarbon in the shales is not really oil but is mostly in the form of a material called kerogen. This is a highly reactive complex organic material which under some conditions can spontaneously ignite at temperatures below 100°C. Under normal conditions, however, to extract the kerogen from the shale requires temperatures in the range of 500 – 700°C.

Three general methods have been developed to obtain oil from shale (1) mining and retorting (2) in-situ retorting and (3) modified in-situ retor  ı. These methods are described as follows:

## 8.2 – MINING AND RETORTING METHODS

### a) Gas Combustion Process

This pioneering process developed by the US Bureau of mines is shown schematically in Figure 8.1. In this process cold crushed raw shale is fed into the top of a vertical retort where it encounters recycled product gas in the so-called cooling zone. Here the shale is partially heated and the hot gaseous and vaporized products are cooled. In the next zone, shale is heated to retorting temperature by burning recycle gas with air plus any organic material still present in the shale. As the shale passes further down in the retort, it comes into contact with cold recycle gas to transfer its remaining heat. The processed shale is then discharged from the botton of the report. The Petrosix process, which is the basis for the semi-industrial prototype plant at S. Mateus do Sul, is quite similar to The Gas Combustion Process. The flow diagram for Petrosix is shown in Figure 8.2.

### b) The TOSCO II Process

When air is used as the oxidant, as in the Gas Combustion Process, nitrogen comes into contact with the hot shale and undesirable fixation of nitrogen occurs. The TOSCO II Process gets around this problem by transferring heat to the shale by means of hot ceramic balls as shown in Figure 8.3. This scheme avoids local overheating of the shale because the temperature of the balls can be controlled. A pilot plant using this process has been operated at 1000 tons shale per day input for extended periods.

### c) Chemical Treatment of Shales

Experiments are underway in the US to improve the extractability of organic matter from shale by

Gas-combustion process for shale oil

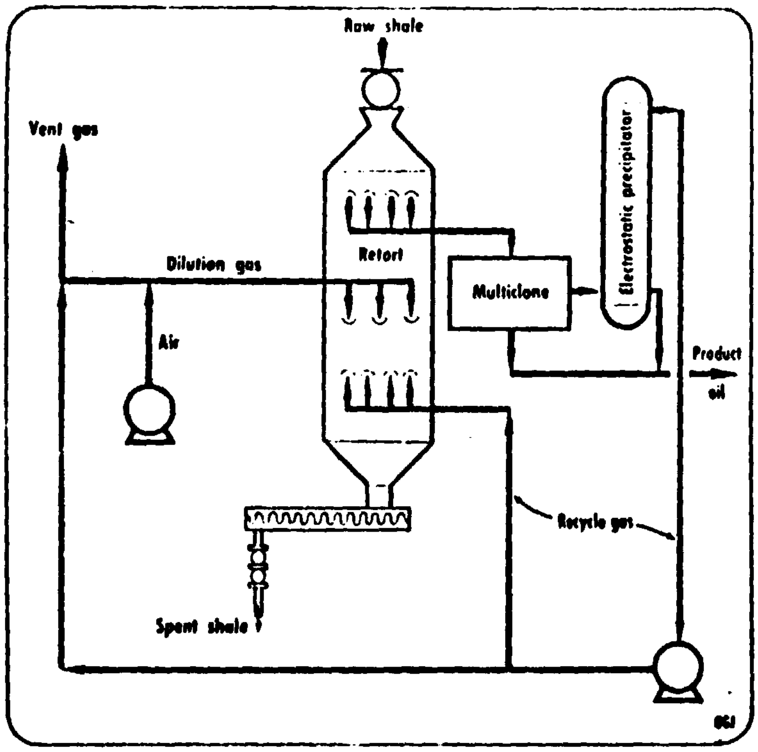



**Figure B.1 – Gas-combustion Process for Shale Oil**

## PROCESSO PETROSIX – DIAGRAMA DE FLUXO

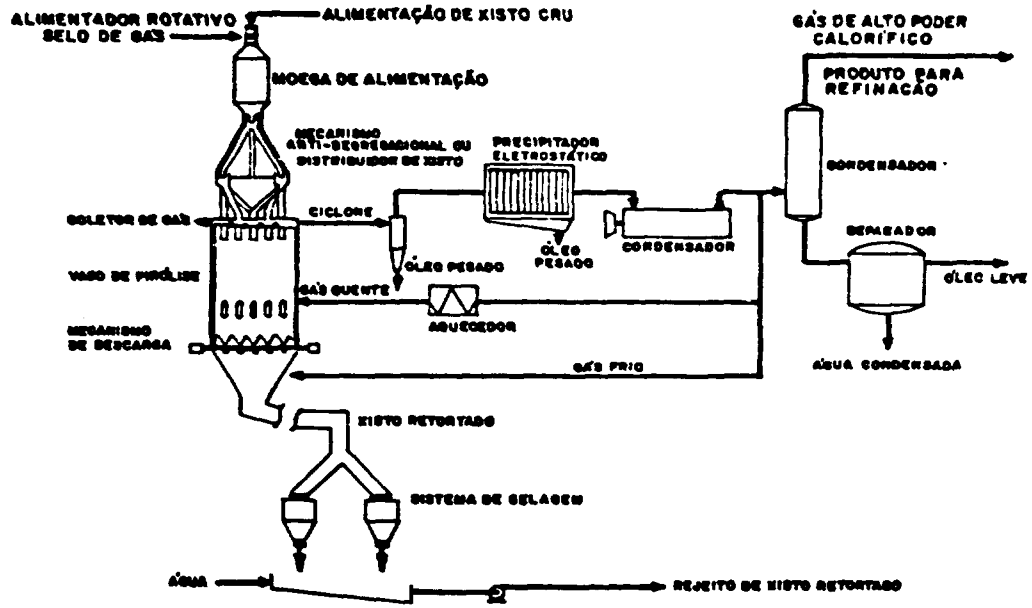



Figure 8.2 – PETROSIX Process

## TOSCO II. PROCESS

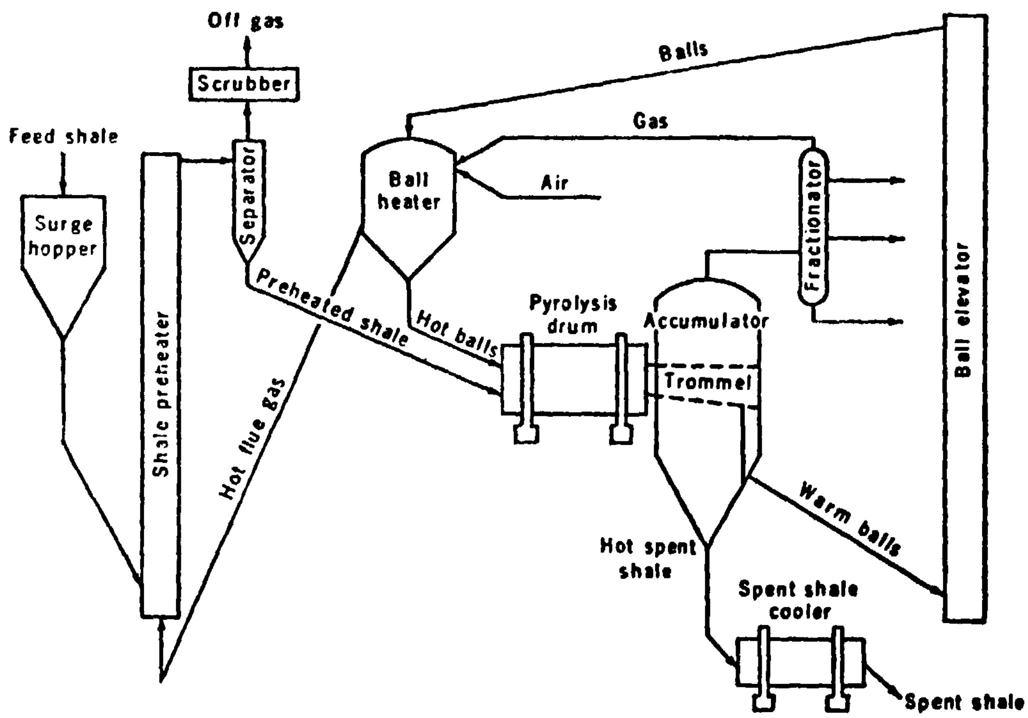



Figure 8.3 – TOSCO II. Process

chemical treatment [1] Ground shale was exposed to CO and steam. After such an exposure, the yield of organics was 29% compared to 5% when dry heat was used. An examination of the shale after the CO steam treatment showed much greater porosity. In other experiments at the Inst. of Gas Technology, Chicago, shale was treated with hydrogen at 33 atmospheres and temperatures in the range 600 – 700°C. Oil yields were increased by 25% over those obtainable by simple pyrolysis. Hydrogenation may be key to making some shales practical sources of oil.

## 8.3 – IN – SITU PROCESSING

A substantial problem of all mining and retorting methods is the disposal of the processed shale. About 5 to 10 tons of material must be disposed of for each ton of oil produced. Only part of this can be returned to the mine because the volume of processed shale is greater thant that of mined shale.

Because of the disposal problem and because deep mining by the room and pillar method leaves half of the shale behind, considerable effort has been devoted to achieving pyrolysis of shale in place the so-called "In – Situ Process". In the true in-situ method, wells are drilled to reach the oil shale bed and the shale is ignited at one or more wells and a combustion front is moved by controlled injection of air. Product gases and liquids are collected at other wells. In principle, this approach seems ideal, but in practice there are difficulties. The primary one is that the shale is not very permeable to the flow of gases and liquids. It is thus necessary to break up the shale underground (usually by explosives) or provide permeability by Hydraulic fracturning.

In these operations there are problems if the fragmentation leaves large chunks unbroken or if the hydraulic fracturning leaves relatively open flow paths between injection and production wells. In such cases heating tends to be non uniform or substantial portions of the shale may be bypassed.

In spite of these problems the true in situ method merits sustained effort for it avoids many of the disposal problems.

## 8.4 – MODIFIED IN – SITU PROCESSING

This is a combination of mining and in-situ processing and is the most publicized method of obtaining oil from Green River Shale (the largest shale deposit in the US). In this scheme developed by the Occidental Petroleum Co. a vertical section is processed. It starts with the mining out of material at the bottom of what is to become a rubble-filled room. About 20% of the contents of the vertical section are removed. Following this there is a sequence of explosions starting near the bottom of the remaining unmined material. A fire is started at the top of the section and is sustained by pumping in air. Gases and oil exit at the bottom. As the heat and fire move down they pyrolyze the shale.

As of Sept 1977, Occidental Petroleum had conducted pyrolysis in four rooms (sections) and was retorting a fifth. They claimed 60% recovery of total oil in the rooms.

## 8.5 – STATUS OF TECHNOLOGY

### a) US Program

The technology of producing oil from shale appears to be fairly well advanced with most effort being devoted to the mining and retorting approach. The use of this method of producing oil was practiced in many countries of the world from the late 1800's to the mid 1960's. Most all of the production efforts

(1) Cummins and Robinson "Thermal Conversion of Oil-Shale" 172 nd. Nat. Mtg., Division of Fuel Chem. ACS 21 94 (1976)

ceased, however, when faced with competition from cheap mid-east oil. With present high oil prices and with potential oil shortages in sight there is considerable development underway in the US and elsewhere to develop new methods of retorting shale and improve on old ones.

In the US, the Paraho Kiln of the Development Engineering Co. has been tested at the level of 400 tons of shale per day. The Union Oil SGR intermediate scale plant has processed shale at 1200 tons per day. Standard Oil and Gulf Oil have announced the construction of a commercial plant for operation in 1980.

Although much of the shale oil R + D in the US is being carried out by private companies, the Department of Energy's FY1979 hudget for this activity is about $ 34 million. The goal of this program is to produce 40,000 to 130,000 barrels/day of shale oil by 1985 and 800,000 to 2 million b/d by the year 2000.

**b) The Brazil Program**

A semi-industrial prototype plant located at S. Mateus do Sul in the State of Parana (see Figure 8.4) went into operation in 1975. This plant was designed by Petrobras to process 2200 tons of Irati type shale per day producing 160 $m^3$ of oil (1000 barrels) 17 tons of sulfur and 36,500 $m^3$ of fuel gas. This latter product was used by the process (Petrosix) for pyrolysis of the shale. The plant performed excellently from 1975 through the end of 1977 when it was shut down in order to concentrate on the design of a large scale industrial plant. This design work is still in progress. The output of the industrial unit would be about 45000 barrels per day (7100 $m^3$) plus smaller quantities of liquified gas, naphtha and sulfur. LPG and sulfur would be marketed at the plant. Pretreated oil would be mixed with light naphtha and sent through pipelines to the Parana Refinery The fuel gas and fuel oil produced would be consumed by the plant as the necessary heat source.

## 8.6 – THE ECONOMICS OF SHALE OIL PRODUCTION

At the present time the cost of a shale processing plant in the US producing 50,000 barrel/day of synthetic crude oil is estimated to range from $ 600 million to $ 1 billion. Such a plant could produce shale oil at 12/barrel to $ 17/barrel of which 7 – $ 12/bbl. would be for investment costs and the remaining $ 5/bbl for operating costs.

One factor that is important in connection with the economics of shale oil is the excellent quality of fluids that can be refined from its crude oil. The raw oil contains 2% nitrogen and 1% sulfur, however these elements can be removed through hydrogenation. It is feasible to obtain a fuel oil that contains only 0.01% sulfur.[1] To obtain fuel of comparable quality starting with coal would be extremely expensive. In view of the quality of oil and the fact that costs are in the range (even slightly lower than) world oil prices, the question arises as to why the commercialization of oil from shale has not proceeded faster in the US. The first answer to this question is that average crude prices to refineries are below world oil prices because of lower prices for domestic oil (which are controlled by the US government). This situation could well change in the not too-distant future.

The second answer to the slow commercialization of oil from shale is the environmental concern in the US. For a 55,000 barrel of oil/day plant, the material to be disposed of would amount to from 60,000 to 100,000 tons/day. Studies show that this material could be disposed of by filling some of the many canyons in the region. The processed shale cements together and would support vegetation growth.

Whether this method of disposal would be acceptable to the public, however, is an open question shale oil companies are unwilling to face.

(1) P.H. Abelson, "Oil Shale: Resources and Prospects" Presented at the Conference on Energy and Development in the Americas, Guaruja, São Paulo, Brazil, 12 – 17 Mar. 1978

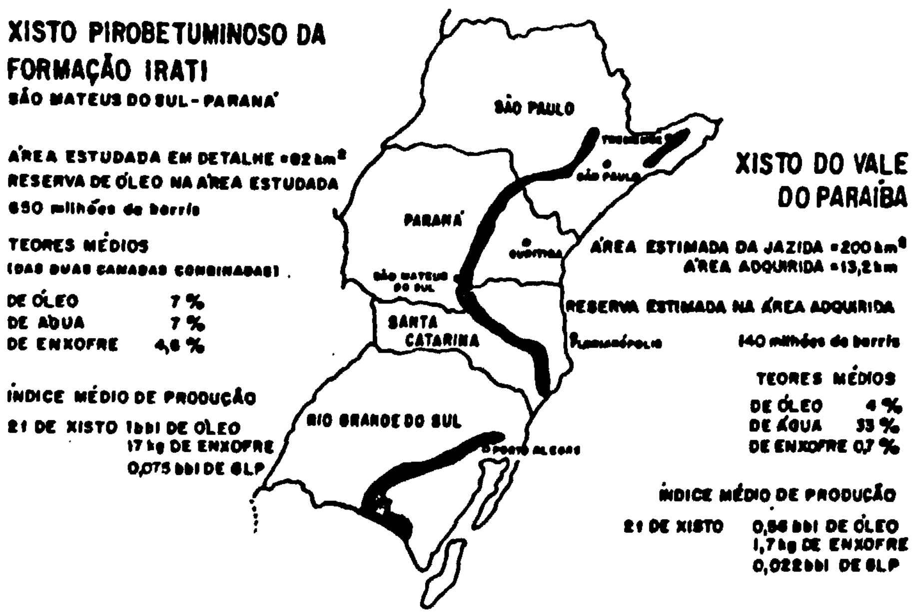



Figure 8.4 – Location of Important Shale Deposits in Brazil

A second environmental problem arises from the Clean Air Act passed the US Congress last year. Air Quality Standards set for the region of the Green River Shale are such that development of the area as a source of shale oil is virtually impossible.

In May 1978, the US Government decided to grant a \$ 2/bbl entitlement and certain tax credits to makers of synthetic liquid fuels, such as shale oil. This would essentially remove the economic barrier to shale oil production leaving only the environmental barrier to overcome.

One would hope that in Brazil, the environmental aspects associated with the production of shale oil would not act as unsurmountable barriers to this source of energy. At a price of \$ 11 – \$ 12/barrel, the production of oil from shale would make good economic sense.

## 8.7 – POSSIBLE CONTRIBUTION TO BRAZIL ENERGY SUPPLY

### a) Near Term Contribution (1986)

Following operation of the 2400 ton per day UPI prototype plant at S. Mateus do Sul, a commercial plant using multiple retorts of the Petrosix type is planned for operation in 1983. This plant would initially process about 56000 tons of shale per day and produce about 3500 $m^3$/day of crude oil ($1.2 \times 10^6$ tons/yr) plus 160000 tons of sulfur, about 90000 tons of liquified gas and 50000 tons of light naphtha. Production would be doubled by 1986. Although such a production would contibute only 4% of Brazil's petroleum demand in 1986, this constitutes an excellent start toward a commercial shale oil industry.

### b) Longer Term Contribution (2000)

Using the planned nuclear power growth in Brazil as a basis it is possible that up to 16 commercial shale oil plants could be in operation in Brazil by the year 2000. The total output of these plants would amount to about $32 \times 10^6$ tons of oil/yr. corresponding to 20% the projected petroleum demand in the year 2000. Although the investment in each plant would be of the order of \$ $1.5 \times 10^9$ (1978 dollars), this same plant would save about \$ $6 \times 10^9$ in imported oil costs.

## 8.8 – POSSIBLE AREAS FOR RESEARCH AND DEVELOPMENT

None are recommended because Petrobras already has an on-going program. In addition, the Chemical Institute of the Federal University of Rio de Janeiro has a Shale Chemistry Project underway.

# CHAPTER 9, BIOMASS CONVERSION

## 9.1 – INTRODUCTION

Biomass to energy conversion systems are of three major types (1) direct combustion of biomass materials generally to generate process heat, steam, or electricity (2) the manufacture of liquid or gaseous fuels and (3) the feeding of biomass to animals. The first approach requires engineering ingenuity in order to obtain low moisture biomass boiler feed and to conduct direct combustion efficiently. The second approach is of most interest scientifically because of the need to supplement naturally occurring oil and gas. The third approach, though seemigly straight forward, might stand further consideration because many biomass materials such as cornstalks which could be used as feed for ruminant animals are not so used at the present time.

The energy farm concept in which biomass is produced solely for energy production has received considerable attention in the US and elsewhere. The economics of this approach are at present quite uncertain. First of all, large areas of land are required. If such a power plantation were based on rapidly growing trees or plants, about 130,000 hectares would be required to support a 1000 MWe plant. Water requirements of 300 million cu.m/year and the logistics of handling the large volumes of materials involved would also be problems. Because of these uncertainties, the emphasis of current research and development programs is mainly on the technology of biomass conversion. The FY 1979 U.S. bundget for this is about 27 million US $.

## 9.2 – DESCRIPTION

### a) Silviculture

The use of wood and wood products such as charcoal is an important energy source in Brazil. In 1977, the consumption of firewood and charcoal amounted to $93 \times 10^6$ metric tons or $23 \times 10^6$ tons oil equivalent (TOE). This wood consumption represented 0.3% of the total stemwood inventory of Brazil's 320 million hectares of forest land.

In contrast to cropland, most of the forest land is not actively managed. Since the wood that is harvested represents a growth over a period of from 20 to 40 years, the above production corresponds to a deforestation of about 1 million hectares.

The concept of intensive tree farming in which elements of cropland agriculture (high machinery use, high fertilizer use, short rotation harvesting) are applied to fast growing trees (sycamores, aspen) is receiving attention in the U.S. however of extensive forest resources it is unlikely to play an important role in Brazil.

### b) Agriculture

The production of alcohol from sugar cane has been assigned a high priority in Brazil, therefore, it is unlikely that any significant areas of good cropland will be devoted to other types of biomass solely for energy production. Bagasse, the by-product of sugar production already constitutes an important source of fuel in Brazil. In 1977, the production was about 23 million tons corresponding to about 4,7 million tons of oil equivalent. It is expected that bagasse production will approximately double over the next ten years.

### c) Biomass residues

Urban and municipal solid wastes, crop residues and uncollected forest residues provide a potential source of fuel. The conversion or organic waste into heat or gaseous fuel not only helps to solve the problem of costly municipal refuse disposal but also provides a relatively economical source of energy. This practice is followed widely in Europe and is receiving increased attention in the US. The first step in a large scale process is to separate the refuse into various fractions including a solid shredded fuel similar to shredded paper. At the present time this shredded fuel is burned but several development projects are underway in the US to convert this to a gaseous fuel. The investment cost of a large plant handling up to 3000 tons per day of municipal solid waste is of the order of $ 15000 per ton of daily capacity. After allowing for metal recovery values, costs would amount to about $ 6 per ton of waste.

The Union Carbide Corporation has developed a so-called PUROX process based on a unique oxygen-fed slagging gasifier to produce medium Btu gas from municipal waste. A pilot plant yielding 200 tons per day is in operation in South Charleston, West Virgina.

## 9.3 – STATE OF THE TECHNOLOGY

The technology of biomass conversion in some areas such as the production of alcohol is relatively well developed. Processes for converting organic materials to liquid and gaseous fuels by thermochemical methods have been known for a long time however, more research and development is needed for a better understending of the economics compared to other synthetic fuel processes. Four biomass conversion approaches are receiving most attention. These are receiving most attention. These are:

### a) Fermentation

Most organic materials in the presence of some moisture are subject to natural fermentation leading to the production of alcohols. If the fermentation is carried out in the absence of oxygen and allowed to proceed to completion a large percentage of the carbon content in the material is converted to a mixture of 50% to 70% methane and carbon dioxide.

### b) Pyrolysis

Pyrolysis is a process of destructive distillation carried out in an unoxygenated closed system. This approach has for a long time been used commercially for producing organic byproducts such as methanol, acetic acid, turpentine and residual charcoal. Pyrolysis might be used in a total system of recycling of waste materials into usable fuels helping alleyiate the problem of disposing of refuse.

### c) Chemical Reduction

Organic materials when subjected to elevated temperatures and pressures in the presence of water, carbon monoxide and a chemical catalyst are partially converted to oil.

### d) Enzymatic Reduction

This process is closely related to the conversion of organic materials to gaseous fuel by fermentation. Enzymatic action can convert some organic materials to valuable pure products, chemical materials and clean fuels.

## 9.4 – FUTURE OUTLOOK FOR BIOMASS CONVERSION

### a) The US Program

The department of Energy's program on biomass conversion technology though small relative to some of the other programs has been increasing rapidly. In FY 1978, $ 21 million was authorized for this purpose and this increased to $ 27 million in FY 1979. An additional $ 10 million was proposed to provide additional incentives to accelerate the commercialization of this source of energy. There is particular interest in the use of biomass conversion processes to provide feed stock for the petrochemical industry. At the present time the US consumes about 10 million metric tons of ethylene and higher olefins. Fermentation of twenty percent of the US corn crop would suffice to produce this amount of ethylene. The economics of this approach, however, would determine its feasibility.

Studies by the MITRE corporation and by SRI International indicate that biomass conversion will play an important role in meeting the long term energy needs of the US.

### b) The Brazil Program

The biomass conversion program in Brazil is heavily oriented toward the production of alcohol from sugar cane (discussed elsewhere) and Cassava; however, there is some interest in other areas.

## 9.5 – CONTRIBUTION TO BRAZIL ENERGY SUPPLY

The contribution of biomass sources other than those now being used in Brazil (sugar cane, cassava, wood and cocoanut residues) is not likely to be important within the time frame of this study.

## 9.6 – AREAS FOR POSSIBLE RESEARCH AND DEVELOPMENT

One area that might be useful in connection with the use of biomass energy would be a study of the extensive literature on the yields and other characteristics of the many possible sources. This might indicate which of these sources might be of most interest in Brazil.

# CHAPTER 10, SYNTHETIC FUELS FROM COAL

## 10.1 – INTRODUCTION

Because of the foreseeable depletion of naturally occuring oil and gas, there is considerable interest in converting the five times more abundant proven world resources of coal into liquid and gaseous fuels. There are three basic ways of liquefying coal (1) add hydrogen (hydroliquefaction) (2) take away carbon (pyrolysis) and (3) break coal down into individual carbon atoms and rebuild (gasification + catalytic conversion). All of these approaches are being developed. The gasification of coal, on the other hand, has one basic approach, the reaction of coal with steam in the presence of oxygen or air. Depending on the techniques used, gases with high, medium and low calorific values can be produced.

To summarize, coal is an abundant energy resource but in its natural form it is hard to handle (relative to oil and gas) and it has impurities which cause environmental problems. Thus the conversion of coal to such products as boiler fuels, gasoline, substitute natural gas and petrochemical feed stocks is a desirable goal. Many processes are being developed, some of which are described below:

## 10.2 – DESCRIPTION OF COAL LIQUEFACTION PROCESSES

### a) Solvent Refined Coal

This is a hydroliquefaction process in which finely ground coal is slurried in an organic solvent mixed with a hydrogen – containing gas and reacted at elevated temperatures and pressures. The conversion reaction depends on the apparent catalytic effect furnished by coal ash constituents. Reaction products are separated by flashing to low pressure, removal of unconverted coal and ash by a suitable separation technique and fractionation. Waste streams are treated before discard. Sulfur removed from the coal during conversion is recovered as salable elemental sulfur. Depending on operating conditions the product from the SRC process can be either a solid or a liquid. SRC-I yields solids, SRC-II yields liquids.

### b) H – Coal

This process is essentially the same as the SRC process except that the conversion takes place in the presence of a bed of catalyst (cobalt molybdate) and higher reactor pressures are used (2700 psi vs 1200 psi). The product here is mainly char-oil, containing unconverted solids. This can be used as a boiler fuel or can be carbonized to obtain more liquid product. Other products of the H – Coal process must be subjected to further refinery operations.

### c) Donor Solvent

The donor solvent process is characterized by a relatively low pressure (325 psi) noncatalytic hydrogenation of the feed coal and a high pressure (4200 psi) catalytic hydrogenation of the coal liquids to produce a hidrogen donor solvent and synthetic crude oil. The char – oil by product slurry is carbonized to produce char and synthetic distillate oils.

### d) COED

The Char Oil Energy Development process is based on the multistage fluidized bed pyrolysis of coal to produce oil, gas and char. Catalytic hydrotreating of the oil yields a synthetic crude oil suitable as a petroleum refinery feed stock. The product gas can be reformed to produce a high Btu pipeline gas or hydrogen. The char product can be used as a boiler fuel or it can be gasified to produce synthesis gas.

**e) Indirect Liquefaction**

This approach involves gasification of coal by any one several gasification methods to produce synthetic natural gas (SNG). The SNG is purified and converted to organic liquid by catalytic conversion. This process is being used by the South African Coal, Oil and Gas Corp. in Sasolburg, S.A. In the SASOL-I plant coal is gasified with steam using a Lurgi gasifier. Here a downward moving bed of coal is gasified by an upward flow of oxygen and steam, Ashes are removed through a revolving grate at the bottom of the gasifier. Crude gas is washed with methanol to remove $CO_2$ and $H_2S$ and reformed with oxygen and steam over a nickel catalist to produce SNG. This SNG is reacted in the presence of a powdered iron catalyst to produce hydrocarbon liquids (Fisher – Tropsch Process). These are distilled into gasoline, ethanol, diesel fuel and other organic products. The SASOL-1 plant produces about 4000 barrels per day of gasoline and 400 barrels per day of diesel fuel. SASOL-II scheduled to begin operation in 1980 will have 4-5 times this capacity.

**f) Coal Gasification**

There are three basic types of gasifiers which are characterized by the method of contacting the coal with the steam – oxygen (air) reactants. These are (1) fixed bed (2) fluid bed and (3) entrained gasifiers. The fixed bed gasifier is best represented by the LURGI gasifier now being used commercially in South Africa. This type uses relatively large size feed coal and operates satisfactorily only on non caking coal.

Fluid bed gasifiers use an intermediate size coal which is maintained in a fluid state by the upward passage of the steam-oxygen mixture. The Winkler gasifier is a commercial version of the fluid bed type.

The entrained gasifiers use the smallest coal particle size and have a very small inventory of coal in the gasifier relative to the other types. The fine particles are entrained in the gas stream and react as they are carried upward. The reaction temperature at the base of the gasifier exceeds 1650°C so that coal ash is removed as molten slag. The Koppers Totzek entrained bed gasifier is of this type.

## 10.3 – STATUS OF THE TECHNOLOGY

**a) USDOE R + D Program**

In FY 1979, the authorized budget for developing the technology of converting coal into liquid and gaseous fuels is about $ 600 million. Of the various processes being developed, the SRC process is in the most advanced stage of development. There are two pilot plants in operation processing 50 tons per day and 6 tons per day of coal respectively. The design and site selection of on SRC demonstration plant is underway.

An H-Coal pilot plant is under construction and scheduled for completion in 1979. This will produce either synthetic crude oil or fuel oil using 250 t/d and 600 t/d coal feed respectively.

A Donor Solvent pilot plant is also scheduled for completion in 1979. This will process 250 t/d of coal. A test facility at Cresap W.Va. was operated 40 months during the period 1966 – 1970.

A COED pilot plant has already been operated and dismantled. It performed well mechanically and achieved its objectives of establishing the feasibility of the process.

Eight pilot plants have been operated in the U.S. to test fluid bed and entrained gasifiers and a fluid bed demonstration plant is being designed.

**b) Other Programs**

Programs are underway in West Germany to demonstrate the performance of gasifiers at higher pressures. These include testing advanced Koppers-Totzek, Winkler and other gasifiers at 30 atmosphere pressure and a Lurgi gasifier at 100 atm.

High Btu coal gasification demonstration plant programs are also underway in the U.K.

## 10.4 – ECONOMICS OF SYNTHETIC FUELS FROM COAL

Conceptual designs of four large scale coal conversion complexes were prepared for the USDOE in 1977 to provide a basis for estimating costs of synthetic fuels. These are described as follows:

a) **COED-Based Pyrolysis Complex** – This conceptual design includes a "captive" coal mine (owned by complex) producing 36000 tons per day of high sulfur coal. The output of the complex includes 28,000 barrels per day (BPD) of synthetic crude oil plus 830 MWe of electricity.

b) **Fisher-Tropsch** – This complex, also based on a captive coal mine, utilizes 40.000 tons per day of high sulfur coal to produce 7 x $10^6$ cu. m. of SNG and 50.000 BPD or organic liquids.

c) **OIL/GAS** – This design based on SRC-II technology yields 5 x $10^6$ cu. m SNG and 75,000 BPD of liquids from a daily production of 47,000 tons high sulfur coal.

d) **POGO** – This complex produces Power Oil Gas Other using SRC-II technology. Daily outputs are 4 x $10^6$ cu. m. SNG 80,000 BPD of gasoline and low sulfur fuel oil, 1400 tons of crystalline coke and about 1000 MWe of electrical power.

Capital investment costs for these complexes in $ billions (first quarter 1978 U.S. dollars) were estimate at 1.4 (Oil/Gas) 1.5 (COED-Based) 1.8 Fischer-Tropsch and 2.5 (POGO). Required product selling prices were estimated using economic ground rules peculiar to U.S. companies. These included a 12% discounted cash flow rate of return, financing with 65% debt, 35% equity capital, five year construction schedule, 20 year operating life at 90% on stream time and 9% interest rate. Sale of electricity at 30 mills/kWh was also assumed. On this basis required product prices in terms of barrels of oil equivalent were estimated at $ 12,50 (Oil/Gas), $ 13,00 (POGO), $ 16,00 (Fischer-Tropsch) and 30,00 (COED-Based). For 100% equity financing, prices would be 30% higher.

With the exception of the COED-Based complex, these results indicate that for large coal conversion complexes, complete with large efficient captive surface coal mines, coal conversion offers the potential of supplying synthetic fuels at cost that deserve serious consideration.

It should be pointed out that the economics of synthetic fuels from coal are quite sensitive to the cost of the coal. In the examples given, coal costs were in the range of $ 10 per metric ton. Every, $/ton increase in coal costs would add about 50 ¢/BOE to the figures given.

## 10.5 – CONTRIBUTION TO BRAZIL'S ENERGY SUPPLY

The feasibility of producing synthetic fuels from coal appears to depend very strongly on the existence of a large source of cheap coal. Unfortunately, the proven reserves of bituminous coal in Brazil are only about $1.2 \times 10^9$ tons (an additional $2 \times 10^9$ tons are "indicated" and $8 \times 10^9$ tons are "inferred"). Large coal conversion plants such as those described above require about $330 \times 10^6$ tons of coal over a 20 year lifetime. Only at one location (Charqueadas) are proven reserves of this magnitude. On this basis, the production of synthetic fuels from coal is likely to play only a minor role in Brazil's energy supply.

In the short term (up to 1986) synthetic fuel production in the world will be very small and in Brazil will be negligible.

In the long term (the year 2000) there might be one large coal conversion plant in Brazil if the development programs in industrialized countries result in economically competitive synthetic fuels. Such a plant, however, would contribute only about 1.5% of Brazil's anticipated petroleum demand in the year 2000.

## 10.6 – POSSIBLE AREAS FOR RESEARCH AND DEVELOPMENT

None are recommended, however, developments in industrialized countries should be followed very closely.

# CHAPTER 11, HYDROGEN FROM WATER

## 11.1 – INTRODUCTION

The technology of hydrogen production falls into three categories (1) current (2) near future and (3) long term. **Current** technology involving the production of hydrogen by the steam reforming of natural gas ($CH_4$) will continue to dominate the industry until at least 1985 – 1990 when natural gas shortages will become more apparent. **Near future** technology involving the production of hydrogen from coal will begin to emerge as an important source of hydrogen in about 1990 and will sustain the industry well after the year 2000. In the very long term, however, the production of hydrogen from water represents a truly unlimited source of fuel. Hydrogen, moreover, is transportable through pipelines and can be stored unlike the products of most of the renewable energy sources. Thus people envisage a "hydrogen economy" in which, in the absence of fossil fuels, hydrogen is used as the substitute fuel for automotive, domestic, and industrial uses. Although such a hydrogen economy is likely to materialize only in the far distant future, research and development of new methods of splitting water into hydrogen and oxygen, now underway, may have much shorter term implications.

The most important of these methods are described in this chapter. They rely on three basic approaches (1) electrolysis (2) direct thermal and (3) thermochemical. In some cases, all three approaches are combined into a single process.

## 11.2 – HIDROGEN PRODUCTION BY ELECTROLYSIS

Electrolysis of water has been known and practiced for a long time and is presently used to produce relatively small amounts of hydrogen of high purity. The most common practice is to operate at 25°C with a 30% solution of KOH. Because of the high cost of this source of hydrogen, commercial quantities are produced from natural gas or petroleum.

The primary disadvantage of electrolysis as a source of hydrogen, other than high costs, is the low efficiency of the process. If a LWR nuclear plant is used as the source of the electricity, the conversion of thermal energy to electricity is only 33% efficient. The electrolysis units operate at about 75% efficiency and the liquifaction step at 80% efficiency. Thus the overall efficiency of converting nuclear heat to liquid hydrogen is only 20%. Actually the heating value of the liquid hydrogen produced by electrolysis using an LWR as the source of electricity is 25% of that of the nuclear fuel consumed.

Because the stability of water decreases as the temperature increases, there is room for improvement in the efficiency of the electrolysis approach, namely by operating the electrolysis unit at higher temperatures. At present there are several institutions in the US doing research on materials and designs for working in the range of 100°C.

## 11.3 – DIRECT THERMAL DECOMPOSITION OF WATER

In order to reach appreciable dissociation of water using direct heating, required temperatures must exceed 2500°C. Although these temperatures can be achieved in solar furnaces and by other means, the problem of separating hydrogen and oxygen at high temperatures is very serious. Separation is necessary because the two gases would combine to form water on cooling. Separation schemes require the development of high temperature materials with the proper selective permeability properties at reasonable costs.

Experiments using the solar furnace at Odeillo, France, indicate that water can be dissociated into a mixture of $H_2$, $O_2$, H, OH and O in the temperature range of 2000 – 3000°C. The feasibility of this approach on a commercial scale, however, remains to be demonstrated.

## 11.4 – THERMOCHEMICAL CYCLES

A different approach to the application of thermal energy to the decomposition of water is the use of thermochemical cycles. These consist of a series of chemical reactions performed at various temperatures in such a way that the products of one reaction become the reagents of another and after all of the reactions have been performed the sequence can start again. The net effect is the input of heat and water and the output of hydrogen and oxygen. These cycles can be envisioned as a means of converting heat into chemical energy which in turn is used to split water.

Not all of the thermochemical cycles proposed are based solely on heat input. For economic reasons, some use a combination of heat and electricity or heat and solar radiation. In those that use electricity, the required amounts are much smaller than when electrolyzing water directly.

The selection of elements to be used as compounds in thermochemical cycles is based on the overall efficiency of the process.

The selection of suitable thermochemical cycles has been performed by computer search, by experimentation or by a combination of both. Presently there are more than 200 such cycles at different levels of development. A few examples are described below to illustrate those being worked on most intensivelly.

**a) Iron – Chlorine Cycle** This cycle being developed world-wide consists of the following reactions:

1. Hydrolysis – $3\ FeCl_2 + 4\ H_2O \rightarrow Fe_3O_4 + 6\ HCl + H_2$

2. Chlorimation – $Fe_3O_4 + 8\ HCl \rightarrow FeCl_2 + 2\ FeCl_3 + 4\ H_2O$

3. Decomposition – $2\ FeCl_3 \rightarrow 2\ FeCl_2 + Cl_2$

4. Regeneration – $Cl_2 + H_2O \rightarrow 2\ HCl + 1/2\ O_2$

These reactions have all been studied quite extensively in laboratory scale experiments. These investigations indicate that reactions 1, 2 and 4 are rapid enough for technical applications with adequate yields of the various products. Reaction 3, however, is complicated by the fact that the decomposition reaction is overlapped by the formation of $Fe_2Cl_6$ gas resulting in very low yields of chlorine. A special hot-cold apparatus being developed at Aachen W. Germany[1] may solve this problem however.

**b) Sulfur – Hybrid Cycle** – This cycle, being developed by Westinghouse is a two step process involving the following reactions:

1. $SO_2\ (g) + 2\ H_2O\ (l) + \text{electricity} \rightarrow H_2SO_4\ (aq) + H_2\ (g)$

2. $H_2SO_4\ (g) \rightarrow H_2O\ (g) + SO_3 \rightarrow H_2O\ (g) + SO_2\ (g) + 1/2\ O_2\ (g)$

(1) K.F. Knoche et al "Feasibility Studies of Thermochemical Cycles" Int. J. of Hydrogen Energy 4 No.4, [illegible], 1977.

Reaction 1 is carried out by electrolysis (thus the term "hybrid cycle") however, the power requirements are only 15% of those required for conventional electrolysis. The equilibrium for reaction 2 proceeds toward the right at temperatures above about 700°C.

In practice, the thermal reduction of $SO_3$ would be carried out at about 870°C, the maximum achievable value in the near future. Preliminary process designs and cost estimates have been prepared by NASA. These studies show that the process is potentially capable of achieving overall thermall efficiences between 40 and 60%.

c) **Sulfur — Iodine** — This cycle is being developed in the US by Gulf General Atomic. It consists of the following reactions:

1. $SO_2 + I_2 + 2\ H_2O \rightarrow H_2SO_4 + 2\ HI$

2. $H_2SO_4 \rightarrow H_2O + SO_2 + 1/2\ O_2$

3. $2\ HI \rightarrow I_2 + H_2$

d) **Iron-Sulfur — Iodine Hybrid** — This cycle is being investigated at Yokohama University, Japan. It consists of three reactions, namely,

1. $2\ FeSO_4 + I_2 + H_2SO_4 \rightarrow Fe_2(SO_4)_3 + 2\ HI$

2. $2\ HI \rightarrow H_2 + I_2$

3. $Fe_2(SO_4)_3 + H_2O \rightarrow 2\ FeSO_4 + H_2SO_4 + 1/2\ O_2$

The unique aspect of this approach is that reaction 1 is carried out photochemically using sunlight, reaction 2 is carried out thermochemically using an auxiliary heat supply and reaction 3 is carried out by electrolysis. Theoretical studies indicate overall thermal of 30 – 35% are possible.

## 11.5 – STATUS OF THE TECHNOLOGY

Although hundreds of cycles for splitting water into hydrogen and oxygen are under consideration, with the exception of direct electrolysis most of these have not developed beyond the theoretical stage. Those that have had some experimental work done, moreover, have not gotten beyond the laboratory bench phase. Only one process, the Westinghouse Sulfur Cycle has been looked at from a plant design and economic stand-point.

## 11.6 – THE ECONOMICS OF WATER SPLITTING

In order to become a practical source of hydrogen, methods of producing it from water will have to compete with its production from natural gas, petroleum or coal. At the present time, 75% of the US production of hydrogen is from natural gas the remainder from petroleum. Throughout the rest of the world the source of hydrogen is natural gas when it is available. The reason is that steam reforming of natural gas is the cheapest source of hydrogen. Production costs, however, vary widely depending on the scale of operation and the cost of natural gas.[1] With very large scale operation ($70 \times 10^6$ SCF/day = $2 \times 10^6$ Cu.m./day.) production costs range from \$ 0,60/1000 SCF (standard cubic foot) to \$ 1.25/1000 SCF, for natural gas costing 60 ¢ and \$ 2.00 per $10^6$ Btu respectively. These costs correspond to \$ 10/BOE and \$ 20/BOE (barrel of oil equivalent).

These costs should not be confused with the hydrogen market prices. In the US, these range from \$ 5/1000 SCF to \$ 30/1000 SCF depending on the monthly amount purchased. This is important because production costs of new processes are often compared with market prices rather than with production costs of competing processes.

Regarding the cost of producing hydrogen from coal, design studies of large plants producing $20 \times 10^6$ Cu.m./day of hydrogen have been carried out for different gasifier technologies[2]. Estimated costs of hydrogen from such plants were \$ 0.77/1000 SCF in mid 1974 dollars. In 1978 dollars, costs would be about \$ 1.10/1000 SCF.

These low costs were based on the assumption that the plant would use cheap Montana coal at \$ 0,30/$10^6$ Btu.

K. Darrow and co-workers at the Institute of Gas Technology, Chicago, have studied the possible use of off-peak electricity to produce hydrogen by electrolysis using conventional (Teledyne and Lurgi) electrolyzers and also an advanced electrolyzer being developed by the General Electric Co. in the U.S. Off peak electricity costs were assumed to range from 5 mills/kwh to 15 mills/kWh. For the low plant factors attainable with off peak operation, hydrogen costs ranged from \$ 3 – \$ 5/1000 SCF. With the advanced electrolyzer design (projected technology) costs would be reduced to about \$ 2 – \$ 4/1000 SCF. The conclusion was that this mode of operation is too costly.

For an electrolysis plant dedicated to the full time production of hydrogen using electricity costing 20 mills/kWh, hydrogen costs were estimated to be \$ 3,70/1000 SCF. About 80% of this cost was for the electricity consumed.

No economic data are available for the production of hydrogen from direct thermal or thermochemical processes.

## 11.7 – POSSIBLE CONTRIBUTION TO BRAZIL'S ENERGY SUPPLY

Of all of the water splitting processes mentioned here, the only one that might become important as an energy source in Brazil is electrolysis.

As seen above, however, the problem with electrolysis is high costs resulting from the high cost of electricity. It is possible that there are some favorable hydroelectric sites in Brazil which are too far from electrical load centers for the economic transmission of electricity. If such sites exist where electricity can be generated at costs in the range of 5 mills/kWh, an electrolysis plant using this electricity could produce hydrogen for about \$ 1,60/1000 SCF. Such hydrogen could be used for the synthesis of ammonia.

## 11.8 – POSSIBLE AREAS FOR RESEARCH AND DEVELOPMENT

A utility such as CESP has a fairly large amount of off-peak power capacity. Studies might be carried out to evaluate the economic feasibility of using such off peak power for the production of hydrogen. This would depend on the value of such power and its availability.

(1) K. Darrow et al. "Commodity Hydrogen from Off-Peak Electricity", Intl. J. of Hydrogen Energy 2 175, 1977.

(2) C.L. Tsaros et al. "The Manufacture of Hydrogen from Coal" Intl. J. of Hydrogen Energy 2 41, 1977.

# CHAPTER 12, GEOTHERMAL ENERGY

## 12.1 – DESCRIPTION

It is theoretically possible to drill a hole in the ground anywhere in the world and use the temperature difference from the bottom to the top of the hole as a source of energy. Such an approach called "normal gradient" geothermal is impratical because the amount of energy recoverable from such a hole is far too small to cover the cost of extracting.

It is also theoretically possible to drill a hole through the earth's crust and tap the unlimited energy in the molten rock below the crust ("magma" approach). This approach is also not practical because the technology does not exist for recovering this source of energy.

Thus the term "geothermal energy" usually refers to the recovery of energy from specific locations where nature has created conditions allowing molten rock to move upward through shattered crustal material providing a source of heat energy fairly close to the surface. A geothermal reservoir is formed, as shown in Figure 12.1 when water comes in contact with such a heat source. The difficulty of discovering these so called hydrothermal reservoirs is the greatest obstacle to the wide spread use of geothermal energy. When found, however, hydrothermal reservoirs appear to be economically competitive with other energy sources. They still must be considered of interest only to the area they serve. The creation of artificial hydrothermal reservoirs, where surface water is forced under high pressure through cracks in hot rock formations ("hot dry rock" approach) is also being considered in the USA.

Hydrothermal energy sources may be classified into four types depending on the nature of the circulation system and the temperature and pressure of the reservoir. These are, (a) dry steam or vapor dominated (b) high temperature water dominated (above 150°C) (c) intermediate temperature water dominated (90°C to 150°C) and (d) low temperature water dominated (below 90°C).

There is one other type of geothermal energy in the U.S. (geopressurized fluids) however, this is in an early stage of development and peculiar to the US.

## 12.2 – PRESENT USE OF GEOTHERMAL ENERGY

The difficulty of discovering hydrothermal sites suitable for power production is illustrated by the fact that there are only 18 geothermal power installations in operation through-out the entire world. The total installed capacity of these plants is only about 2000 MWe. Only three of these stations are of the dry steam type, the remaining are high temperature water dominated with temperatures ranging from 170°C to 300°C. The average well depth is about 900 m.

In spite of the slow growth of geothermal power to date, many experts believe this source of energy has great potential for local applications. At least 38 countries other than the 11 with existing installations have an active interest on geothermal exploration. The United Nations has exploration underway or planned in 15 developing countries.

## 12.3 – PRESENT STATE OF TECHNOLOGY

The location of a potential hydrothermal reservoir starts with the identification of sites where hot springs discharge at the surface. Thousands of such sites are located throughout the world and many of these serve Spas and provide warm water for other local uses. These springs, through their chemical

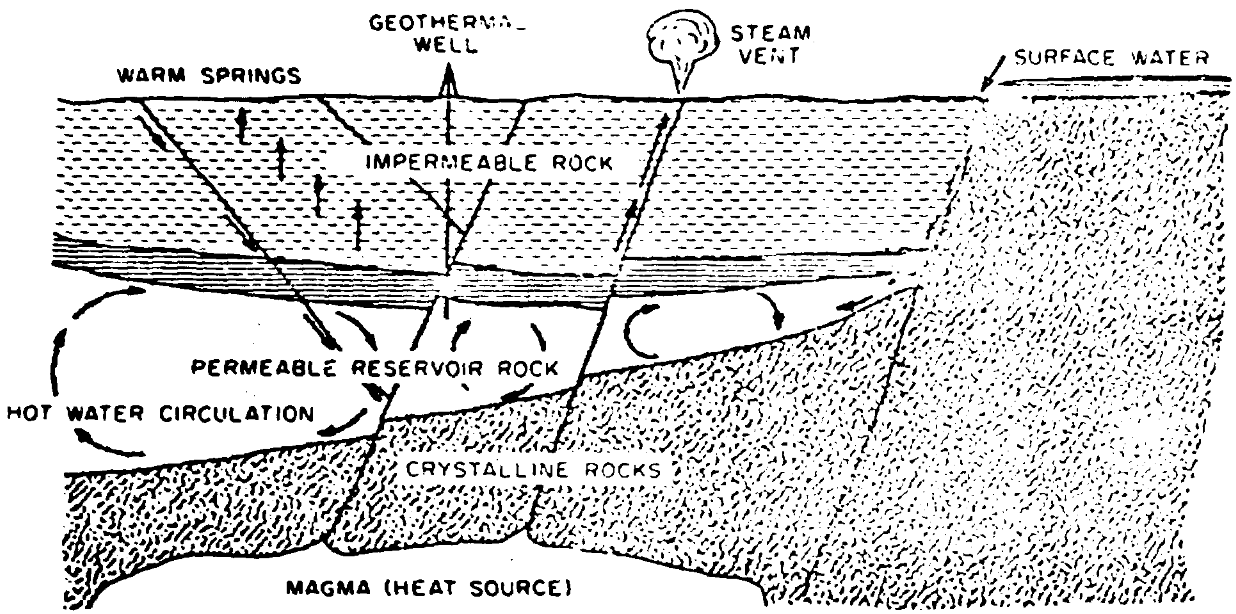



**Figure 12.1 — Schematic of a Geothermal Reservior Capped by Impermeable Rocks Within a Faulted Structure**

composition, area coverage, and associated geophysical data provide useful evidence on probable temperatures and size of the underground reservoirs, however, in each case extensive drilling is required to adequately assess the potential of the site. This need for many exploratory drill holes makes the development of any particular site a high risk venture. This has greatly hampered the development of geothermal energy by private companies.

The technology of generating electricity from a dry steam well is straight foward but such steam wells are quite rare. To use the water dominated hydrothermal sources requires considerable technical development. The main problems are the relatively low temperatures of most hydrothermal sources, the reduction in temperature of source fluid as heat is extracted, the high degree of corrosiveness and scale forming tendencies of the dissolved solids of many of the systems. The USDOE plans to spend more than $ 600 million through FY 1981 to solve these problems.

## 12.4 – GEOTHERMAL ENERGY POSSIBILITIES FOR BRAZIL

The geological characteristics of Brazil on the whole are not conducive to the widespread utilization of geothermal energy. There are, however, a few unique areas with geothermal possibilities. One of these is Poços de Caldas, located about 200 km north of the city of São Paulo in the state of Minas Gerais. Within a roughly circular area, 30 x 40 km (minimum and maximum diameters) there is evidence of ancient volcanic activity.

The cones of these old volcanoes, however, have been flattened by erosion. There are numerous hot mineral springs in the area with surface water temperatures in the range of 40° – 50°C. Although, water at these temperatures is not of commercial interest, many experts believe there may be a large magmatic chamber fairly close to the surface. If so, this area could become a source of geothermal energy. The extent of this resource, however, is not known.

One feature of the Poços de Caldas area is that it is an important source of minerals such as zirconium, uranium, molybdenum, cerium and thorium. Estimated resources of uranium in the area amount to 13000 tons $U_3O_8$. Thus geothermal energy, if it exists, could become an important local energy source for the mining and milling of the Poços de Caldas ores.

## 12.5 – AREAS FOR RESEARCH AND DEVELOPMENT

It may be possible to determine from the chemical composition and area coverage of the hot springs at Poços de Caldas information on probable subsurface temperatures, reservoir volumes and heat contents. The first step, therefore, would be to obtain such data in order to estabilsh whether not experimental drilling is justified. If successful, such a program might result in the development of a geothermal energy source in the relatively near term (by 1990).

# CHAPTHER 13, DIRECT SOLAR RADIATION

## 13.1 – INTRODUCTION

The statement is often made by solar enthusiasts that, "solar energy is free and it is renewable". The same statement may be made for flowing water; however, in both cases, the cost of converting the free energy into a useful form has hampered the development of these sources of energy. In the case of hydropower development, only 7% of the world's energy consumption in 1977 was from this source. As for solar energy, the contribution was essentially zero.

The advent of the oil crisis in late 1973, early 1974, however, made people generally realize that the era of cheap energy, particularly oil, gas and electricity had come to an end. It also became clear that some time in the not-two-distant future the world will have to rely on energy sources other than naturally occurring oil and gas. At the same time, there was a growing awareness everywhere of the problems that would be imposed on society by an "all nuclear economy". Thus attention focussed on alternative energy sources, particularly solar energy, as means of alleviating the future energy supply problem. In the United States, funds for the development of solar energy applications increased rapidly starting in about FY 1975 and are now at level of $ 390 million per year. Three basic approaches to the use direct solar radiation are being under the current US program. These are (1) hot water heating (2) heating and cooling of buildings and (3) the generation of electricity. These applications are described in the following paragraphs:

## 13.2 – SYSTEM DESCRIPTIONS

### a) Hot Water Heating

Several million simple, natural convection circulation systems are already in operation in Japan, Israel, Australia and South Africa for the production of domestic hot water.. A schematic of this type of system is shown in Figure 13.1. The key to the success of this approach at least in the US, is the development of a cheap, reliable flat plate collector (radiation absorbing unit) such as that show in Figure 13.2.

In order to compete with the production of average residential hot water from electricity costing 5 US ¢/kWh (annual consumption equal 6000 kWh) solar hot water heaters would have to cost about $ 2,000.00 installed. This is about one-third the present cost of such units.

### b) Heating and Cooling of Buildings

Despite the high costs of solar collectors, there is a tremendous interest in the US in the use of solar radiation for the heating and cooling of buildings. The reason is that 22% of US total energy consumption goes into the heating of buildings and 3% into air condictioning.

In principle, the heating of buildings uses the same concept as for hot water heating; however, in this case the hot water is used to heat an air distribution system or piped around the building. Although one could have a heat storage system sufficient to supply all of the building needs when the sun is not shining, such an approach is not economically atractive because of the high cost of heat storage. The best approach appears to be a combination of solar and conventional heating in which solar energy would supply about 60% of total needs in warm to temperature climates.

The use of solar heat for air conditioning is more complicated because this requires a heat actuated air

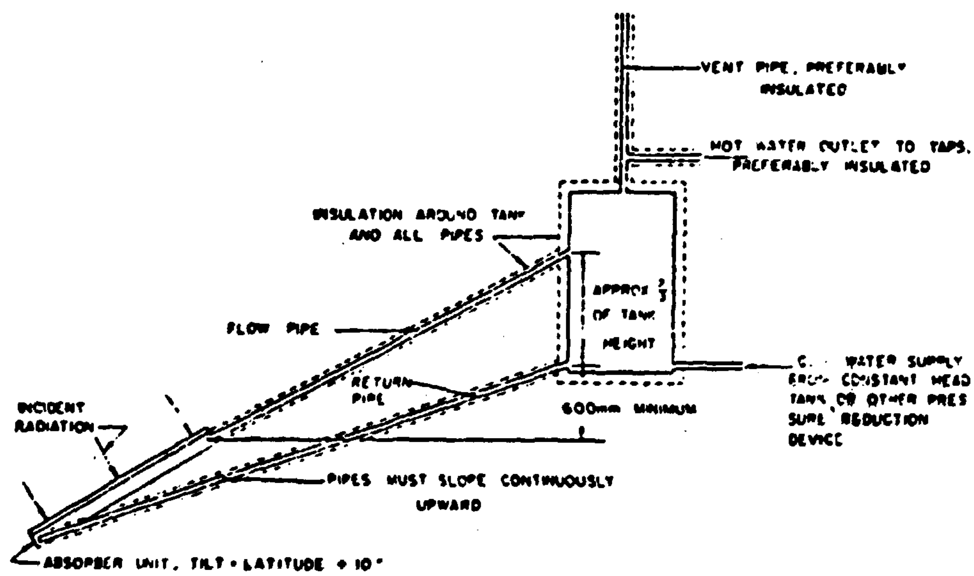



**Figure 13.1 – Schematic Layout of a Solar Water Heating System**

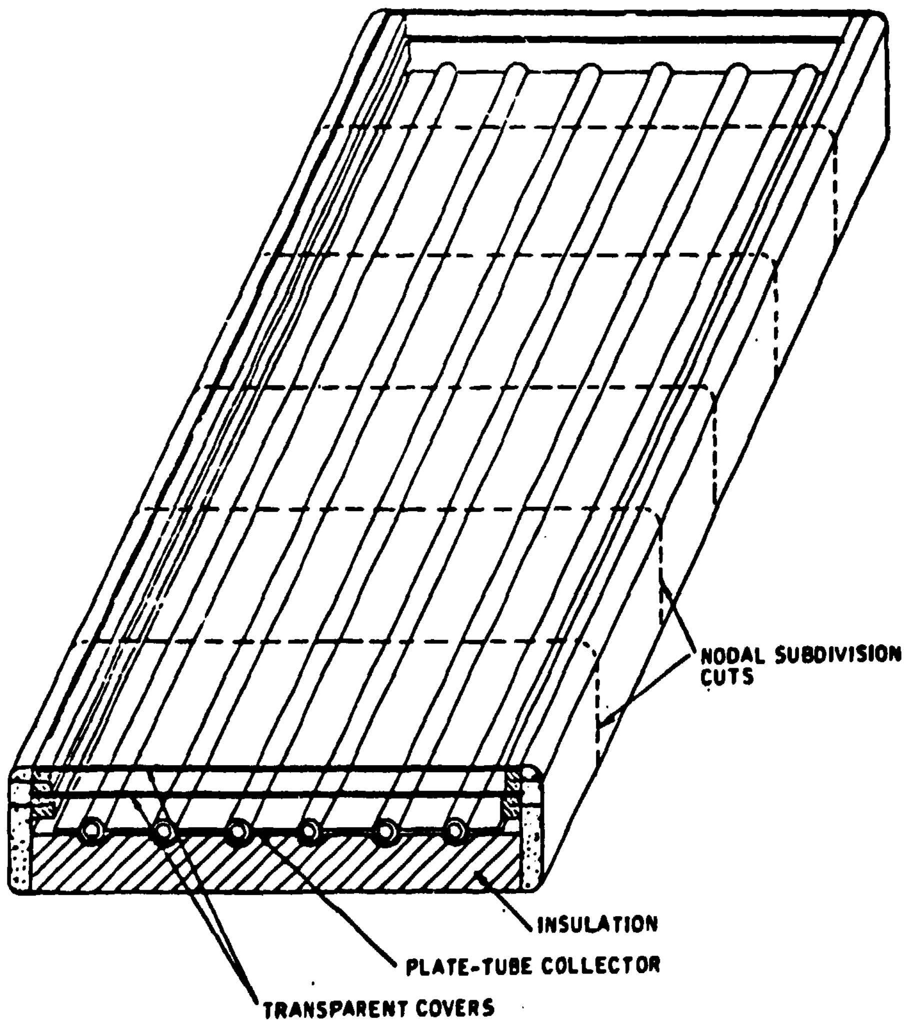



Figure 13.2 – Schematic of Flat Plate Collector

conditioner, such as a water cooled lithium bromide abs· ·tion machine. In this case also, an auxiliary conventional air conditioner is required.

In both the heating and cooling aplications, the solar energy system acts as a fuel saver since the conventional backup system must be sized to supply the entire building requirements when necessary.

**c) Electricity Generation**

Three approaches to the generation of electricity by solar radiation are being considered in the US. The first two are (1) a collector pipe system and (2) a tower receiver system. Both of these approaches are for central station power production. The third approach involves the use of a photovoltaic cell which converts sunlight directly into electrycity. This might be used for residential electricity, central station power or even in a satellite power station.

The collector pipe system shown in Figure 13.3 uses a large field of individual reflectors, each of which concentrates solar energy on an absorbing unit containing a heat exchange fluid or gas. The heated fluid is piped to a central heat storage system where it is used to generate steam to drive a conventional turbine generator. A wide variety of combinations of various reflectors, absorbers, heat transfer fluid, heat storage s: stem and working fluid are possible. Three types of reflectors are shown in Figure 13.4.

In the tower receiver concept shown in Figure 13.5 a large number of reflectors (heliostats) focus the sun's rays on a heat absorbing system located on top of a tower. Again heated fluid is used directly or indirectly to generate electricity via a conventional steam driven turbine generator set. A variety of heliostat designs, receiver designs and steam generating systems are being investigated.

Solar photovoltaic cells offer a potentially attractive means of converting sunlight directly into electricity. These are made of semiconductor materials, two of which are being considered as candidates for a large scale solar conversion system. The first is a single crystal silicon cell and the second is a thin polycrystalline film of cadmium sulfide on which a thinner layer of a different semi-conductor such as copper sulfide is grown. Under the influence of direct sunlight these photovoltaic cells generate about 5 to 10 watts per sq. ft. (50 – 100 watts/sq.meter). The use of reflectors to concentrate the solar radiation on the photovoltaic cells can increase the output of each cell.

A very long range proposal for utilizing solar energy is to put the power station on a satellite. The energy captured by the photovoltaic cells would be sent to an earth receiving station via microwaves. Since the cells would be exposed to sunlight 24 hours a day and there would be no radiation loss by absorption in the earth's atmosphere, about 10 – 12 times as much incident radiation would be received per sq. meter of photovoltaic cells compared to a similar station on earth.

## 13.3 – STATUS OF THE TECHNOLOGY

**a) Hot Water Heating**

The technology of heating water with solar radiation is straight forward and well demonstrated throughout the world. The main problem for applications in areas accessible to electricity or other fuels is that of costs. Also, solar hot water heating is not as applicable to high rise apartment or office buildings because of limited roof area per occupant. Solar hot water heating is also not feasible in areas which receive heavy winter snowfalls.

**b) Heating and Cooling of Buildings**

The technology of using solar radiation for heating buildings is essentially the same as for hot water

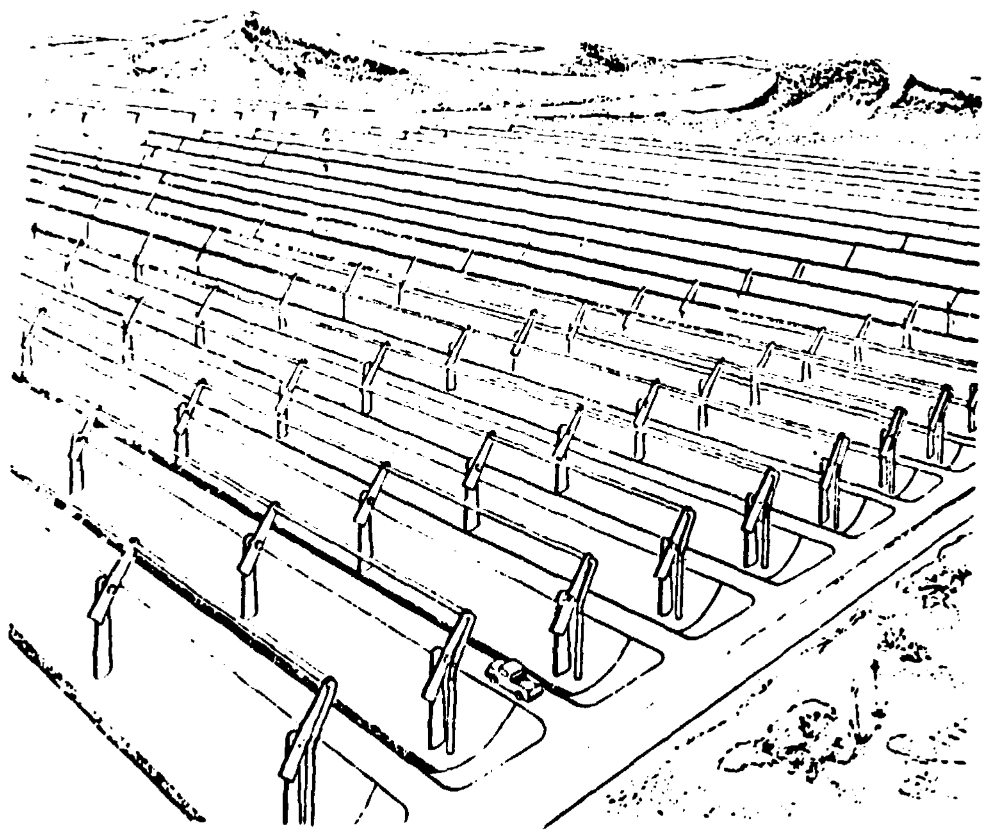


Figure 13.3 — Artist's Concept of Fixed-Mirror Solar Concentrators Showing the Mirrors and the Tracking Heat Absorber Pipes

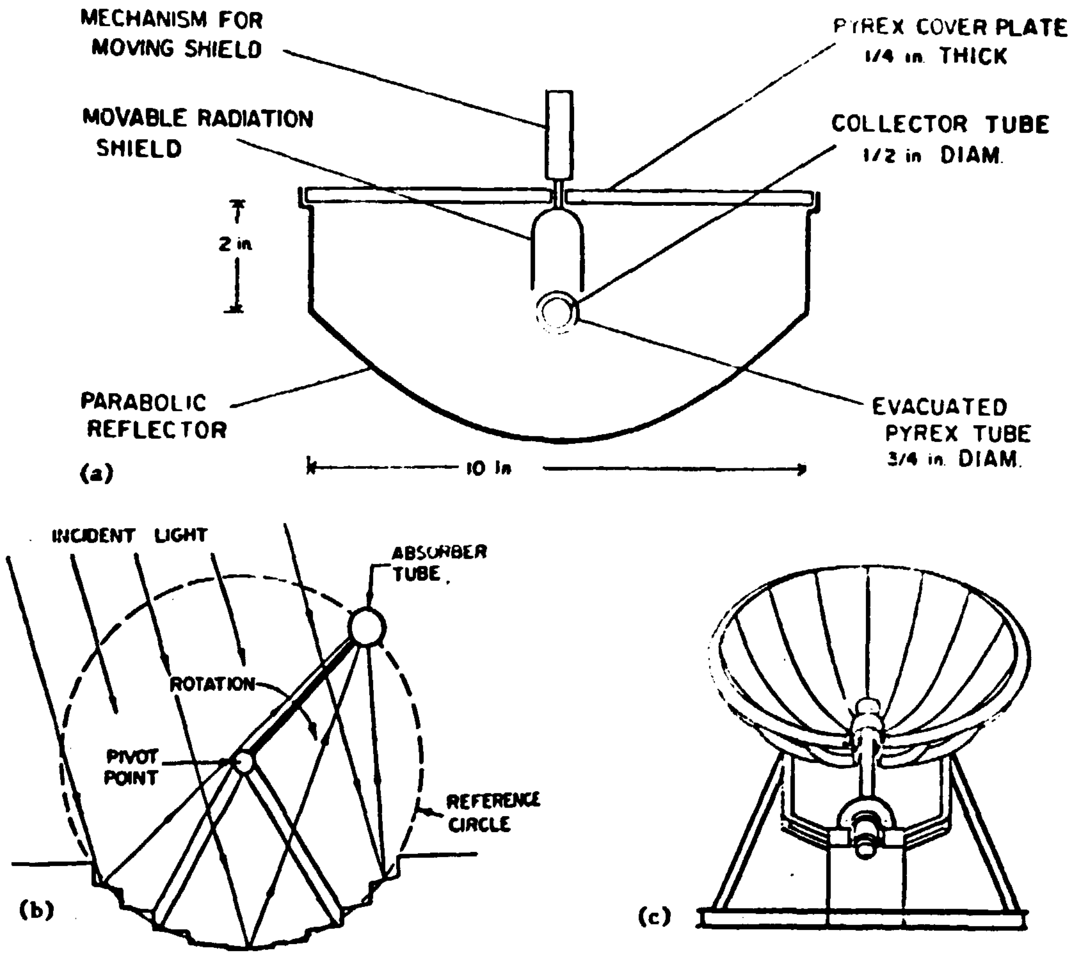



Figure 13.4 – Reflectors for Distributed Collector Systems. (a) Parabolic Trough with Single-Axis Tracking. (b) Fixed Mirror with Tracking Absorber Tube. (c) Paraboloid-of-Revolution Dish with Two-Axis Tracking.

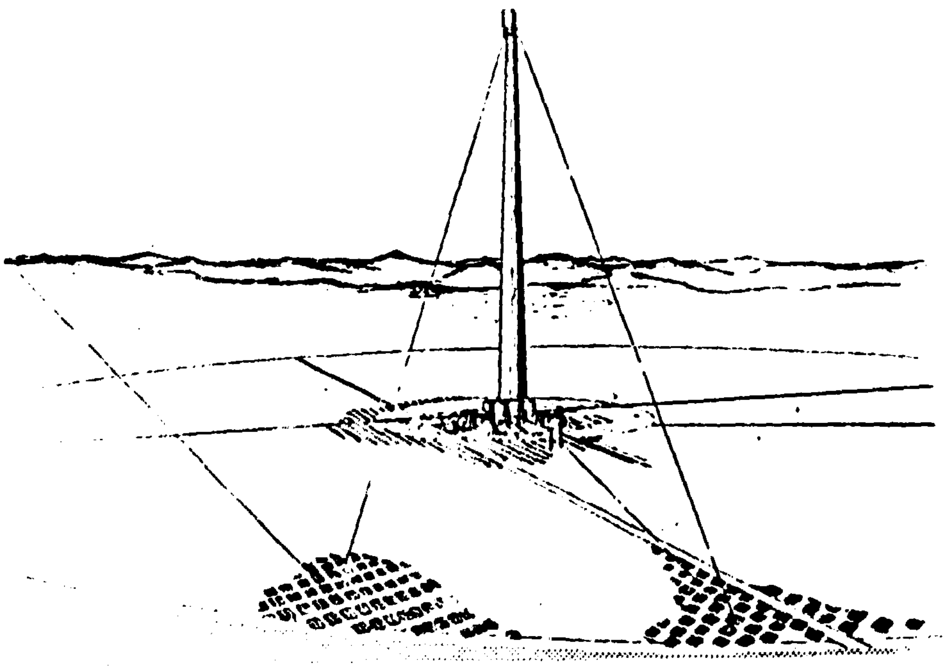


Figure 13.6 – Schematic Diagram of Tower Receiver Concept.

heating except it is more complicated because of the problem of heat storage. Economical heat storage devices of sufficient capacity to meet all heating needs when the sun is not shining have not yet been developed.

One method of avoiding this problem is to use a conventional heating system assited by solar heat. Experimental solar heated homes in the US using this approach were found to require annually only one-third as much electricity as a comparable all electric home. The cost effetiveness of the combined solar conventional heating system must, however, be evaluated for each application.

The use of solar radiation for air conditioning is still in the development stage.

**c) Distributed Collector System for Electricity Generation**

The development of this type of solar conversion system is essentially the same stage as nuclear power was 25 years ago, the main effort being directed toward alternative system studies, component designs and economic analysis. The most promising distributed collector systems are those based on parabolic troughs, fixed mirror with tracking absorber and dish collectors with two axis tracking. These reflectors have been studied intensively. Considerable work has also gone into the development of absorbers, particularly those with selective coatings to achieve a high ratio of absorptivity to emissivity. Test facilities for this approach to solar-electric plants will be establised to investigate the engineering problems involved. Pilot plants will be constructed and operated by 1981 with the objective of having a demonstration plant operating by 1985 or shortly, there after.

**d) Tower Receiver System for Electricity Generation**

The tower receiver is also in an early stage of development although a 10 MWe pilot plant is being constructed in the US. This plant will be located in Barstow, California and be put into operation in 1980 – 81. Its purpose is to actually demonstrate and produce solar thermal electricity. The US FY 1979 budget for the development of solar thermal electricity is $ 72 million of which $ 30 million will go toward the Barstow plant.

**e) Phtovoltaic Cells Electricity Production**

The technology of photovoltaic electricity production centers around the development of low cost cells. This can be divided into three categories (1) reducing the cost of manufacturing the single crystal silicon cells that are now on the market (2) developing techniques for mass producing and increasing the performance of cells made from thin films of materials such as $CdS/Cu_2S$ or amorphous silicon and (3) developing high efficiency cells which can be installed at the focus of magnifying optical systems. All of these approaches are just starting to show promise.

**f) Satellite Power Stations**

This approach is in a very early stage of development; however, numerous aerospace industries in the US have expressed interest in continuing studies.

## 13.4 – ECONOMICS OF SOLAR RADIATION ENERGY

The economics of heat applications of solar energy have already been discussed. In general, costs have to be reduced a factor of three or more for such systems to be cost effective.

The economics of electricity generation using solar radiation are such that solar-eletric plants are not likely to be competitive with nuclear (LWR) plants for base load power generation. Detailed cost studies by the Honeywell Corporation[1] indicate with a dish collector system, generating costs (in 1984 U.S. dollars) would be about 100 mills/kWh and with a tower receiver system about 70 mills/kWh. Both costs are for plants without storage. A pressurized water storage system would add about 9 mills/kWh for each hour per day of heat storage. By comparison, a 2 x 1232 MWe Nuclear plant can generate electricity at 30 mills kWh.

The economics of photovoltaic conversion hinge on the cost of th... ...s themselves. In 1973, 1000 sq. meters of cell arrays were produced at costs of $ 8000 per square meter for the space program in the U.S. To be competitive, cell costs will have to be reduced to about $ 20 per square meter. Plans are to establish pilot plants by FY 1983 capable of producing more than 5 million $m^2$ /year of silicon sheet at a value added cost of $ 18/$m^2$. This is a very ambitious economic goal; however, USDOE believes that photovoltaic conversion will be economic by 1986.

## 13.5 – CONTRIBUTION TO BRAZIL ENERGY SUPPLY

The near term contribution of solar radiation as a source of energy in Brazil will be negligibleup to at least 1990. If anticipated developments in industrialized countries materialize as hoped, the production of hot water by solar energy might make a small contribution (less than 1%) to the total energy needs in the year 2000.

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(1) J.C. Powell "Dynamic Conversion of Solar Generated Heat to Electricity NASA/Cr 134724-6 vols I and II, August 1974.

# CHAPTER 14, WIND ENERGY

## 14.1 – BACKGROUND INFORMATION

The use of wind mills to pump water or generate electricity is well established technology if carried out on a small scale. Numerous manufactures in the U.S.A, Europe and Australia are selling wind powered generators with ratings from 1 kWe to 20 kWe to satisfy small power requirements in remote areas. The most promising application is water pumping. Regarding the production of electricity, wind generating costs for these small machines are in the range of 0.15 to 1.00 U.S.$ per kWh depending on such factors as installation costs, interest rates, local wind conditions and the required amount of storage. These costs are higher than for electricity supplied by a utility but are in a range which makes the use of wind generators economically feasible in areas where the alternative would be diesel generators.

The problem then, is not the development of wind energy generation, as such, but the development of wind machines large and cheap enough to permit wind energy to supply a significant fraction of man's energy needs. The wind energy development program, therefore, is oriented toward the largest conceivable machines (1/2 to 2 MWe) which are still very small compared to nuclear and fossil-fired electricity generating plants in the 1000 MWe size range. These so called "large scale" wind machines fall into two classes, "horizontal axis" and "vertical axis" which are described in the following paragraphs.

## 14.2 – DESCRIPTION OF HORIZONTAL AXIS WIND MACHINES

The traditional approach to wind machine design is a horizontal shaft (axis) turned by propellors, blades or sails.

The largest wind powered generator, the Putnam-Smith wind turbine, shown in Figure 14.1, was of this type. This unit, constructed in Vermont, U.S.A., in the early 1940's used a two blade propeller, 55 meters in diameter to drive a generator rated at 1.25 MWe. The unit operated intermittently until 1945 when one blade failed. Its annual use factor was 14%. A 1.5 MWe production model was proposed as a follow-up design however no machines of this design were ever built because anticipated power costs were about twice those from conventional plants.

Interest in horizontal axis wind machines was revived in the U.S. in the early 1970's and a joint National Science Foundation – NASA project to build a pilot wind generator with 100 kWe capacity was initiated in FY 1974. This generator, shown in Figure 14.2, is driven by a two blade propeller, 38 meters in diameter, and produces its full power at wind speeds above 30 km/hr. Although the NSF/NASA wind generator was considerably smaller than the Smith-Putnam machine it was designed to demonstrate technical innovations such as automatic blade pitch control and the performance of new materials of construction.

A somewhat less traditional approach is being followed by Dr. W.L. Hughes of Oklahoma State University in the U.S. (see Figure 14.3). The rotor is this case is a 48 bladed, light weight affair similar to a bicycle wheel. Power take off is from the rim rather than the shaft of the rotor eliminating the need for a heavy and expensive gear box. Because of its light weight construction, however, it is doubtful whether the Hughes' design can be scaled up to 1 MWe.

Another approach to a light weight wind machine is being developed at Princeton University in the U.S. This is a sail wing windmill which uses a tubular rigid leading edge and a cable supported trailing edge to hold the sail. The maximum practical size of this type of machine, however, is of the order of 15 meters in diameter which would generate only 30 to 40 kWe.

In summary, the two blade propeller approach appears to be the only horizontal axis machine capable of generating 1 MWe or more.

Figure 14.1 – Smith-Putnam Wind Turbine

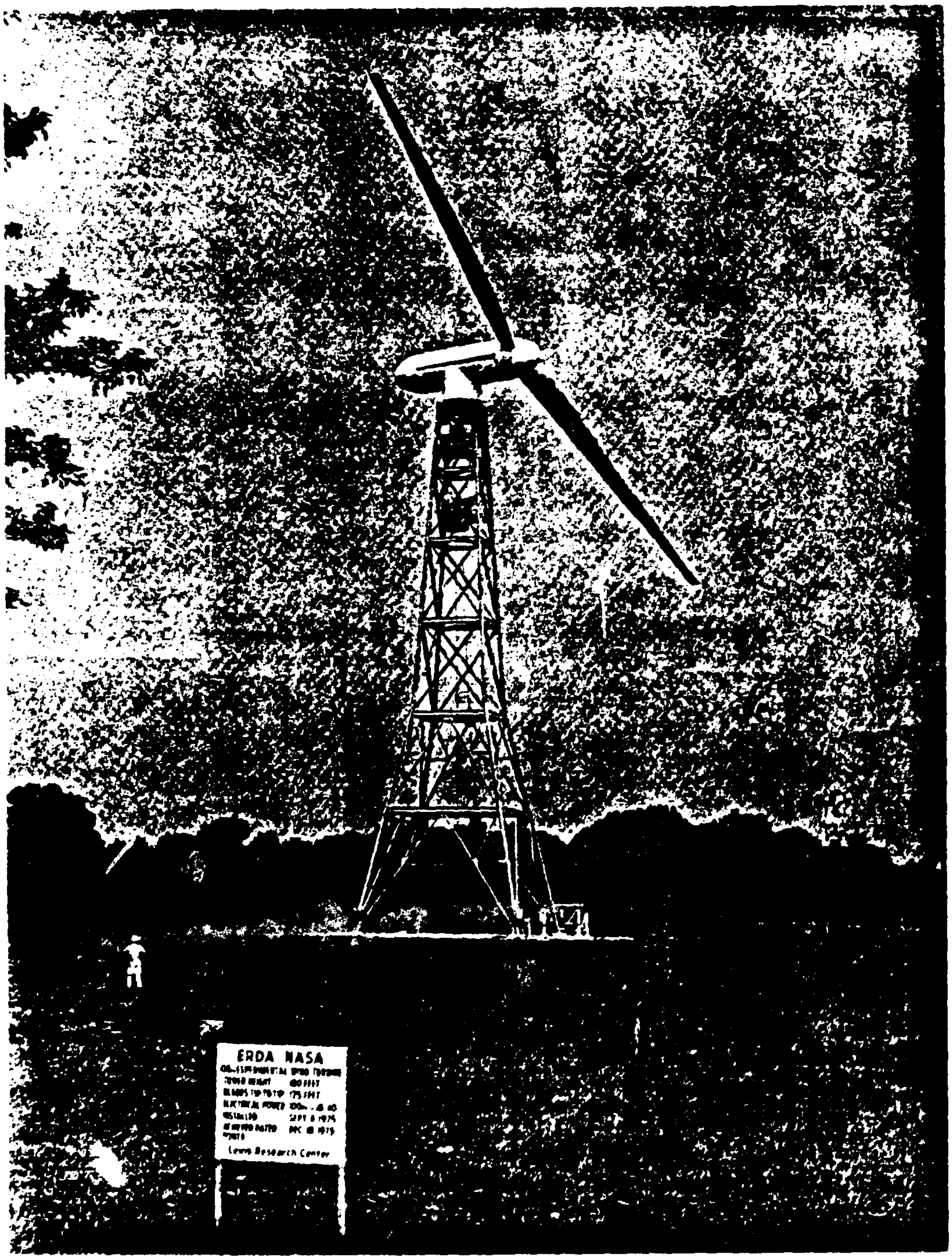


Figure 14.2 – ERDA/NASA Mod-0 Wind Turbine

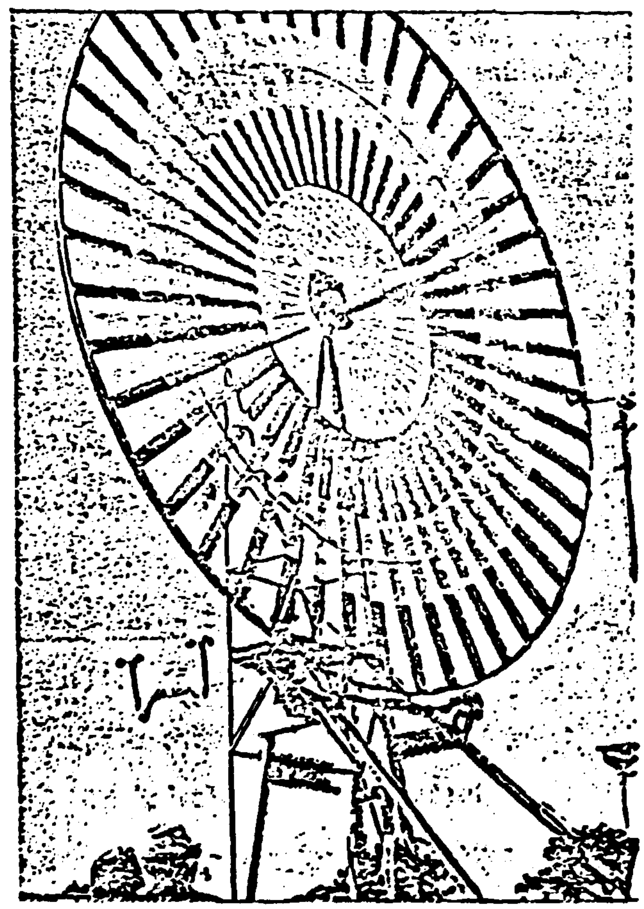

Figure 14.3 – Huges Wind Generator

## 14.3 – DESCRIPTION OF VERTICAL AXIS MACHINES

Vertical axis machines are less developed technically than the horizontal shaft propeller designs, however, they give promise of much larger power outputs. Two approaches to large scale wind machines are being investigated in the U.S. The first is being investigated at Montana State University. This involves sail powered cars running on a closed track to generate electricity. A circular track, 5 km in diameter, operating with a continuous string of cars would be required to generate 10 MWe. A schematic of a rotor powered string of cars is shown in Figure 14.4.

A second approach to a 10 MWe or larger wind machine is the tornado type wind energy system, shown in Figure 14.5. In this approach, wind energy is collected in an enormous stationary tower open at the top. Vertical vanes opened in the windward side and closed in the back side allow wind to enter the tower and form a vortex or "tornado" in the tower. This vortex creates a low pressure core drawing air upward through a horizontal turbine from inlets also located at the base of the tower. Wind tunnel tests have verified rough analysis of system performance but no experimental machine has yet been built.

Two other vertical axis machines, the Darrieus rotor, (see Figure 14.6), and the Savonius rotor are being studied in the U.S. however these approaches are limited to small and intermediate power applications.

## 14.4 – WIND ENERGY APPLICATIONS

Applications of wind energy are based on the principle that the energy of a flowing fluid (wind) can be converted directly into mechanical energy which can be used to drive a generator, pump or compressor. Thus one can generate electricity, pump water or compress air using wind energy. Because of the intermittent nature of wind, a wind energy system operating independently of other sources of energy requires energy storage. The production of hydrogen by electrolysis the pumping of water into a storage resevoir and the use of compressed air storage are suggested means of overcoming the storage problem. Other energy storage devices, such as batteries and flywheels do not appear to be economical for use with wind machines.

## 14.5 – PROBLEM AREAS

Problems associated with the development and use of large scale wind machines fall into four classes. (1) structural integrity of large rotors (2) adapting to the intermittent nature of the wind (3) development of economical energy storage systems (4) deployment of a large network of units in a manner acceptable both to utilities and to society.

Structural failures after short periods of time on previously built large scale machines indicates the importance of designing and testing models and prototype machines. The aim is to produce a reliable long-lived machine that is a large, and at the same time, as cheap as possible.

The rotational speed of the windmill varies with wind velocity which varies with time. Special generators have been developed for which output frequency is independent of shaft speed. Other approaches such or generating DC current and inverting this to AC are also being studied. Economics and systems considerations, however, favor adjusting the rotor blade pitch to wind velocity. Such a rotor has increased stress and greater failure rate, however.

Storage systems such as described above increase the cost of wind generated electricity. The problem here is to find the least cost storage method for each application.

## 14.6 – US RESEARCH AND DEVELOPMENT PROGRAM

During the period FY 1974 to FY 1981, the U.S. Federal Government will spend about $ 160 million

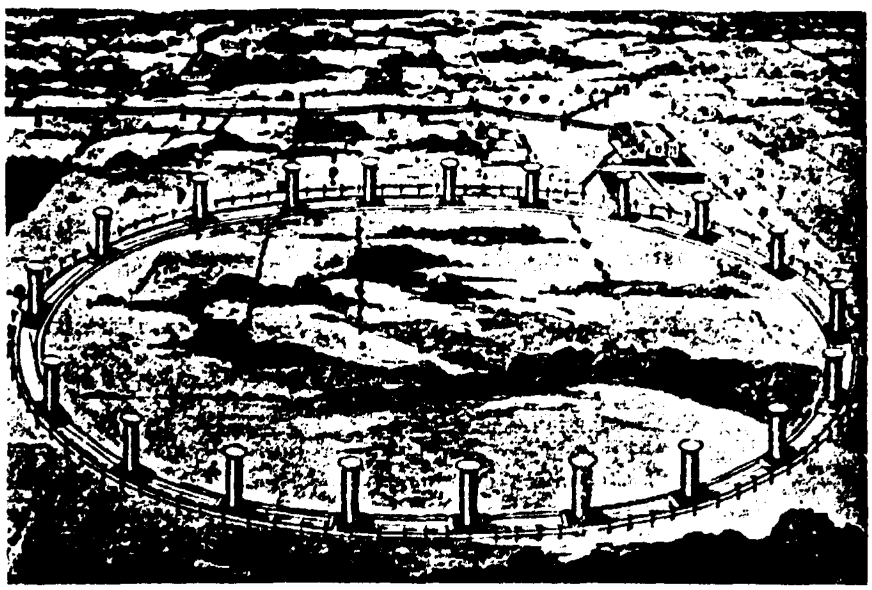

Figure 14.4 – Rotor Driven Wind Energy Train

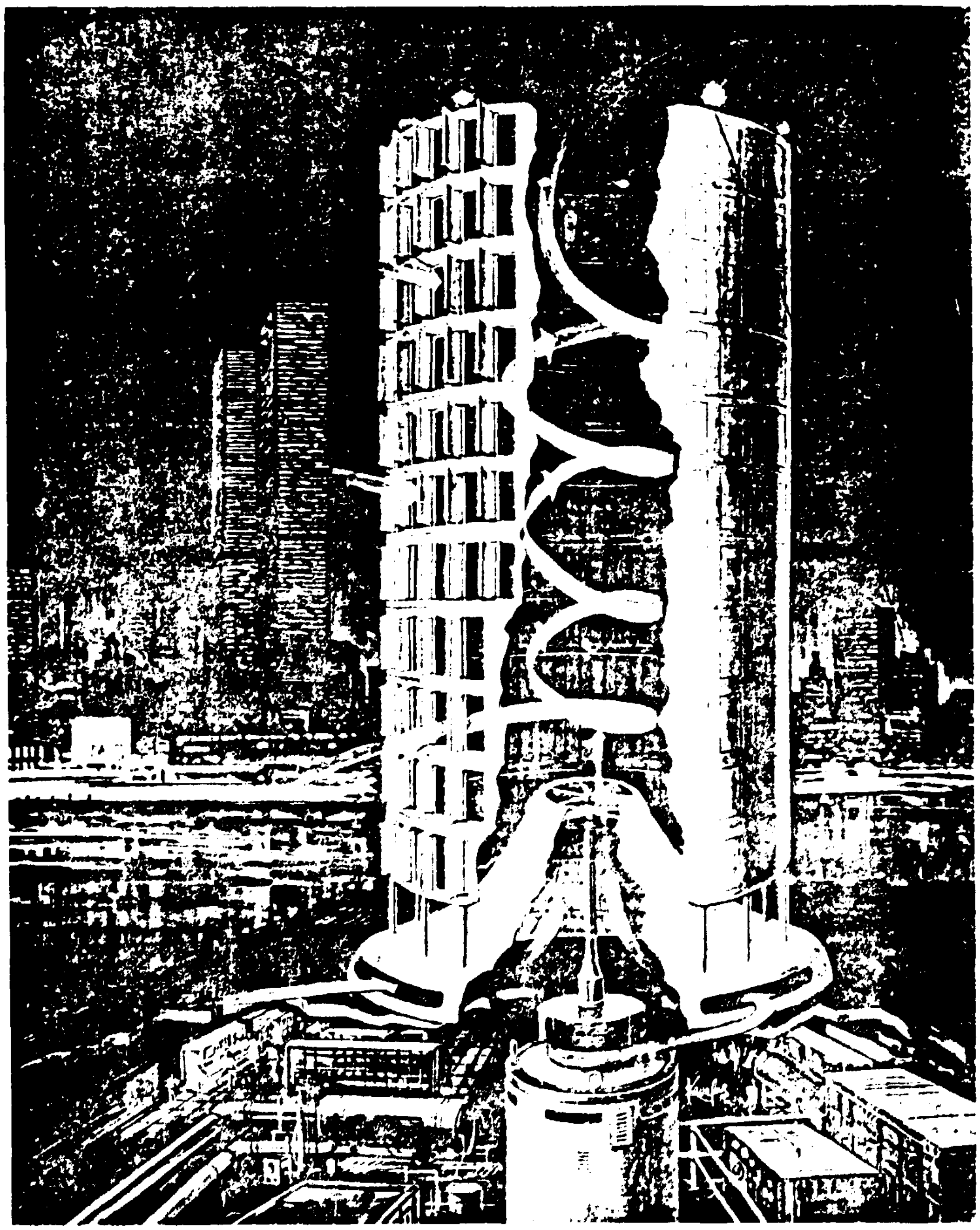

Figure 14.5 – Artist's Conception of a Tornado-Type Wind Energy System

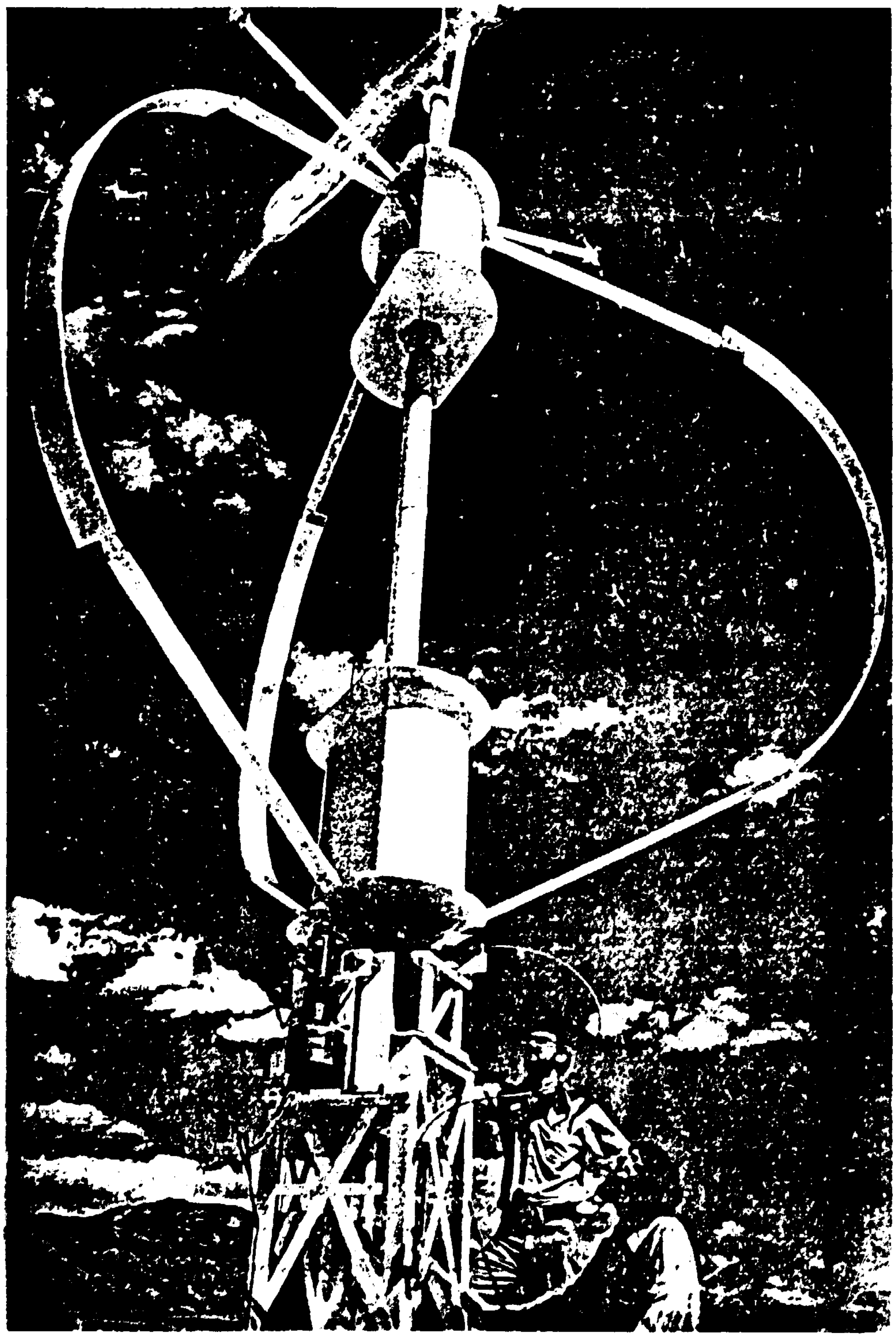

Figure 14.6 — Darrieus Vertical Axis Rotor

on the development of wind energy conversion systems (WECS). The program includes the following goals (1) completion and testing the pilot models 100 KWe and 200 KWe generators (2) initiation of the detailed design and fabrication of a second generation 100 KWe unit and first generation megawatt unit (3) completion of assessment studies of wind system concepts and applications (4) complete compilation of US wind data (5) initial testing of WECS units for farm applications and (6) initial testing of WECS for space heating applications.

The overall objective of the US program is to provide by 1985 the technical capability (if adopted by US industry) of producing from 5 to 12 billion KWhs electricity per year corresponding to saving of 6 to 14 million barrels of petroleum.

The NSF/NASA 100 kWe unit at Sandusky, Ohio, has operated successfully since 1975. In Jan 28 1978, the DOE/NASA 200 KWe wind turbine started operation. This machine has a rotor 76 m. in diameter (twice the length of the 100 kWe machine). Other characteristics are similar.

By 1980, DOE/NASA expects to have two more 200 kWe units in operations in Rhode Island and Puerto Rico and a 2 MWe unit at Boone, North Carolina.

A $ 20 million USDOE incentive program to accelerate the development of wind turbines has been proposed under which the US Federal government would purchase six additional machines in the 1 – 2 MWe size range and 50 small (1 – 15 kWe) machines for test purposes. The aim is to reduce electricity costs from the large machines to 30 mills/kWh by 1985 and speed the commercialization of the small machines.

## 14.7 – THE ECONOMICS OF WIND GENERATORS

### a) Without Energy Storage

In the absence of storage, wind energy generators require backup electrical capacity and can be considered only as fuel saving devices. Their competitiveness, therefore, depends on the cost of the fuel they are saving. If installed on a utility grid, consisting of hydro power, nuclear and oil-fired units they would be used to save the highest cost fuel, namely oil. Based on the present price of light Arabian crude of $ 12.70 per barrel, the break-even investiment cost of wind generators would have to be lower than about $ 250 per installed KWe. This is in the same range as projected costs for an advanced WECS by proponents of such plants.

### b) With Energy Storage

An evaluation of the economics of a WECS with energy storage is difficult because of the uncertainty regarding costs of the wide variety of storage methods currently being investigated. The following, however, will give an aproximate indication of costs of wind energy with either pumped hydro storage or compressed air storage compared to the use of a gas turbine only. A peak load duty cycle of 5 hours perday, 200 days/yr was assumed. The amount of storage required to cover a 3 days calm period would be 15 kWh per kW of WECS capacity. With such a storage system, the WECS could operate as a reliable peak load unit. Peak load electricity costs based on a total system cost of $ 400/kWe would be about 60 mills/kWh which would be competitive with a gas turbine burning light oil at about $ 3.10/MBtu ($ 18/bbl, in 1978 prices).

### c) Generation of Hydrogen

The possibility of storing wind energy by generating and storing hydrogen has often been suggested by wind proponents, however, here again the problem is not technical but one of costs. As an example one might convert the electrical output from a 500 kWe wind generator (2 x $10^6$ kWh/year) to hydrogen (140 kg/day) liquify and store the hydrogen for 4 days. When required, the hydrogen would be reconverted back to electricity using fuel cells. This stored electricity, however, would cost 70 times that from the wind machine itself making the overall electricity from the system quite high. These high costs result not only from the high costs of electrolysis, liquifaction, storage and fuel cell equipment but also from the losses which occur at each step in the process. Only about 30% of the wind generated electricity is recovered with the assumed efficiences (electrolysis units 75%, liquifaction step 80%, fuel cells 50%)

## 14.8 – CONTRIBUTION TO BRAZIL ENERGY SUPPLY

### a) Near Term (1986)

Although the use of wind energy is just as feasible in Brazil as in the US and other countries, the penetration of the electrical market by wind machines is likely to be very slow in Brazil. Even though wind generators may be developed and sold in commercial quantities in the US as the result of the vigorous development program, even there, the contribution of wind energy to the electricity supply system will only be about 0,2% in 1986 and about 3% in the year 2000. Since it would be unwise for Brazil to depend largely on imported wind generators, a local production and marketing infrastruture will have to be developed. This means a lag of at least 10 years between a possible Brazilian program and say, the US program. Under such condition the near term contribution of wind in Brazil would be negligible.

### b) Long Term (2000)

If wind generators turn out to be economically competitive with other sources of electricity, they certainly would find a place in Brazil's long term electricity supply system, possibly in conjunction with hydro power stations. Taking into consideration the necessary lead time for the establishment of a Brazilian industry and the possible rate of penetration of the electric power market by wind generator however, an upper limit to their contribution in the year 2000 would be about 1% of total electricity generation. Even so, such a contribution would require about 4000 x 1 MWe WECS units or 2000 x 2 MWe machines.

# CHAPTER 15, OCEANIC ENERGY

## 15.1 – INTRODUCTION

There are three possible systems for extracting energy from the ocean. These are (1) tidal power (2) wave energy and (3) ocean thermal energy conversion (OTEC). Two tidal power stations are actually in operation, the other two approaches are in a very early stage of development.

## 15.2 – DESCRIPTION OF SYSTEMS

### a) Tidal Power

This is essentially a low head hydro power station where an upper reservoir is filled during high tides, the water passed through a turbine generator to the sea or to a lower reservoir which is discharged during low tides. Although a simple tidal power project based on water flow back to the sea at low tide would provide power for about three hours twice a day, variations on this scheme are being considered as a means of generating more reliable power. One of these is based on the use of low-head (15 m to 30 m) axial flow turbine-pump generators such as those produced by the Neyrpic Co. in France. In this scheme, two inland reservoirs are employed. One is used to catch tidal water. The other is higher and is used as a pumped storage reservoir. The basic operating principle is that water is pumped to the higher reservoir using off peak power generated by the tidal plant or from a grid.

### b) OTEC Systems

At many places in the tropical and sub-tropical regions of the world, the ocean suface temperatures are in the range of 25°C to 30°C whereas at depths of 600 meters or so, the temperatures range from 2°C to 7°C. This temperature difference is sufficient to drive a heat engine and generate electricity. Although the efficiency of a power plant at these low temperature differences would only be the order of 2 – 4%, the heat source and heat sink are essentially unlimited. Thus the question of low thermal efficiency reflects only on its influence on the investiment costs of an OTEC unit.

Two types of OTEC systems may be considered. The first in an open cycle which uses the sea water itself as the working fluid. Studies of this approach indicate that the open cycle system is not economically feasible. Thus present interest in the US is on closed cycle systems using ammonia, propane or freons as the working fluid. Designs of prototype plants based on this approach have been prepared by various engineering groups in the US and are being evaluated by the USDOE.

These plants float mostly beneath the surface of the ocean so they are unaffected by bad storms. Although the electrical generating plant is near the surface, cold condenser water must be brought up from the bottom through a large diameter pipe about 600 meters long. The maintenance of the integrity of this pipe over a long time may be the most important barrier to the development of OTEC systems.

### c) Wave Energy

The possibility of capturing the energy from waves is being investigated primarily in the United Kingdom at the University of Edinburgh. The system of most interest uses and ingenious device for capturing wave energy, a bobbing duck-shaped cam. Experiments in a ship model testing tank indicate that 90% of, the wave energy can be recovered with this mechanism. The Edinburgh research team believes that 1000 strings of cams, each 500 meters long, would be able to produce electricity equal to that currently used by the U.K.

Other wave energy approaches include the use of sea walls with hydraulically adjusted heights combined with the use of a turbo ram to increase the hydraulic head.

## 15.3 – STATUS OF THE TECHNOLOGY

### a) Tidal Power

Tidal power production is technically feasible in a few places in the world. Two stations are in operation, the 240 MWe La Rance station in France and the 400 kWe prototype plant at Kislogubsk in the USSR. Sites with necessary range of tidal heights, suitable geographical features and proximity to load centers are quite rare. Nevertheless, more sites will probably be developed in the future. Tidal power, however, is not likely to become a widespread source of electricity.

### b) OTEC

This system is in an early stage of development and a realistic assessment of its long term possibility can not be made at this time. Even if a competitive OTEC system is developed, however, it might be more useful for land based applications such as waste heat utilization than in the ocean.

### c) Wave Energy

This system is also in an early stage of development. The Central Electricity Generating Board of the U.K. has made an analysis of its potential and concluded that even though wave energy is "free", the investiment costs are too high to be competitive with nuclear power stations.

## 15.4 – POTENTIAL CONTRIBUTION TO BRAZIL ENERGY SUPPLY

Oceanic energy is not likely to make any contribution to the Brazilian energy system at least within the time frame of interest (up to the year 2000).

## 15.5 – POSSIBLE AREAS FOR RESEARCH AND DEVELOPMENT

Research and development of oceanic energy systems is not recommended.

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