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CONF-760744
Distribution Categories UC-2 & UC-13

ENERGY SOURCES FOR THE FUTURE

Proceedings from symposium*
held at
Oak Ridge, Tennessee
July 5-23, 1976

Edited by

Jerome L. Duggan
North Texas State University
and
Roger J. Cloutier
Oak Ridge Associated Universities

ORAU Editorial/Production/Manufacturing Manager
Raymond A. Schultz

Published by
Oak Ridge Associated Universities
Oak Ridge, Tennessee
April 1977

*The symposium from which this proceedings volume was developed was conducted by the Special Training Division of Oak Ridge Associated Universities and sponsored by the U.S. Energy Research and Development Administration, Office of University Programs

PREFACE

Each year the U.S. Energy Research and Development Administration sponsors several summer symposiums (or institutes) at Oak Ridge Associated Universities (ORAU), Oak Ridge, Tennessee. The programs are designed for college faculty members who are teaching or plan to teach energy courses at their own educational institutions.

The Special Training Division of ORAU designed and conducted eight conferences during the summer of 1976. The 1976 symposiums included *Energy Production and the Social Sciences; Nuclear Power Safety; Energy Conservation: Theory and Practice;* and *Energy Sources for the Future.* The speakers (some of whom also conducted laboratories during the institutes) at each symposium were carefully chosen and assembled to include energy experts able to present their material in a manner easily understandable to scientists and educators unacquainted with the speaker's discipline. During the presentations, most speakers distributed graphs, charts, and other material that the participants acknowledged to be highly valuable to their own teaching programs.

To make some of the material just mentioned more readily available to the teaching community, several speakers for the symposium *Energy Sources for the Future* were asked to submit papers to be incorporated into this proceedings volume. The material in this book may be reproduced and used without permission.

J. L. D.
R. J. C.

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ENERGY
SOCIAL AND POLITICAL ASPECTS

by

F. S. Patton

ABSTRACT

The industrial capitalist democracies (First World) and the over one hundred poor Third World countries are economically interdependent. The First World countries cannot survive without the energy supplies and raw materials generated by the Third World; the Third World is dependent upon the First World for quality manufactured goods. There would be no demand for much of the poor countries' raw materials and energy supplies without the First World markets, as the socialist-communist spheres of the USSR and the Peoples Republic of China are essentially self sufficient in these raw materials.

First World technology based heavily on oil and natural gas as primary fuels is dominant; less than 2% of all patents originate in the Third World. While world petroleum supplies are adequate to maintain the industrial democracies in prosperity for several decades, they are inadequate to offer the half of the world's people who live in the poor countries hope for attaining a great improvement in living standards. New energy technologies and energy conservation in the First World are required.

A national energy program is difficult to develop because of regional differences; seven east-central states dominate in coal production, five southwestern states in natural gas, a group of northwestern states in hydro-electric power, while six southern states are heavily committed to nuclear power. The northeastern coastal region of the United States, where 20% of the US population lives on 3% of the land, has no remaining appreciable indigenous energy sources. Any policy that features one of the major energy sources in a favored way is likely to benefit one region while having no effect on, or depressing, the economy of another.

The one approach that is beneficial to all parts of the United States is energy conservation.

ENERGY
SOCIAL AND POLITICAL ASPECTS

I. The Three Worlds

There are on Earth today some 150 countries. It has become common usage to group these countries along the lines of similarity in political and economic characteristics into three "worlds" as follows:

First World — The capitalist democracies with free-market economies — the United States, Canada, Australia, Western Europe, and Japan. They import much of their raw materials and energy from the large group of countries comprising the Third World. *The First World at present has about 18% of the world's people, but consumes about 65% of the world's income.(1,2)*

Second World — The socialist-communist countries — USSR and the Eastern European Block, the People's Republic of China and its allies. Within their own political and economic spheres, these groups of countries are largely self-sufficient in raw materials and energy.

Third World — The nonindustrialized 100+ countries producing raw materials and energy which are sold to the First World. *Only 5% of their trade is with the communist-socialist Second World, while about 75% is with the free-market, capitalist democracies of the First World.(3)* The vast bulk is poverty stricken and is experiencing a population explosion.

A. The North-South Conflict

A long-term confrontation has been developing between the First World and the Third World on economic issues, which is sometimes referred to as the "North-South" conflict, as the bulk of the Third World is geographically south of the First World. The struggle centers around the drive of the 100+ Third World countries, acting in concert, to create a new international economic order that will give them a bigger share of the benefits from trade at the expense of the First World countries, which now have the highest living standards ever known.

The economies of the First World and Third World are massively interdependent — the First World being unable to survive without the energy supplies and raw materials generated by the Third World, and the Third World being dependent upon the First World for manufactured goods. *Indeed, there would be no market for the bulk of Third World raw materials and energy supplies without the First World as the socialist-communist Second World is essentially self-sufficient within its sphere.*

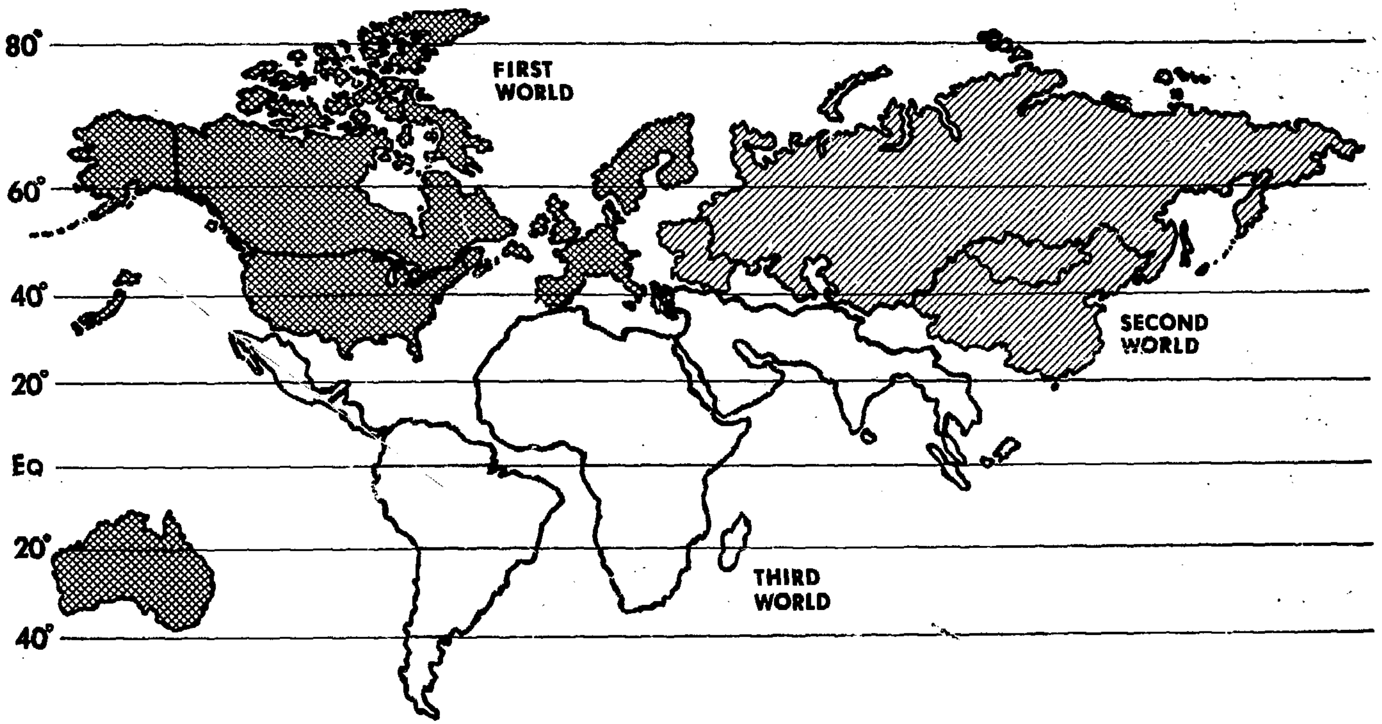
However, there is vast dissatisfaction within the Third World with their returns from this trade. The poor countries charge that the constant fluctuation of low prices they receive for raw materials and energy in the markets of the western countries and Japan keep them in an unsettled state that makes effective long-term planning and improvement impossible. At the same time the prices of manufactured goods from the capitalist countries — in good part manufactured from poor country raw materials — have spiraled steeply and seemingly irreversibly upward. In the late 1950's two tons of rubber would purchase a tractor; in 1976 six tons of rubber are required for a similar purchase.

Prior to World War II there were about 60 nations on Earth. Some 90 new nations have been formed since that time, in major part in the Third World, from the colonies and dependencies of European nations. This phenomenon, the drive to subdivide into smaller homogeneous cultural and ethnic groups, is not yet at an end (witness the separatist movement in Quebec). The United Nations is making plans in its facilities to accommodate up to 170 sovereign states. In the past, ethnic conflicts, such as in Lebanon, have diluted the impetus toward collective economic negotiation with the First World.

Two events galvanized the Third World into a more cohesive economic bargaining group — the 1973 quadrupling of the price of oil by the Organization of Petroleum Exporting Countries (OPEC) from $2+/barrel, and the Arab nations' imposition of an oil embargo at the time of the October War with Israel. These actions were taken as proof that the First World was vulnerable to collective economic and political pressure from the poor nations. Their stated aim is the transfer of a substantial portion of the wealth of the industrialized capitalist countries to themselves — an action they regard as simple, long overdue justice. A current objective is a one-fourth share of the gross world product by the year 2000 as opposed to today's share of about one-eighth.

Figure 1

THE THREE WORLDS



B. Geographical Factors

Figure 1 is a map of the world in which liberties have been taken with the longitudinal positions of countries while their latitudes have been held true. The purpose of this action is to bring into focus certain geographical features.

It may be observed that the land masses of the First World, Second World, and Third World are roughly equivalent.

It is seen that much of the land of the First World – including nearly the whole of the United States – is in the central sector of the north temperate zone. The bulk of the People's Republic of China is also in the temperate zone, while the mass of the Union of Soviet Socialist Republics (USSR) is considerably further north. In turn, the Third World is centered around the equator with relatively lesser land in the temperate zones.

It is also to be seen that the bulk of the Earth's temperate zone land mass is in the Northern Hemisphere, and little temperate zone land exists in the Southern Hemisphere.

The importance of these geographic circumstances is that the First World countries (and China) have the advantage of a healthy and invigorating climate as well as a food advantage. *Seventy-five percent of the calorific value of the foods that the peoples of the Earth consume is derived from cereal grains.(4)* The cereal grains grow best in the temperate zones. An abundance of these grains also stimulates the production of meat animals.

C. Population and Energy

Figure 2 indicates the world population growth. In 1950 the population of the Earth was approximately 2.5 billion. It is noteworthy that, at that time, the consensus of the United Nations, the US State Department, and other authoritative sources was that the world would reach a population of 4 billion by the year 2000.*(5)* The level of 4 billion was actually achieved in 1976. This is an average increase over a 25-year period equivalent to an addition each year to the Earth's population of 60 million people. The current projection for the Earth's population by the year 2000 is 6–7 billion. Needless to say, the Earth's consumption of energy over the 1950-1975 span was correspondingly underestimated with world energy consumption *tripling* in this period.*(6)* As will be pointed out, population growth profoundly impacts future energy requirements.

From Table I it may be observed that this population increase is largely taking place in the Third World regions of Africa, Asia, and Latin America, which have a collective population rate increase 4–5 times that of the First World regions of the US and Europe.

Figure 2

WORLD POPULATION GROWTH

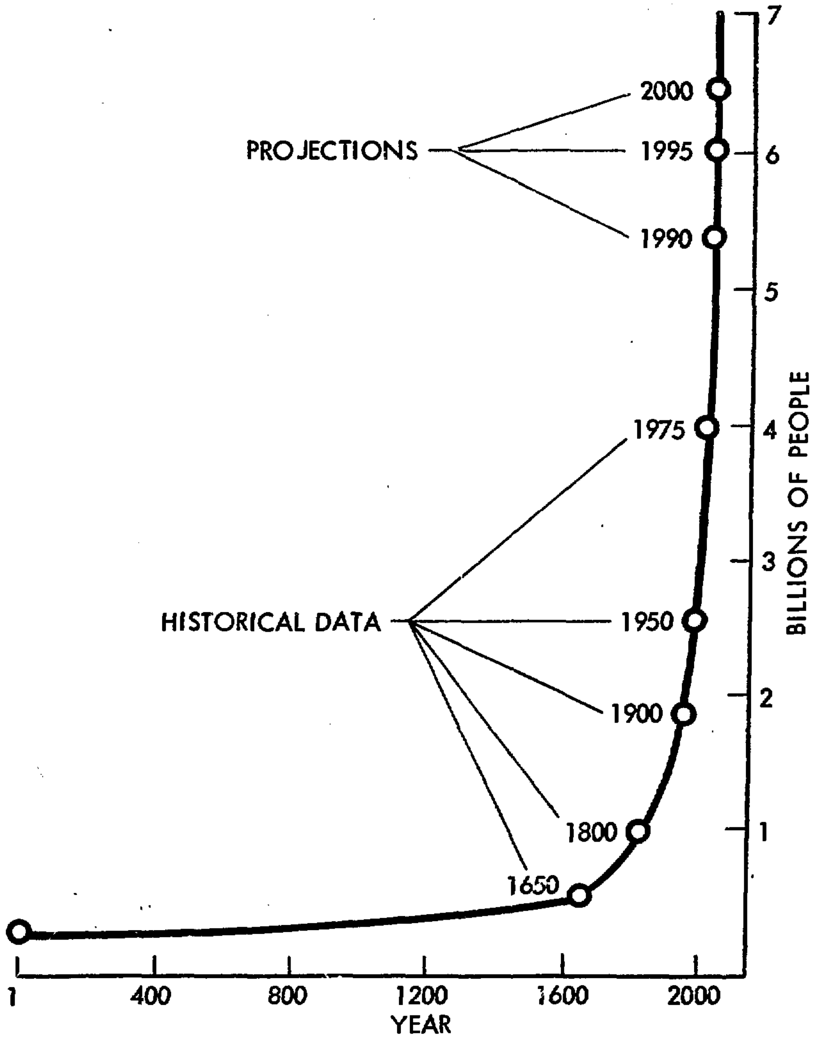


Table I

POPULATION BREAKDOWN

AREA	PEOPLE IN MILLIONS	BIRTHRATE PER 1000/YR	DEATHRATE PER 1000/YR	INCREASE PER 1000/YR
AFRICA	375	46	19	27
ASIA	2,200	38	14	24
LATIN AMERICA	265	38	18	20
USSR	250	18	8	10
U.S.	210	15	9	6
EUROPE	472	16	11	5

Table II

WORLD ENERGY USAGE

	ENERGY IN METRIC TONS OF COAL EQUIVALENT (Millions)		PERCENT OF TOTAL	
FIRST WORLD				
USA	2,426		33	
CANADA	235		3	
WESTERN EUROPE	1,435		19	
JAPAN	344		5	
SUBTOTAL		4,440	60	- 700 MILLION PEOPLE
SECOND WORLD				
USSR & SATELLITES	1,668		23	
CHINA & ALLIES	482		7	
SUBTOTAL		2,150	30	- 1.3 BILLION PEOPLE
THIRD WORLD		820	10	- 2.0 BILLION PEOPLE
WORLD TOTAL		7,410 *		

*1972

From Table II it may be observed that the First World, with little more than 700 million people, uses about *60%* of the Earth's energy production. The socialist-communist Second World, with nearly twice as many people as the First World, consumes about half as much of the Earth's energy production. The Third World, with half the Earth's people, consumes little more than *10%* of the Earth's energy production.*(7)*

By drawing together the indications of Figure 2 and Tables I and II, the projected approximation for the year 2000 may be examined. It is seen from Table III that, with the declines in population rate increase now being experienced in the First World, the population by 2000 could be as low as 800 million, a small increase from the present. The socialist-communist Second World, with a somewhat larger projected population increase, will probably grow from 1.3 billion to above 1.7 billion, but the Third World will have *doubled* from the current 2 billion to 4 billion.

At that time, the First World will no longer be 18% of the Earth's people, consuming 65% of the Earth's income; they will approximate *12%*. The Third World — the poor nations block — will no longer be half of the Earth's peoples; they will be nearly *two-thirds*.

The central question which must be addressed is: *Will the block of have-not countries, which will grow to be two-thirds of the Earth's population, accept a continuance which would result in the proportionately shrinking First World with about 12% of the people having two-thirds of the Earth's income in the year 2000?*

D. Long-Term Economic Roles

Already collective economic organizations *(3,8)* and news gathering and dissemination services — the First World's news services being suspect to the Third World *(9)* — have been formed and regularly meet. Although no major gains have been made as yet, the mere fact of successful organization and periodic meetings is a clear signal that more formidable tactics for forcing concessions are to be expected.

The increasing hostility and frustration of the Third World nations manifest themselves in confiscatory actions toward First World industrial facilities located in their lands, discouraging further investments, and thereby hardening Third World nations in their roles as supplies of raw materials.

The situation regarding automobile production is indicative of present industrial disparities. Of the 26 million produced in the world per year, only 2 million are produced in the Third World, little more than 2 million in the Second World, and over 20 million in the Fist World.*(10)* The US

Table III

WORLD POPULATION

	1975	2000 *
FIRST WORLD	700 MILLION	800 MILLION
SECOND WORLD		
USSR & ALLIES	350 MILLION	
CHINA & ALLIES	950 MILLION	
	1.3 BILLION	1.7 BILLION
THIRD WORLD	2.0 BILLION	4.0 BILLION
TOTAL	4.0 BILLION	6.5 BILLION

* First World Annual Rate of Population Growth is~0.6% per Year
Second World is~1.0% per Year
Third World is~2.5% per Year

alone consumes over 10 million automobiles per year. The resultant recognition of role inescapability firms the resolution of Third World nations to act collectively in economic bargaining for their raw materials and energy supplies.

In amplification of contrasts, the foremost country of the First World, the US, may be compared with a Third World nation, its neighbor, Mexico. In 1950 there were 25 million Mexicans and 150 million citizens of the US. Thus, there were six times as many Americans as Mexicans. In 1976 there are 62 million Mexicans and 220 million Americans, the US advantage having shrunk to 3.5 to 1.*(11)* The Mexican current population rate increase of 38/1000/year is over *six times* that of the US. If these relationships should continue, in the next century there could be more Mexicans than Americans. *About half the population of Mexico is 15 years old or younger.* By the year 2000 there may well be more Mexicans under age 15 than Americans of the same age group.

The southwest border states of the US, which have a relatively low population density, face a prospect analogous to that prevailing along the Russian-Chinese border — the population density on one side being manyfold larger than on the other.

These Mexicans have an economic income one-tenth that of the US. The 62 million citizens of Mexico consume about as much electricity as the approximately 3 million US citizens living in Arizona and New Mexico.*(12,13)* Mexico has a land mass one-fourth the size of the US. Its arable land under cultivation is roughly equivalent to that of the state of Iowa.*(14)* The rural population of Mexico is 23 million. The amount of corn produced, the principal cereal grain crop, is about 8 million tons per year. In contrast, Iowa, with the same equivalent arable land in production, has a farm population of only 550,000 but manages to grow about four times as much corn as Mexico (33 million tons/year).*(15)*

The basic reason for these disparities, above and beyond differences in climate, is the great use of technology, energy (including fertilizer), and machinery in the US.

II. The First World Society

The high living standard, and indeed, the infrastructure of First World society is built upon the pervasive use of low-cost energy and machinery — manufactured from low-cost raw materials — as a replacement for manual labor. The impact of this energy-machinery deployment can be illustrated by examining the situation in agriculture. Figure 3 is another map segment in which the United States has been moved on its parallel to a position adjacent to the USSR. It is to be observed that the center of the US is near the 40th parallel and that the center line of the USSR is near the 60th parallel. Note also that the land mass of the USSR is 2-1/2 times that of the US. The US has the advantage of more arable farmland while the USSR, with its greater land mass, encompasses the energy resources and raw materials to make it essentially self-sufficient in these vital areas — an enormous strategic advantage.*(16)*

The People's Republic of China, which actually fits into the geographic position that the US has been shown in on Figure 3, has comparable available land mass and arable farm land to the US. In Table IV, typical cereal grain production projections for the US, the USSR, and the People's Republic of China, together with their populations are shown. It is seen that the farm workers of the US (about 3.5 million)*(15)* produce more grain than the farm workers of the USSR (35-45 million)*(17)* and the economically active farm population of the People's Republic of China (500-700 million). *(18) The basic reason for this dramatic differentiation is the massive substitution of energy in the form of fuel and manufactured fertilizers, and machinery, for manual labor and natural organic fertilizers.* Indeed, if the whole world grew and prepared its food in the same manner as is done in the US, over 75% of the Earth's current energy budget would be required for food alone.*(19)* This same circumstance of low farm population and high energy and machinery use, while most pronounced in the US, is characteristic also of the other First World countries; in general, the farm population is a small fraction of the total population.*(20)*

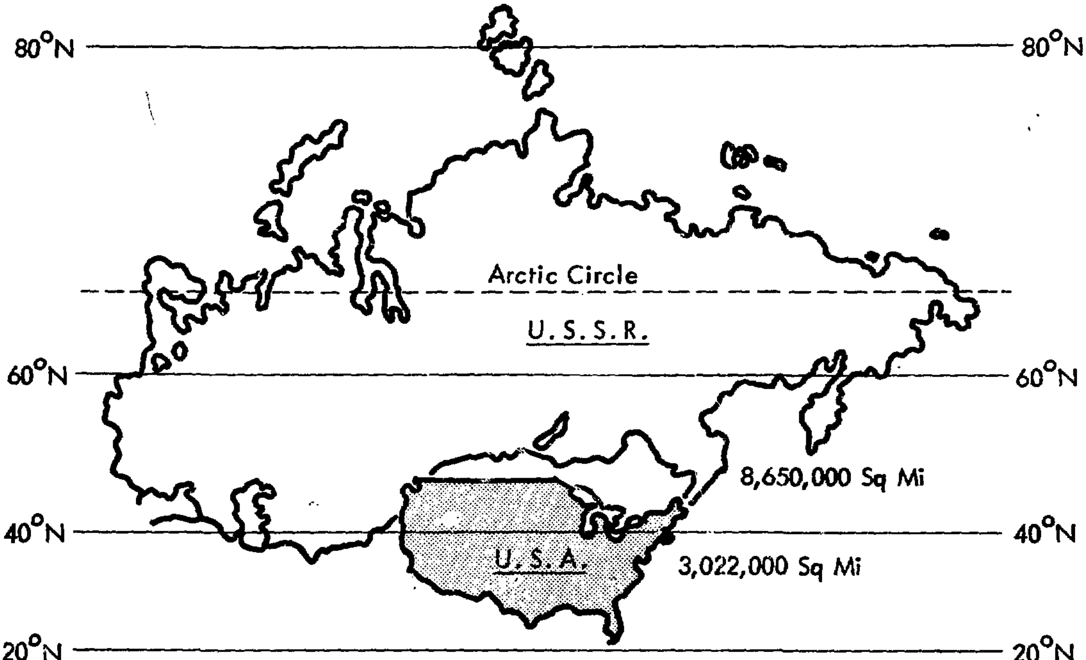
A. The "Post-Industrial" Society

There has been a dramatic growth in energy consumption in the First World since the end of World War II. Energy use in the US has increased by a factor of about 2.5 since 1950.*(21, 22)* In this same 25-year period, even after making allowance for increased taxation and inflation, the average American is today about twice as prosperous as in 1950.

Table V illustrates changes in the make-up of the work force since that period. In 1950 there were about 60 million employed persons in the US in a population of 150 million.*(23)* In 1976 there were about 85 million employed persons in a population of 220 million.

Figure 3

GEOGRAPHICAL COMPARISON OF US & USSR



U.S. - 1.41 Tons Grain/Acre
U.S.S.R. - 0.63 Ton Grain/Acre

Table IV

COMPARISON OF FOOD PRODUCTION

COUNTRY	POPULATION (Millions of People)	PRODUCTION OF GRAIN (Millions of Metric Tons)	PERCENT OF POPULATION REQUIRED TO PRODUCE FOOD
USA	220	240	2
RUSSIA	255	220	15
CHINA	900	210	60-70

Table V

MAKE-UP OF WORK FORCE

WORK	PERCENT OF WORK FORCE *	
	1950	1976
FARMING	15	4
MANUFACTURING & CONSTRUCTION	40	26
GOVERNMENT	10	21
SERVICES	30	41
UNEMPLOYED	5	8

* Work Force of the US in 1960 was About 63 Million People
Work Force of the US in 1976 is About 93 Million People

The fraction of the total population that is employed has remained fairly constant, but a significant shift has occurred between the proportion in the "producing" sectors (farming, manufacturing, and construction) and the government and service sectors. The number of people in the "producing" sector in 1950 was little more than 25 million. This number is approximately the same in 1976, with the increased total from 60 million to 85 million being nearly entirely in the government and services capacities.*(24)* Indeed, much of the "government" increase is a form of services: policemen, firemen, road maintenance, parks, etc. This condition of an increasing population supported by a constant or diminishing base of "producers" is sometimes styled a "post-industrial society". Currently this producing base is about one-tenth the total US population. *This society is built on the pervasive substitution of technology, machinery, and energy for human manual labor.*

B. The Impact of Energy and Technology upon Education

This high-energy society makes it possible for 60 million Americans to be supported in educational activities. It is instructive to compare the numbers of college students in various parts of the world as is done in Table VI. The US has over 10 million college-level students in some 2,700 institutions of higher learning. Over 1.2 million college degrees are granted per year currently, nearly triple the number in 1950. The US now has 280,000 PhD's in engineering and science and correspondingly larger numbers with lesser degrees.

The educational ascendancy of the US — and to a lesser extent the other First World nations — renews and enlarges the technological, social, and financial expertise required to sustain the high-energy consuming, First World society. Ninety-eight percent of all patents issued (outside the communist Second World) are in the First World and only two percent in the Third World.*(25)* Also since in nearly all areas except weapon systems and certain heavy industries First World technology is more advanced than in the communist Second World, First World technology is paramount and preferred in the Third World. *It is technology based heavily on oil and gas as primary energy sources.*

The vast numbers of educated people in the First World are sustained in occupations for which there would be no requirement in a low-energy, manual society. Indeed, their own manual labor would be required for sustenance. *The resistance to new energy technologies and energy growth does not reside in the producing sector of the First World society where the essentiality and benefits of high energy substitution for manual labor can be directly observed. This resistance is rooted in the service and academic areas in the generation which grew up between 1950-1975; a period of prosperity in the First World, unparalleled in history.*

Table VI

HIGHER EDUCATION

	POPULATION	NUMBER OF COLLEGE STUDENTS
UNITED STATES	220 MILLION	OVER 10 MILLION
USSR	255 MILLION	UNDER 5 MILLION
PEOPLES REPUBLIC OF CHINA	900 MILLION	ABOUT 400 THOUSAND
THIRD WORLD	2 BILLION	ABOUT 6 MILLION

The only direct contact that the bulk of the currently active population has with energy is in the form of electricity, natural gas, and gasoline. Since, with the brief exception of the 1973 embargo, they have been unfailingly available, the necessity for energy conservation and moderation of environmental goals to maintain, not only their own life styles and livelihoods but also, the special values they seek to protect such as clean air, clean water, birds, wildlife, etc., have not generally perceived or supported.

Considerable evidence can be generated supporting the thesis that the large proportion of US land devoted to public outdoor recreation is a direct benefit of high energy utilization in the producing sector. About 15% of the total US land mass is designated as recreational area in Federal and State forests, wildlife areas, parks, etc. Park area has increased by one-third since 1950 and visitors have increased five-fold. *(15)* Energy-intensive farming makes it possible to devote marginal land to parks and recreation rather than to cultivation and grazing. There was about 10% less land in farms in 1975 than in 1950.

Effective protection of the atmosphere and waters from pollution requires energy and technology. The People's Republic of China, a low-energy intensity country with 85% of its energy derived from coal, has very high air pollution in cities and very few protective measures are affordable. Further, in China, wild birds, dogs, and cats have been largely eradicated to save food. *(26, 27)* Parks and wildlife sanctuaries are limited and would not be accessible to the masses due to the scarcity of automotive transportation.

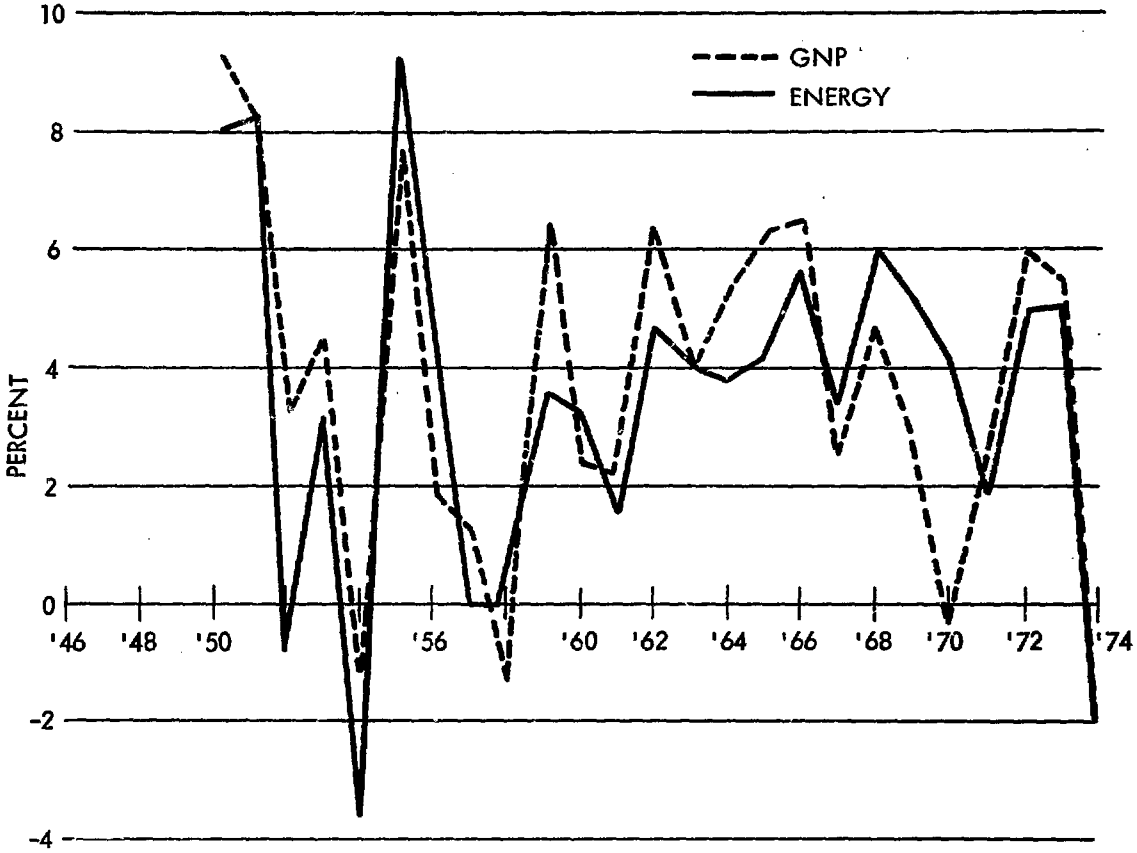
C. Inter-Relationships of Energy, the Economy, and Social Goals

Numerous compilations of economic and energy data have established that there has been over the last 25 years a close empirical relationship between changes in national energy consumption and changes in gross national product in the US, as shown in Figure 4. Some have expressed belief that this lockstep between economic well-being and energy can be undone by conservation measures such as have been effected in Sweden. Sweden consumes only 55% as much energy per capita as the US yet maintains virtually the same gross national product per capita. Conservation of energy is a necessity for the US, but is complicated by the fact that the US is a large country with marked regional differences. Sweden, in contrast, is a small homogeneous country.

Others have examined US birthrate and population increase data and have drawn hope that projected declines will markedly decrease the growth of energy demand and/or the need for drastic conservation measures. However, the Institute of Gas Technology *(28)* has drawn up the empirical approximation from historical data correlations that: *"Energy requirements have increased with the square of the size of the civilian labor force."*

Figure 4

ANNUAL GROWTH IN CONSTANT DOLLARS OF GNP & TOTAL U.S. ENERGY INPUT



Let us here assume that the relationship between energy and labor force size will be more muted in the future; still some increase in energy requirements should be anticipated as the size of the labor force increases. Also we must recognize that factors besides birthrate and the size of the general population affect the size of the labor force. As an example, the Wall Street Journal reported this fall that in the last decade, the adult population of working age increased 19% but the national work force increased 26% through the increased entry of women.*(29)* Thus, the aspirations of women to avoid unemployment or under-employment impact energy requirements. Further, the Humphrey-Hawkins Bill (H. R. 50, 94th Congress) has as a principal measure the legislation of government actions to reduce national unemployment from the current 7-8% of the work force to 3% of the work force within four years. This measure, if enacted, will result in increased energy demands.

The inference drawn is that *the US cannot safely forego energy conservation measures coupled with plans and provisions for significant increases in energy consumption if it expects to meet national, political, and social goals.*

III. The Age of Petroleum

M. King Hubbert has established methodology for estimating potential production of crude oil and other non-renewable energy reserves.*(30)* His estimate for US crude oil is shown in Figure 5. It is seen that the US has already passed its peak in production of a potential resource of 200 billion barrels; 120 billion barrels (60%) have been extracted. Reserves would be even further depleted except for the fact that the US has imported a cumulative total of about 25 billion barrels of crude and refined petroleum.

The liberty has been taken of imposing Dr. Hubbert's estimate for the US on an estimate by Dr. Hubbert for the world in Figure 6. It is seen that the world's projected cumulative production from crude oil reserves (2000 billion barrels) is herein estimated to be ten-fold larger than that of the US. On this basis, about 18% of the cumulative world reserves have been extracted. There is currently on a world basis, no shortage of oil; while world demand is currently about 20 billion barrels per year, production capability is significantly higher, perhaps approaching 25 billion barrels per year. In a physical sense, no crisis need occur until demand exceeds supply which could be several decades away. However, it is likely that political and financial restraints will intervene at an earlier date.

In subjective support of Dr. Hubbert's treatment, the present author refers again to Figure 2 and points out that the addition of even poor people to the Earth's population significantly impacts energy demand while the attainment of modest prosperity results in a many-fold increase.*(31)* Also, as previously noted, First World technology, based heavily on oil and gas, is paramount, and the majority of mankind must accept what is available or do without.

Figure 5

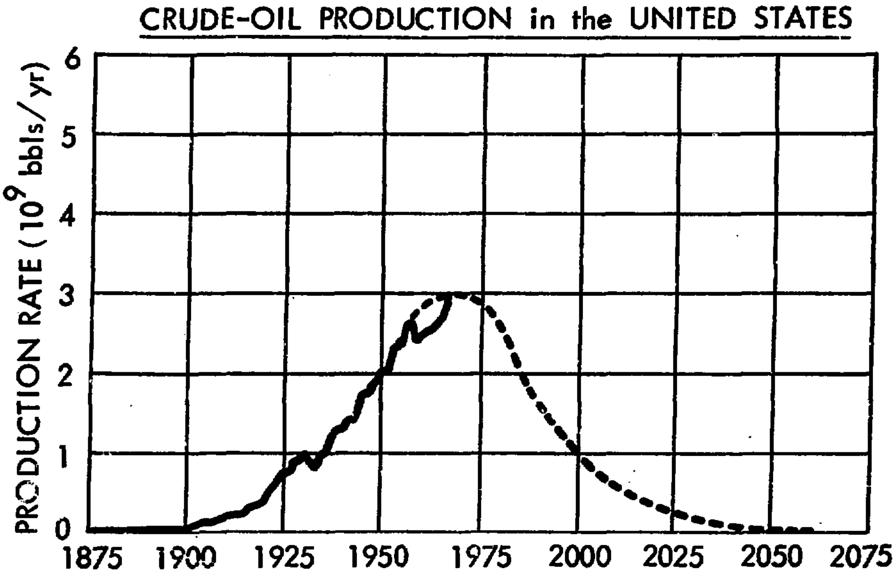
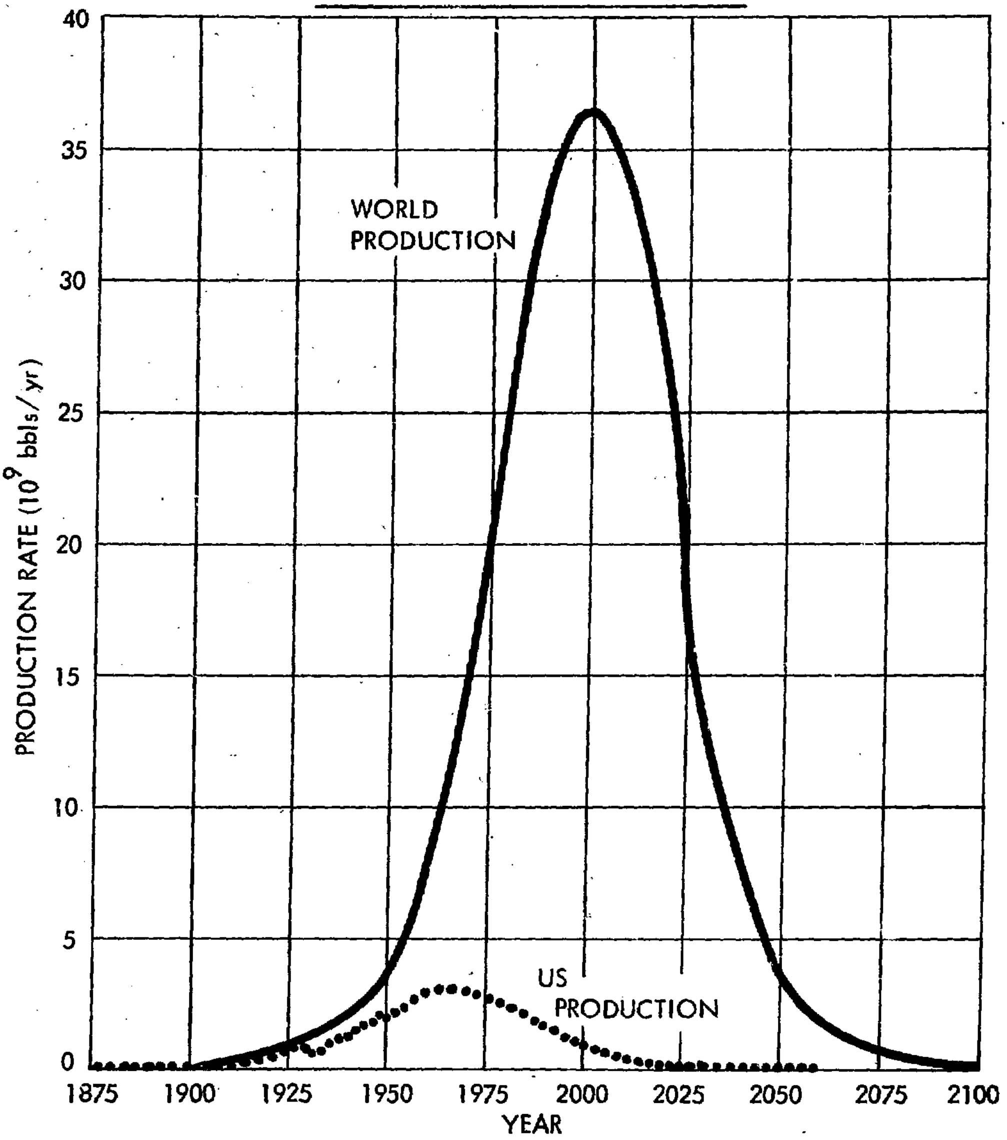

CRUDE-OIL PRODUCTION in the UNITED STATES
PRODUCTION RATE (10^9 bbls/yr)
0
1
2
3
4
5
6
1875
1900
1925
1950
1975
2000
2025
2050
2075

Figure 6

U. S. vs. WORLD OIL PRODUCTION



The period from the point in time when oil and gas technology had been sufficiently developed that 10% of the world crude reserves had been extracted, to the point when only 10% of reserves will remain has been called the "Age of Petroleum", which on the basis of Dr. Hubbert's estimate, presented herein, would be some 65 years in duration (1967-2032).

A sobering observation can be made in the form of a question. If it were somehow now possible for all mankind to enjoy US living standards and to consume petroleum at the US current per capita rate (with no physical limitation on the rate of crude oil extraction), how much longer would the "Age of Petroleum" last?

Answer — *UNDER TEN YEARS*

The profound implication is that it is impossible for all the remainder of the Earth's population to achieve an American standard of living based on current oil and gas technology.

If the masses of mankind are ever to achieve living standards approaching those currently attained by citizens of the US and other First World countries, it must be as a result of advanced energy technologies involving coal, nuclear power*, solar power, energy conservation techniques, more efficient and wiser use of petroleum, developed and implemented by the First World with accompanying attendant increased risks, compromises, costs, and discomfitures to the First World. As economics alone seemingly cannot spur timely acceptance, the dilemma must be engaged by religious, educational, and political leadership *(i.e., energy conservation is a moral responsibility!)*

A treatment for uranium ore similar to that given for oil in Figures 5 and 6 would also show a limited span. Long term nuclear energy application requires the development and widescale application of the breeder reacter.

IV. Energy Regionalism Within the United States

In the Northeastern coastal region** of the United States there are no large indigenous energy resources remaining. The energy consumed is in the form of petroleum brought in from other areas, principally by sea. In consequence, the dominant form of fuel for producing electricity is oil, with nuclear power now supplying nearly one-fifth of the electricity. This area contains about 20% of the US population on 3% of the US land mass. It is the region most seriously affected by increases in the price of oil. *(In Washington, D.C., 75% of the electricity is produced from fuel oil.)(32)*

In 1975 over 80% of the nation's coal was produced in the seven-state cluster of Kentucky, Virginia, West Virginia, Pennsylvania, Illinois, Ohio, and Indiana. In this sector over 80% of the electricity is produced by burning coal. *(In Kentucky, West Virginia, and Western Pennsylvania over 95% of all electricity is produced from coal.)(13)*

Over 90% of the US natural gas production is in the five-state block of Texas, Louisiana, Oklahoma, Kansas, and New Mexico. In this sector over 80% of the electricity is produced by burning natural gas. *(In Texas and Louisiana over 90% of all electricity is produced from natural gas.)*

Over 50% of the nation's hydroelectric power is located in the Pacific Northwest states of Washington, Oregon, Montana, and Idaho. In this region over 90% of the electricity is produced from hydroelectric dams. *(In Oregon and Idaho, over 99% of all the electricity is produced from hydroelectric sources.)*

The remaining states have energy sources which are a mix, dependent upon their distance from the above regions.

The importance of this energy regionalism is demonstrated in Figure 7. Hydroelectricity is the cheapest form of electricity. (Dams have a very long life, and part of the cost is usually charged off to flood control or irrigation.) Seaborne oil is now the most expensive fuel for electrical generation. In consequence, in the winter of 1975-76, a resident on the northeast coast of the United States paid 3.5 to 6 times as much for electricity as residents on the northwest coast.*(33)* Many social institutions in the northeast, such as churches, boys clubs, etc., were forced to curtail their activities.*(34)* Some homeowners paid more for electricity than for their mortgage payments. A decade ago the cost of electricity to large industry was roughly equivalent in Massachusetts and Texas. In 1975 the cost in Massachusetts

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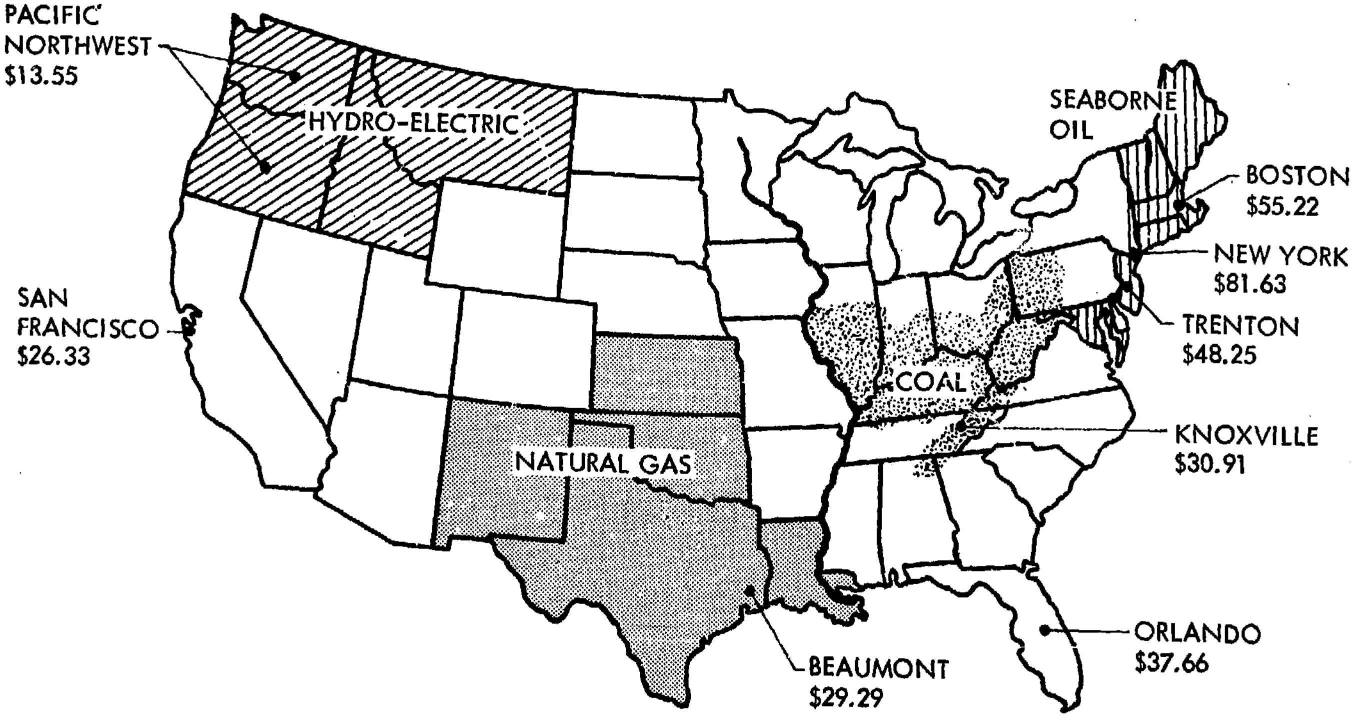
**Defined herein as the New England States (Maine, Vermont, New Hampshire, Rhode Island, Massachusetts, Connecticut), New York City and Environs, Philadelphia and Environs, Delaware, Maryland, Washington, D.C. and Environs.

Figure 7

RESIDENTIAL ELECTRIC RATES
Dollars/1000 KWH
(2/19/76)



was about 2.5 times higher than in Texas. Some forecasts project the price of oil will double in the next ten years. If effective measures are not taken in the interim, contrasts in various energy regions will become more pronounced.

A. The Impact of OPEC and Saudi Arabia on US Energy Regionalism

Prior to 1973, the low price of imported oil depressed the coal market; the domestic petroleum industry was partially protected by Federal measures. When the price of OPEC oil was precipitously quadrupled, the value of all US domestic energy resources also escalated sharply; the price of US domestic oil, while not allowed to reach the OPEC level, is now over twice its October, 1973 rate of $3.40/barrel. *Indeed, each time OPEC increases the price level for its oil, pressure is generated for a rise in the price of all US domestic fuels.(46)* Since Saudi Arabia is the member of OPEC with the largest oil reserves and as its revenues are in excess of its financial needs, this small nation has the power to impact the economic well-being of the United States as a nation and, indirectly the business prospects of individual states.

B. Texas

When the values of energy resources increase in the United States, not only do the owners benefit; but, also, the governments of the individual states in which the energy resources are located, through such revenue generating measures as severance taxes. In 1974, the year following the dramatic OPEC increases, the financial position of the energy producing states was markedly better than the national average.*(35)*

In Texas, the largest energy producing state (about 40% of US oil production and over one-third of the natural gas production in 1974), a state budget surplus of about $1 billion was experienced for the fiscal year 1975.*(36)* Also, there is no personal income tax, no state payroll tax, no state corporate income tax, and a corporate unemployment tax of $26.15 per employee as compared to a national average of $83.72 per employee.*(37)* In 1975, the Fantus Report--a measure of business climate--rated Texas at the top among the mainland 48 states. *A personal income of $20,000 per year in Texas will currently purchase a living standard that would require an income of $24,000 in New England.(38)* Texas, with 12 million residents, is the largest electricity producing state. It produces nearly 20% more electricity than California which has 21 million residents. *Texas has about the same electrical generating capacity as Italy (population 56 million).*

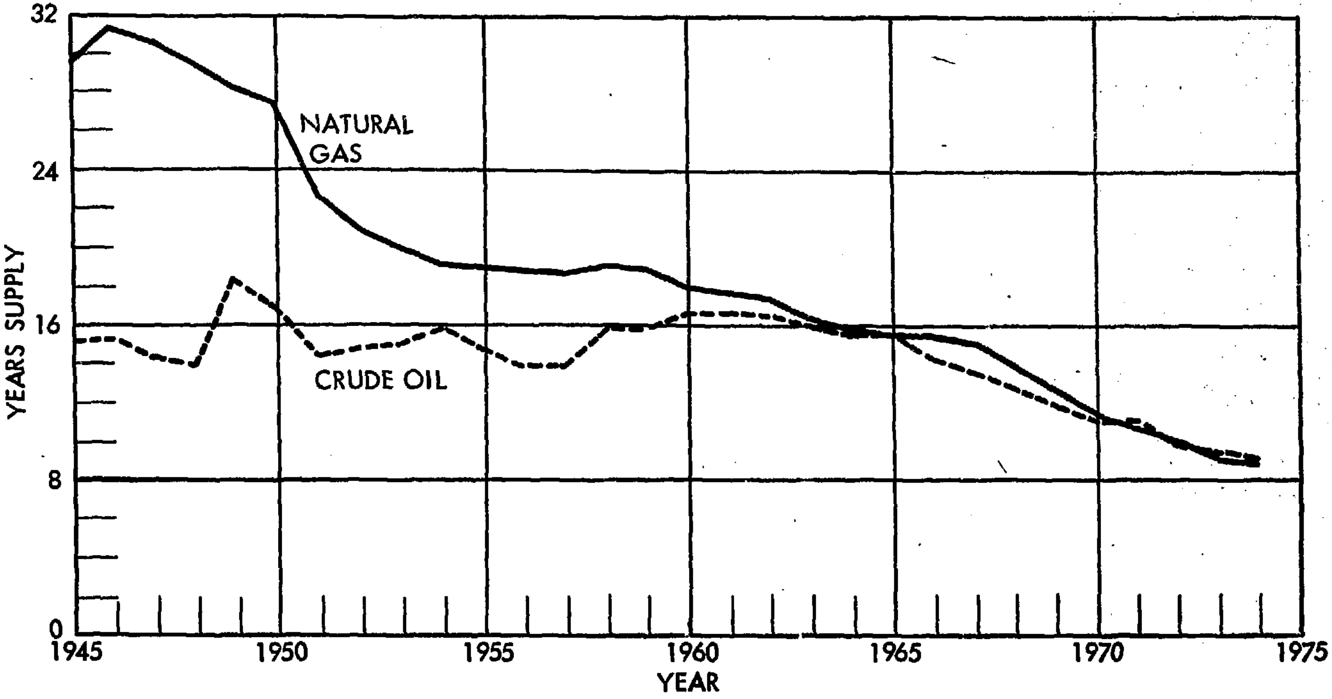
As do all state departments of commerce, the Texas authorities have advertised these favorable conditions widely to attract new industry and business to Texas. However, these special advantages will be difficult to maintain. Ninety percent of Texas electricity is produced by burning natural gas. The Federal Energy

Administration is seeking to have electrical utilities burning natural gas convert to coal. The Texas Railroad Commission has estimated the cost of converting the boilers in its state from gas to Texas Lignite at $14.8 billion, which is considerably more than the cost of the Trans-Alaska crude oil line.*(39)* (In Texas the Railroad Commission is charged with the responsibility for allocation of energy resources in the state.) Figure 8 is a presentation of Texas oil and gas reserves plotted against time. As with the nation, as shown in Figure 5, over 60% of the Texas reserves are depleted. Indeed, it has been projected that Texas may be an energy *importer* by 1985. *(44)* At that time the expectation is that half the State's electricity will be generated from coal and only 15% from natural gas.*(45)*

There is some impetus to proposals to build a super-port for Texas to serve the many petrochemical industries that located in Texas when its oil and gas resources seemed limitless. Also there is a plan to use a pipeline (originally constructed to transfer natural gas to the West Coast) to transfer Alaskan oil from the West Coast to Texas (and other states) in the future.

Figure 8

TEXAS YEARS SUPPLY OF CRUDE OIL & NATURAL GAS
1945 — CURRENT



Prepared by: Texas Railroad Commission

C. New England

New England has about the same population as Texas (12 million), but its energy prospects are far different. Currently, Texas generates over twice as much electricity as New England.*(13)*

The trend of orders for new boilers for electrical generation indicates that this sharp contrast will continue into the nineteen eighties.*(32)* Even Sweden (the often cited model for energy conservation) which has a comparable climate to New England, consumes over 50% more electricity on a per capita basis than New England. (Sweden produces 77% of its electricity from hydroelectric dams*(12)* and 13%*(41)* from nuclear power; New England produced only 13% of its electricity from hydroelectric dams, 21% from nuclear power and 60% from fuel oil).

D. The Regionalism of Nuclear Power

Figure 9 is a map of the United States showing the locations of all nuclear power plants in operation, under construction, or firmly planned. It is apparent that the vast bulk of these locations are east of the Mississippi River in areas of high population density. In the mid-eighties about 75% of the operating nuclear power capacity will be east of the Mississippi River*(40)*. The absence of plans for nuclear reactors in Kentucky and West Virginia, the heart of the eastern coal producing region, stands out. Some uNits are shown in the Pacific northwest where the most attractive hydroelectric potential has been largely developed and other fuel sources for electrical generation will be required in supplement in the future.

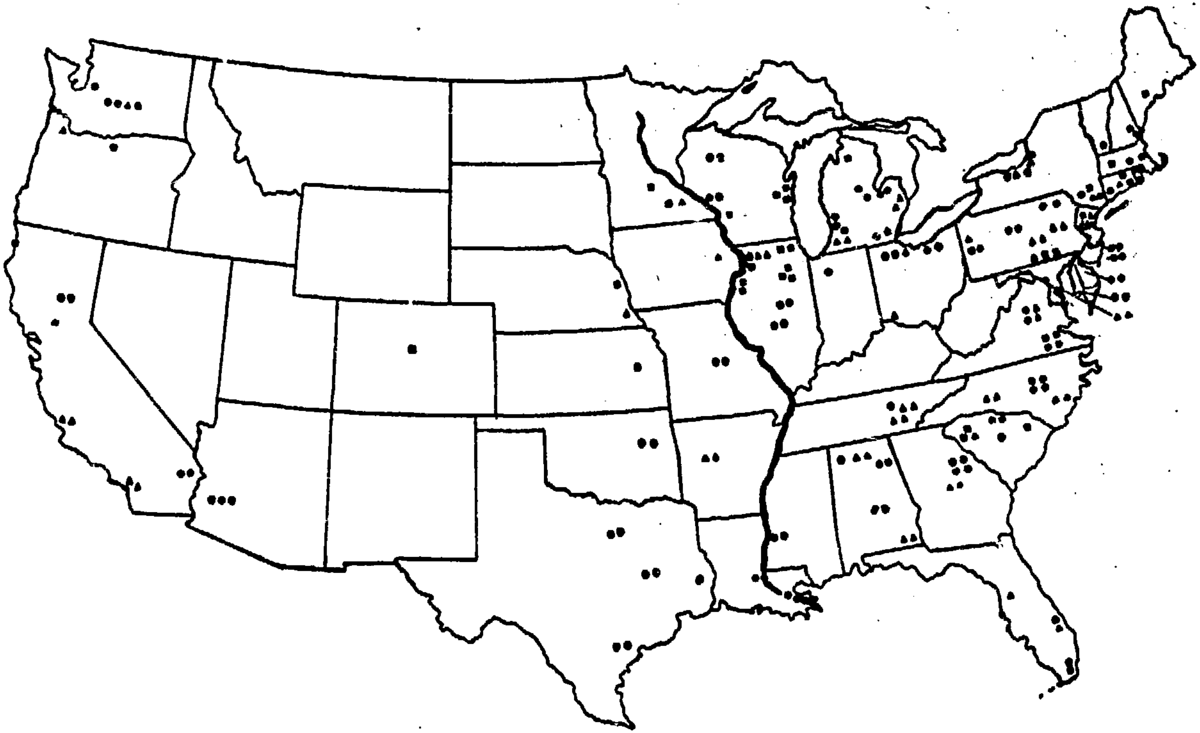
Projecting 20 - 25% of national electricity production from nuclear energy in the late nineteen eighties, as has been done in a number of prominent studies, does not adequately convey that a group of six southern states (Virginia, North Carolina, South Carolina, Tennessee, Alabama, and Mississippi) will be approaching 50% nuclear electrical generation at that time, if plans are full implemented, while ten western states will have no nuclear power. Indeed, this group of six southern states will have more nuclear power than all 22 western states. If this might seem like undue reliance, it is pointed out that in 1985, two-thirds of France's electricity will be from nuclear power. (42)

E. Public Acceptance

The public readily accepts statistical hazards where associated economic advantages or pleasures are commonly judged rewarding in proportion to the hazards. The most prominent example of this commonplace is the universality of automotive transportation in the United States at the price of 50,000 violent deaths per year.

Figure 9

NUCLEAR POWER REACTORS IN THE UNITED STATES



Since commercial nuclear power has not yet produced any radiation casualities, communities which have a strong economic interest in nuclear power are not likely to be easily frightened.

The Southern nuclear block has had two major nuclear centers for over 30 years at Oak Ridge, Tennessee, and Savannah River, South Carolina; the Huntsville, Alabama, Space Technology Center is in this region. Long familiarity, the presence of knowledgeable employees, or former employees in surrounding communities, the retaining over several generations of scientific staff members of regional colleges and universities as consultants at these centers, the remarkable safety records, the prosperity derived from nuclear energy and a remembrance of poverty, all combine to yield a high level of public acceptance of nuclear power.

The Knoxville-Oak Ridge, Tennessee, area seeks to be known as the "Energy Capital of the World"--a World Energy Exposition is being planned. It is the site of the Nation's first large Liquid Metal Fast Breeder Reactor. It is the site of a planned nuclear fuel reprocessing plant. It is the headquarters of the Tennessee Valley Authority, the site of the main campus of the University of Tennessee. The Oak Ridge Facilities employ over 15,000 scientists, engineers, technicians, skilled operators, and craftsmen. The prevailing consensus is that nuclear energy is safe; many believe it to be the safest form of energy. The principal concern of nearby town and county governments is that an appropriate share of revenues accrue to their communities.

As another example of confidence based on familiarity and experience, the Legislative Energy Committee of the New Mexico Legislature has indicated to the Federal Energy Research and Development Administration an interest in having a nuclear waste depository, a spent nuclear fuel reprocessing plant and an enrichment plant in one nuclear fuel park in New Mexico. Experience with the presence of the Los Alamos Scientific Laboratory in the State for 30 years was cited as grounds for confidence and comport; the expectation of employment and business opportunities was given as economic motivation.*(43)*

F. National Energy Policies

Any national policy that limits the utilization of natural gas for electrical generation will obviously have a much greater effect on Texas than on New England. In turn, policies that result in a change in the price of fuel oil will markedly affect New England, while any adverse effect on Texas would be negligible. Any policy detrimental to nuclear power would have little impact on many western states, while having an emphatically adverse effect on the eastern nuclear states. Policies that limit the development of western coal will result in addiitonal reliance on the eastern coal region with accompanying economic impact on both regions. *One national policy that can be pursued with advantage to all areas of the country is energy conservation.*

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Energy Sources of the Future*

by

Dr. John P. Sanders†

Engineering Technology Division, Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830

ABSTRACT

In evaluating the choices for possible energy sources of the future, it is important first to realize that we have come to the end of an era — the era of cheap fossil fuel. A study of the history of energy usage in this country will indicate a "take off" occurred in our energy consumption rate in the mid-1950s; this was followed by an increase in the use of electricity as a more convenient energy source in the mid-1960s. Associated with the generation of increasing amounts of electricity were the conversion losses that are inherent in normal steam cycles. Our future needs can be projected on the basis of the population growth and the energy consumption rate per capita. An extrapolation of these needs minus the amount of fossil fuel that we can obtain or afford to import shows clearly the demand placed on domestic supplies. After an allowance is made for the remaining fossil reserves plus optimistic projections for energy from geothermal, hydroelectric, oil shale, and solar sources, a deficit remains. It appears that nuclear fission energy is the only developed source that has a possibility of filling this deficit between the present and the year 2000. Past that date, there is hope that nuclear fusion energy or some other of the developing technologies will be available to supply the need.

I. INTRODUCTION

The important point to remember about the current energy situation is that we have come to the end of an era. Just as civilization passed through

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*Work done at Oak Ridge National Laboratory, operated by Union Carbide Corporation for the Energy Research and Development Administration.

†This article contains, in part, information presented by the author on July 9, 1976, for the course titled, *Energy Sources for the Future*, which was conducted by the Special Training Division of Oak Ridge Associated Universities.

the stone age, the bronze age, and the machine age, we have now passed the age of cheap fossil fuel. The implication of this fact is that we cannot rely on any application of technology to return to the life-style that was based on an abundance of cheap fossil fuel. We cannot regain and maintain our unrestricted use of energy, nor can we maintain the high level of individual mobility to which we have grown accustomed.

II. PROJECTIONS FOR THE FUTURE BASED ON HISTORY

Just as most major events of the present and future are simply extrapolations of history, we can best understand our present situation and future expectations by reviewing the past. The compilation of information that is presented was furnished in a publication called *Understanding the "National Energy Dilemma"*, which was prepared in 1973 by the staff of the Joint Committee on Atomic Energy. The complete publication is available from the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C., 20402, at a cost of $1.55; it should be referenced by US GPO Stock No. 5270-01974. Even though the publication is based on information obtained during and prior to 1973, the major changes necessary to alter the projections have not occurred. Even though we have come to a high level of public awareness of the energy situation, we have not initiated the long-term policy changes that are necessary to modify the trends that were established at that time.

The changes that have occurred since the document was published have been the "gasoline shortage" accompanied by long lines at the gas station and the significant increase in the price of imported crude oil. The increase in the price of imported crude oil can simply be used as a multiplier for all cost figures in the document relating to the money required to pay for future crude imports.

A. Basis for Comparison

Since many energy sources are to some degree interchangeable, it is convenient to select a common unit on which comparisons may be based. The unit chosen for this comparison is a million barrels per day of oil equivalent (MB/DOE). To obtain some feeling for the size of this unit, you are referred to Table I, which illustrates a few known quantities in terms of this unit.

Table I. Typical "Oil Equivalents"

Source	Energy Form	MB/DOE[a]
Total, State of Texas	Oil production	3.5 and declining (end 1972)
Total, State of Louisiana	Gas production	4.2 (end 1972)
Total, State of California	Oil production	0.9 and declining (end 1972)
Total, State of Pennsylvania	Coal production	0.9 (end 1972)
Total, State of West Virginia	Coal production	1.4 (end 1972)
Hoover Dam	Electric capacity	0.02
Total U.S. nuclear power	Generate electricity	0.3 (end 1972)
Large supertanker	Oil per load	1.5 (per voyage)
Alaska pipeline	Oil transportation	1.5 (projected)
Total U.S. demand	All forms	36.0 (early 1973)

[a] Million barrels per day of oil equivalent.

It was necessary to make some assumptions in establishing these equivalence units. Where possible, it was assumed that either coal, gas, or oil was burned in a fossil-fueled power plant to produce electrical power. In other cases, it was considered that either coal, oil, or electricity could be used to power rail transportation. Possibly the largest extrapolation involved the power requirements of small mobile units (cars and trucks), which cannot now be practically powered by coal, gas, or electricity.

B. The Most Recent Past

In terms of these units as just defined, let us examine the most recent information concerning the use of energy. Figure 1 displays the supply, consumption, and use of all major forms of energy in the year 1960. Note that the display is divided into four areas of interest as vertical slices are made through the plot. At the left are the SUPPLY/DEMAND requirements for each form of energy. Here, supply is equated to demand on the basis that if the energy source had not been in demand, it would not have been supplied.

The next vertical cut shows the form in which energy was used. Some was used directly, but other sources were converted to a more convenient form before use. Most notable among these conversions was the coal and oil used in the generation of electricity. An obvious effect of this conversion are the losses associated with the electrical generating plant. It should be emphasized that these losses are inherent in the steam cycle of the generating plant and not simply the result of inefficient design. These losses can be reduced only slightly by optimizing plant design, going to higher temperatures and pressures, and using more efficient regenerators; they cannot be eliminated in this type of plant.

The next vertical slice shows the end uses for the energy either as residential and commercial heating, industrial use, nonenergy use (manufacture of synthetic materials from petroleum), and transportation. This important profile will indicate where most of our energy resources are going, and, therefore, where the greatest potential for savings exist.

The final vertical slice on the right shows the accumulation of energy lost from various uses and the energy that is effectively used. This is a measure of the overall efficiency of our energy system. Notice that two of the major contributors to losses are those which come from the conversion of less convenient fuels to electrical energy and those which come from the transportation segment. Transportation losses include the energy emitted in the form of heat from automobile radiators, losses from stop-and-go driving, and similar sources. The overall efficiency in 1960 was about 49%.

Note the relative magnitude of the bands in Fig. 1; these will be maintained through the next two figures for the purpose of comparison. Note that in 1960 our use of oil was 9.7 units (MB/DOE) of which only 1.9 units represented imports. Note also that the use of oil in electrical power generation was small (0.3 units) and that more than half of our electrical power generation came from coal (2.0 units). A significant amount of gas (2.0 units) went to home and commercial heating. The amount of electricity used in transportation (in the form of electrified railroads) is too small to show on this plot.

Let us now advance to the situation in 1970 as shown in Fig. 2. The same general format is maintained so that the changing patterns over the decade may be seen. In general, we moved toward increased use of the energy sources that are more convenient, such as gas, oil, and electricity. The units of energy devoted to electrical energy generation has doubled. The use of natural

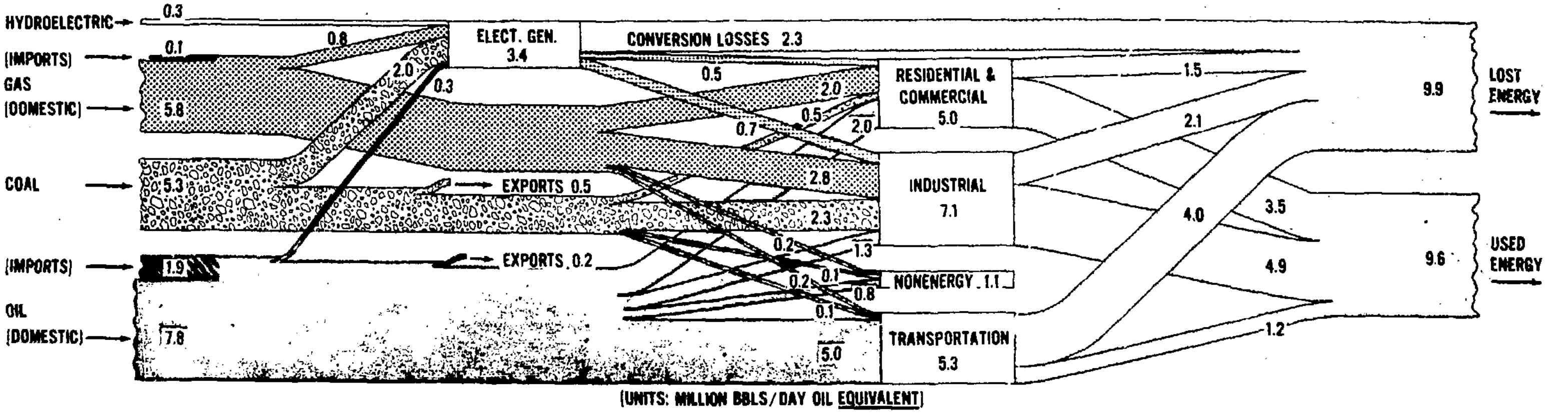

Fig. 1. Energy Use and Consumption in the Year 1960.

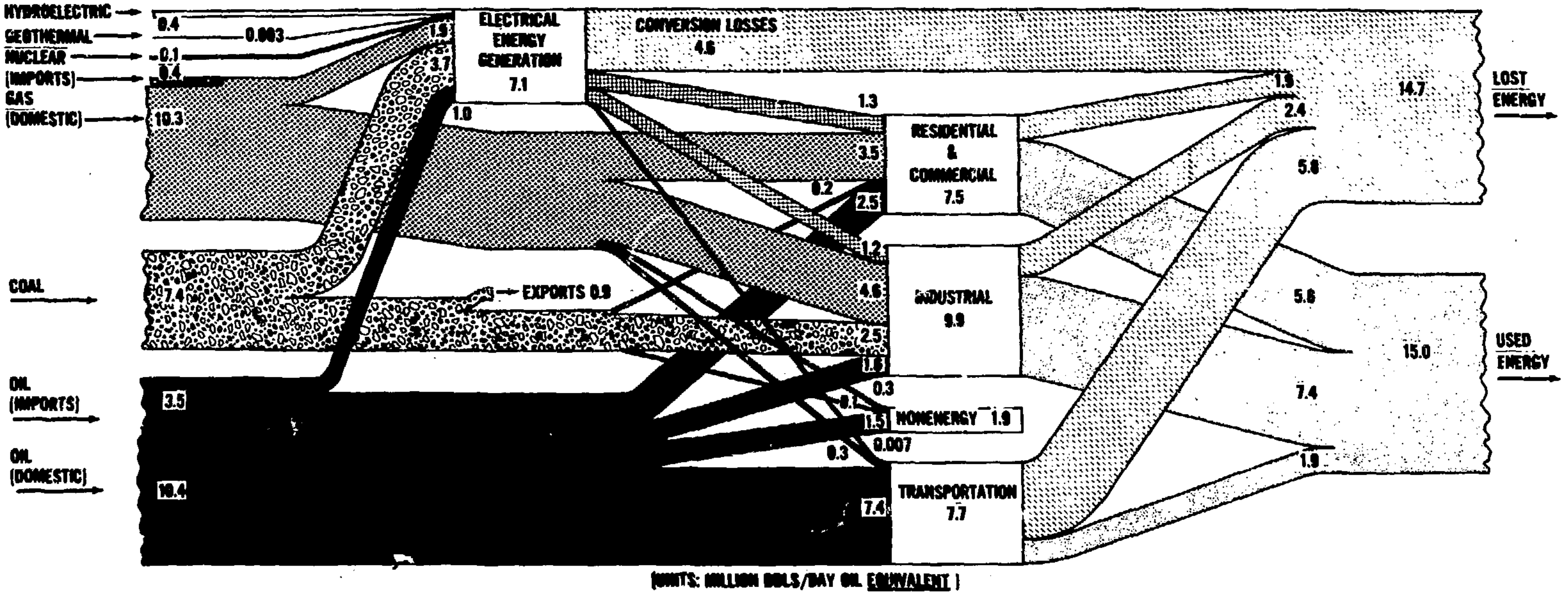

Fig. 2. Energy Use and Consumption in the Year 1970.

gas had doubled. The use of oil is up 50%, while the use of coal is up only 40%. Nuclear power has just been introduced as a significant energy source (0.1 unit) as has geothermal (0.003 unit).

The two most important trends of the decade from 1960 to 1970 are (1) we have begun the take-off toward the greater use of electricity in comparison with previous decades, and (2) at this time, the overall efficiency of the energy system is about 49.5%. This will be the peak efficiency that will be predicted during our review and extrapolation. This is due, to a large degree, to the restrictions placed on both the transportation industry and the electrical power generating industry to control emissions. This statement is not made as a criticism of the regulations to protect the environment; it is made to emphasize the fact that these regulations have a significant impact on the performance of these industries and on the total available energy. This impact should be kept in mind and considered carefully in conjunction with the establishment of these regulations.

Now, a short jump forward will produce a chart for 1980 as shown in Fig. 3. This point in the future can be viewed with a fairly high degree of certainty because all electrical generating facilities that will be operational in 1980 must already be on order. Also, every major rail-based mass-transit system which will be functional at that time must already be under construction. Rather than turning to such means of energy savings, we still continue with the construction of our massive interstate highway system, which is dedicated to the use of the individual automobile with its inherent poor efficiency.

This prediction was made in 1973, and there are some changes that will make relatively minor differences in the values projected. Nuclear power was predicted to contribute 3.6 units, but recent cutbacks in construction will probably result in a significantly smaller contribution. The losses from the transportation sector are probably overestimates because they were based on the large 1973 gas-guzzlers equipped with the first-generation pollution-control devices. We have experienced a concerted drive to reduce home and commercial heat losses plus other conservation measures, which have significantly reduced the presently required electrical capacity from previous projections. There are arguments today about whether this conservation capacity is nearing saturation or whether it has further potential for growth. Notice, however, that the projected oil imports are approximately equal to our domestic oil production; this is not a major contradiction to our current status. Our willingness to import oil appears to be limited only by our abilty to pay for it as the price steadily rises or by the willingness of the suppliers to make shipments.

III. GROWTH PATTERNS

We can combine this three-decade review with some earlier displays of history and some extrapolations into the more distant future and see more easily the trends in energy consumption in this country. For example, these projections indicate a maximum overall system efficiency approaching 50% in about the year 1970. Considerable attention should be devoted to changing this trend, and every decision should be based on increasing overall system efficiency.

In the growth patterns, we see the transportation sector commanding ever increasing quantity of the available energy; it increased from 5.3 to 12.0 units over the period from 1960 to 1980. In the forms of use, we see the previous trend toward more convenient, but sometimes more wasteful, methods of energy usage. The use of electricity, one of the most convenient forms, rose from 1.2 units in 1960 to 4.9 units in 1980; however, the energy input required

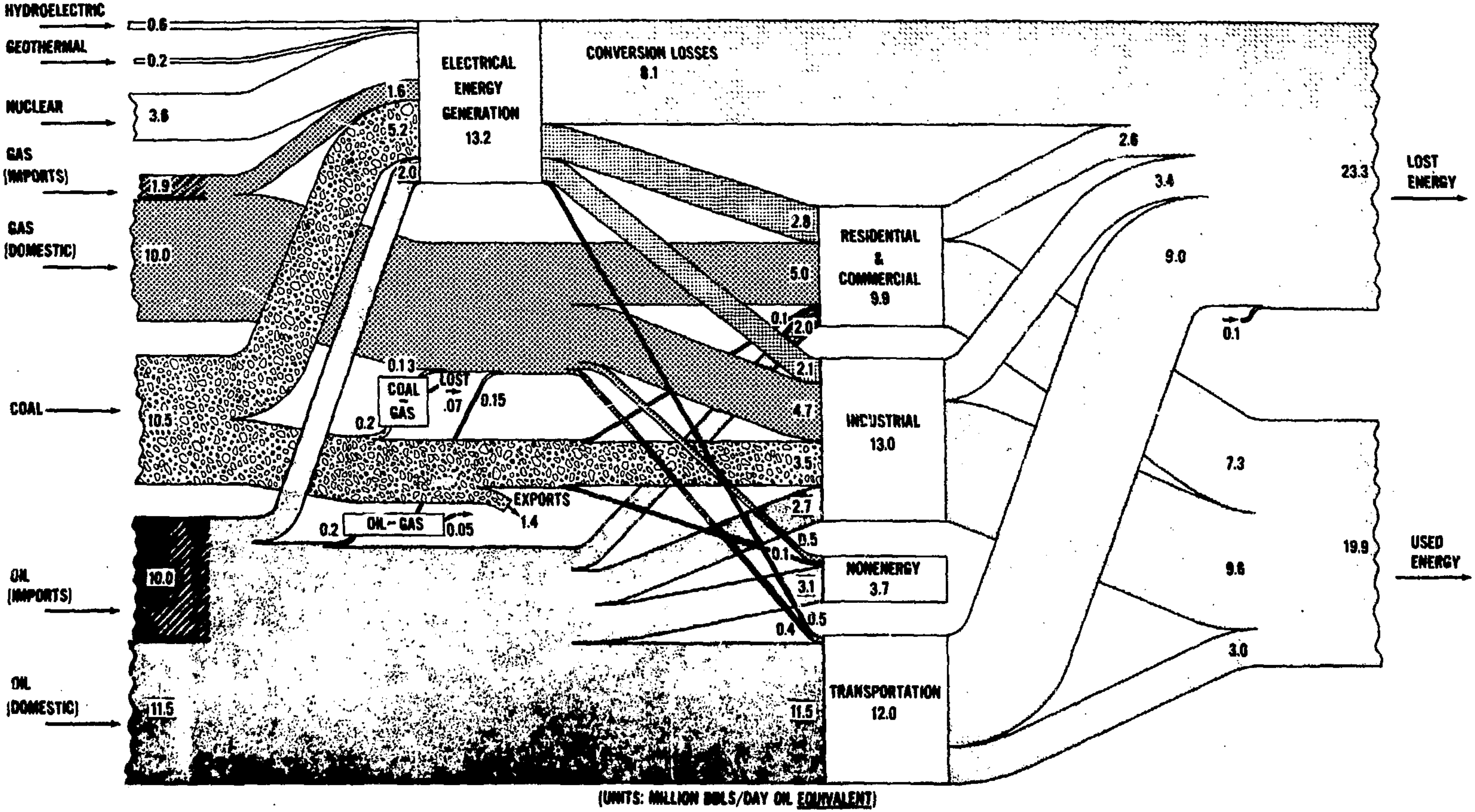

Fig. 3. Projected Consumption and Use of Energy in 1980.

to supply this energy went from 3.4 units to 13.2 units during the same interval. The use of gas and oil, both of which are more convenient fuels than coal, increased over the period from 1965 to 1975, while the use of coal actually declined. Now that we are literally running out of gas, the trend has changed to favor the increased use of solid fuel.

Finally, the SUPPLY/DEMAND pattern becomes the most important. This has been plotted in Fig. 4 over this period of maximum interest. An allowance has been made for completion of the Alaskan pipeline in 1977 followed by the development of an oil shale industry shortly after that. The growth rates of energy from nuclear, geothermal, and hydroelectric sources have been projected

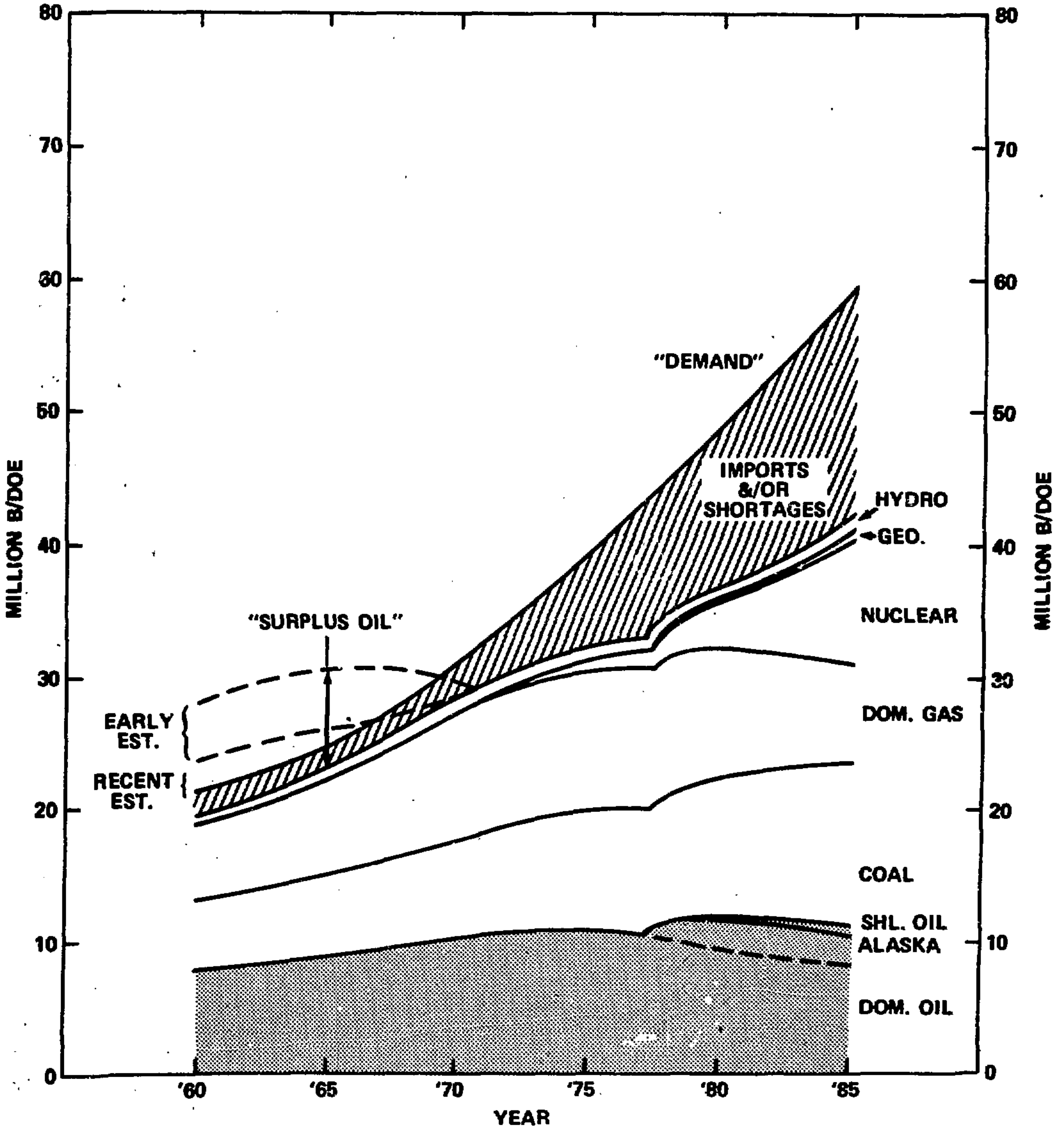

Fig. 4. The DEMAND and SUPPLY of Energy Sources for 1960 to 1985.

at their maximum anticipated rates. Presently, it appears that nuclear power will slip by at least 15% from this estimate; by 1980, this slippage would be equivalent to about 0.5 MB/DOE. At $16/barrel, this would require an additional $3 billion in imports of oil in that year alone.

Note particularly that, on this curve, an early and a more recent estimate of the oil reserve is shown. In effect, the intersection of that curve with the DEMAND curve was the time that our country lost its energy independent. The extrapolation of the DEMAND curve into the future is based on a combination of the projected population and the energy consumption per capita. This will be shown subsequently. The gap between DEMAND and the available domestic energy supply has been labeled IMPORTS AND/OR SHORTAGES. They will represent imports, if we are able to buy them and if they are available; otherwise, they will represent shortages.

IV. GUIDANCE PROVIDED

This figure provides a great deal of guidance concerning our future energy policy and usage. If a decision is made as to how much oil we can afford to import, then obvious adjustments must be made to either the DEMAND (or SUPPLY) curve or the domestic sources will have to be increased. The DEMAND curve can be moved through concerted efforts at conservation, and from our previous plots indicating end uses, those areas where conservation can be most effective can be easily identified. For example, the transportation sector indicates a significant and ever increasing requirement for energy. While many energy conservation measures may be selected on an individual basis, overall legislative action will be required to promote mass-transit systems, which will efficiently utilize energy and also serve the public needs.

Another use of this presentation is to determine the effectiveness of certain alternatives. For example, if we wished to know the effect on the amount of imported oil required of fully insulating all homes and buildings in the U.S. by 1980, we would note from Fig. 3 that 9.9 units were required for residential and commercial uses. If we assume that 60% of this was devoted to space heating and cooling of homes and buildings, the requirement would be 5.9 units. If we were to insulate fully and successfully every structure in the U.S., we would probably reduce the requirement by a maximum of 20% (allowing 40% for new structures and 10% for old structures). The total savings would be 1.2 units, or a little more than 10% of the projected imports.

V. LONG-RANGE FORECAST FOR ENERGY DEMAND AND SUPPLY

Figure 5 presents a number of long-range forecasts concerning the demand for energy to the year 2000. A basic component of this forecast is the projected population for the U.S. We have already passed the point of a declining birth rate; however, the increases in life expectancy (a factor which all should approve) have resulted in a continued population growth. The time of zero population growth is now anticipated at some time between the years 2030 and 2070.

The population at any point in time, multiplied by the energy consumption per capita, will produce an energy demand for that time. It is important to remember that the energy consumption per capita is not simply the energy that the individual uses personally — in transportation or in home consumption. It must represent the total energy that is expended in that person's behalf by others. For example, the amount of energy that a person uses in operating a television set over its normal lifetime is probably small in comparison with

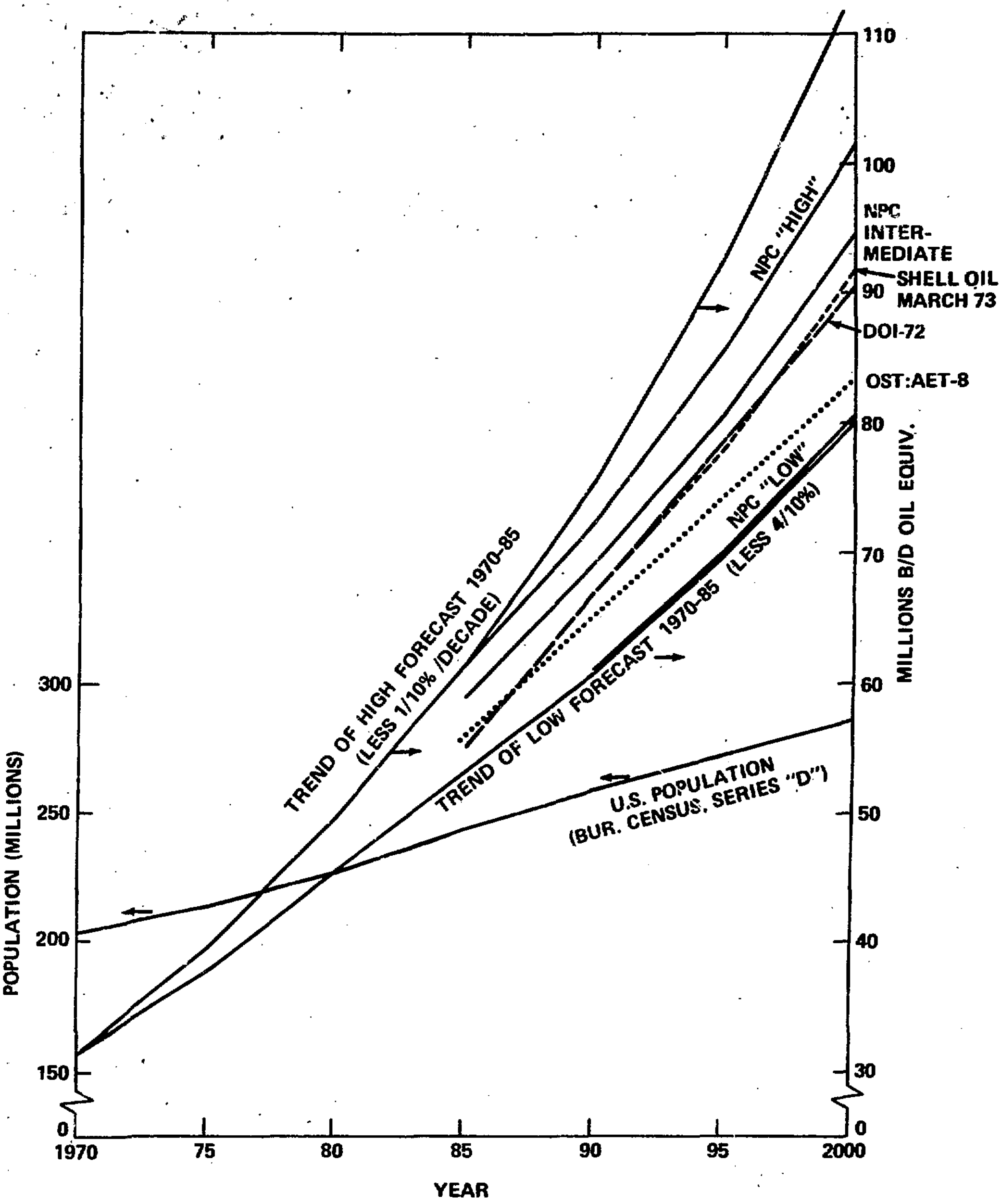

Fig. 5. Forecast of Energy Demand to the Year 2000.

the amount of energy necessary to acquire the raw materials and convert them into the finished product. Energy requirements in the production of the television set must also include the heating requirements for the area in which the set is first assembled and then later sold, plus energy requirements in shipping the component parts and the finished set. The same relationship is true when the energy requirements of the personal automobile is considered. For many items, the energy required for the production of the article is much greater than the energy employed in the use of the article — for example, an electric toothbrush.

From the foregoing examples, it is easy to see that a significant reduction in the per capita consumption must come from major changes in the life-style of the citizens of the U.S. The current attempts to limit energy use, such as changing thermostat settings, turning off lights, reducing driving speeds, or even the purchase of smaller automobiles, cannot produce the reductions that are indicated by these plots. Changes that will be required will involve major dependence on mass transportation (with significant loss in individual mobility), significant labor relocations as industrial requirements change, moving to housing that is closer to work locations, and simply doing without many of the goods and services available today.

If we are to avoid all of these drastic changes, the per capita use of energy must remain within some reasonable bound of its current value. A change to a more affluent life-style is usually accompanied by an increase in the consumption rate of energy per capita. Using the current consumption rate of 36.0 units in the U.S., together with an increase which is 0.1% per decade less than the current value, the consumption rate in the year 2000 will be 120 units. From this "high" value, other forecasters predict values as low as 80 units in the year 2000. There are some who argue that a consumption rate even below 80 can be achieved through conservation efforts alone — without any major disruptions in the life-style of the average person.

VI. AVAILABLE ENERGY SOURCES

Based on this discussion, we can conclude that the energy consumption rate that will be required in this country by the year 2000 will be in the range of 70 to 80 units — unless there is a major change in life-style. In Fig. 6, this DEMAND curve is shown together with all available projected domestic sources. A band of about 10 units is designated as IMPORTS AND/OR SHORTAGES; this is considered to be the maximum amount of oil that the country can afford to import in that period. Almost all the energy sources shown are either the maximum projections that we can envision from our current knowledge or they are goals that we must meet to sustain this minimum energy DEMAND.

The prediction for domestic crude oil is probably about 80 to 85% accurate for the next decade or so; it is based on broad experience in predicting the anticipated rate of finding an oil resource as a function of the number of wells drilled. The projection assumes the immediate development of offshore deposits (Santa Barbara, the Gulf of Mexico, and the outer continental shelf of the East Coast) plus increased efforts in Federal lands in the western part of the country.

The production of coal is shown as almost tripling in the next three decades. This could be accomplished by tripling the strip-mining of coal and by at least a 50% increase in underground mining capacity. Coal is a resource base that could probably support an even greater increase, but the availability of water, reclamation problems, fabrication limitation of the massive equipment required, available steel and transportation, and other such problems make this coal projection optimistic. Strip-mining legislation must be clarified before this energy source can be completely defined.

The availability of domestic gas supply is probably the most difficult to estimate; the long-range projections could be off by 50% either way. Unfortunately, recent attempts to drill very deep wells in Oklahoma in anticipation of finding new and substantial gas reserves have failed to be productive.

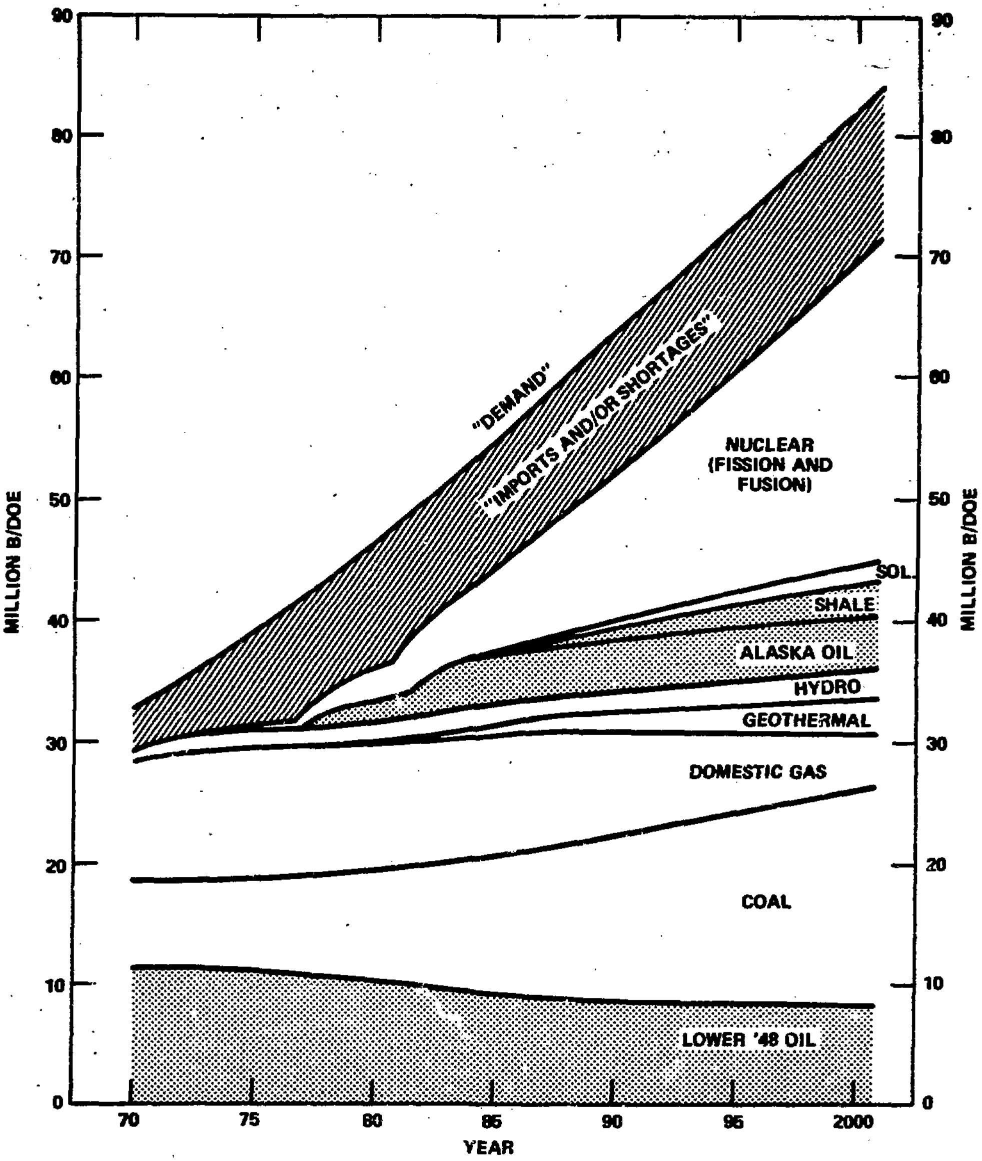

Fig. 6. Projected DEMAND and Available Energy Sources.

Geothermal power is probably fairly predictable, despite present technical unknowns, once the nation has established the level of environmental degradation that it is willing to tolerate and has estimated the amount of capital that can be committed to the development of such power. The projection shown in Fig. 6 indicates plants totalling at least 100,000 MW capacity in operation by the year 2000. A geothermal power input of this magnitude would require a massive effort in California and several other states and would generate the electric equivalent of over 100 Hoover Dams.

The hydroelectric capacity can be projected with almost 100% accuracy — once the guidelines are established. The capacity shown in Fig. 6 for the year

2000 represents a 50% increase over today's capacity. Unfortunately, the great majority of attractive sites are in National Parks and similar scenic areas. It would be necessary to build dams in such places as the Grand Canyon if the nation were to undertake a massive effort to increase its hydroelectric systems.

The availability of Alaskan oil is based on the assumption that construction of the pipeline delivery system and the development of the known oil fields will proceed rapidly. The ultimate production will be capable of delivering over 4,000,000 barrels a day. The Alaskan North Slope production is probably 80 to 85% predictable due to the work already done. The necessary technology exists to bring in this additional energy source, and a mature industry is available to do the job.

Oil shale, like coal is a massive resource; unfortunately, oil recovery from shale may be severely limited by available water supplies at the site. While technology is available for above-ground production, several demonstration plants may be required before financing information is available for the commercial effort. In order to produce 1,000,000 barrels per day using surface technology, it will be necessary to have massive mines with the total daily tonnage of material handled well in excess of our present daily coal production.

Solar technology should permit us to soon take over some of the heating and cooling requirements in the southwestern part of the U.S. Figure 6 shows an estimate of 1 MB/DOE contribution in the year 2000. This would satisfy the heating and cooling requirement of more than the total number of houses that will exist in New Mexico, Arizona, and Nevada at that time. Predictability of solar power is still fairly weak because of the requirements of developing several phases of the necessary technology and the lack of a mature industry at this time.

Many potential energy sources are not displayed in Fig. 6 because of the lack of available information to make reasonable projections. Wind power, tar sands, and tidal sources are some examples. All of these depend upon the development of technology that does not currently exist. In addition, the availability of dependable sources such as wind and tidal motion are limited to certain areas of the country even though conversion is made to electrical power for transportation. Wind energy may not always be available at the times of peak energy requirements; therefore, it must be balanced by other energy sources, or some sort of storage system (such as a hilltop water reservoir) must be used.

The final gap in Fig. 6 above the maximum projections for available sources of domestic energy and the DEMAND curve minus possible IMPORTS has been labeled NUCLEAR (FISSION AND FUSION). Unfortunately, current projections indicate that fusion energy will not be available as a commercial source until after the year 2000. Fission energy is, of course, available today; however, the buildup indicated by the projection in Fig. 6 would require a capacity of over 1,000,000 MW by the year 2000. This is outside of the currently projected capacity of the industry. To attain, or even approach, this estimate would require a massive industrial effort and a major upgrading in a number of areas, such as quality control, industrial performance, and licensing procedures. Problems relating to licensing, construction, and operation of nuclear power plants are emphasized by the fact that identical plants built in Japan and the U.S. by the same suppliers take almost twice as long to bring on-line in the U.S. The development of this power source will require a national effort to develop the required uranium supply and the fuel cycle systems to support the power plants. And, at some point past 1990, it will require the advent of a breeder or high-level converter to maintain the supply of fuel.

VII. THE FINAL OVERALL PICTURE

To broaden our view of the current situation, let us look at the energy situation over the current century as shown in Fig. 7. In the figure, the history of energy consumption in this country is plotted through the year 1973. It is interesting to note that the growth in energy consumption during this 73-year period was a fairly smooth curve — with one exception. There was a major relocation in the curve during the period around 1930; that was also the period in which the country went through a major recession. For those who did not experience this period of U.S. history, it might be helpful to emphasize that there were major relocations in the work force during this period, and there was a significant change in the life-style of most citizens. The implication is clear; there is a direct relationship between the energy consumption and the way of life of the American people. It is difficult to bring about a change in one factor without an almost proportional change in the other.

A few other points are evident from this plot. The steady growth in the requirements for energy and the available domestic supply of cheap fossil fuel are not quantities that changed suddenly at some point in time; each has remained a fairly uniform function as time progressed. The event that triggered our current concern about future energy needs was the intersection of these two functions shortly before 1973. Our current situation results from an extended series of events that can be seen from this curve.

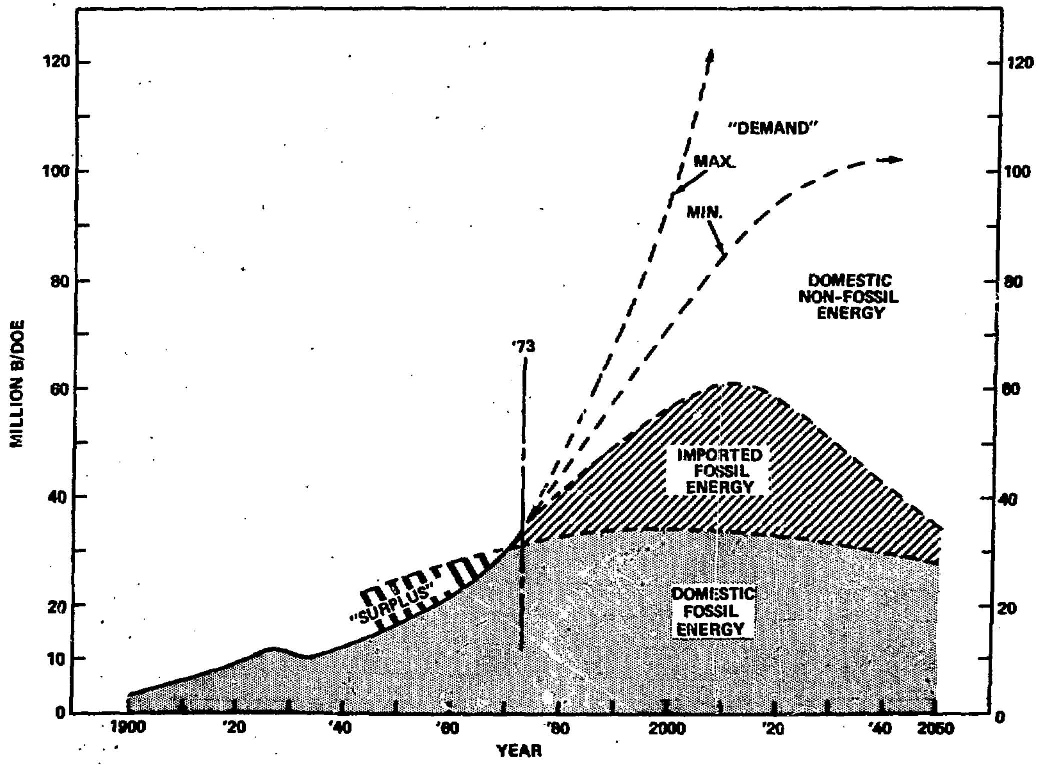

Fig. 7. SUPPLY/DEMAND Curve for this Century.

For example, if the first display of our energy consumption pattern (Fig. 1) in 1960 had been drawn for the time period immediately after World War I, it would have been about 45% the size of the one for 1960. A chart for 1940 would have been about 53%, and one for 1950 would have been about 75% the size of the one for 1960. So sometime in the mid-1950s, the U.S. took off on its energy-consuming growth, which led to the current situation. This, coupled with the trend toward the use of more energy in the form of electricity (with its associated conversion losses) in the mid-1960s tended to amplify the problem. As an illustration of this growth, the trends shown in these projections indicate that the U.S. will use as much oil and gas in the period from 1970 to 1982 or 1983 as it did from the beginning of history to the year 1970.

To add to the problem, the rest of the world has energy consumption patterns that are growing at a faster rate than our own. It now appears that the world as a whole will use as much energy from all forms between the year 1970 and the year 2000 as it did from the beginning of recorded history until 1970. It is this massive growth in the use of fossil fuel that has forced us to seek other energy sources for our near-term future needs.

As a final review of the overall situation, that part of the curve in Fig. 7 beyond 1973 should be examined. Two DEMAND curves are shown; the minimum curve assumes a constant energy consumption rate per capita at the 1973 level plus a zero population growth in 2030. The maximum curve assumes that the energy saturation point in per capita usage occurs near the year 2075. Both curves show a deficit in available domestic fossil fuel. If some reasonable limit is placed on the amount of fossil fuel that this country can afford to import, then the amount of energy that must come from domestic nonfossil energy sources is clearly defined.

Those sources, at least through the year 2000, have been discussed. It is only after that interval that we can hope for a technological breakthrough that will develop from the experimental stage to one of significant energy production. One of the promising sources for that time period that is currently under development is fusion energy. Considerable development is required, however, to make this a viable power source.

"Economic Growth and the Future"

John R. Dyer
Director of Public Relations
Edison Electric Institute

ABSTRACT

The world today is in the midst of a great transitional storm between two energy epochs -- the fossil-fuel age and a future energy era. The impact of this dramatic episode is being felt by all of us every time we buy a tank of gasoline or pay an electric bill.

It is also important to keep in mind during this transitional period that there is a basic difference between an energy crisis and an energy shortage. There is, in fact, no energy shortage. As Edward Teller puts it, "Thermal dynamics teaches us that unlimited energy exists. What is missing is the practical way to use this energy efficiently." In other words, the shortage is not of energy or of fuel, but of conversion technology -- the "smarts" to convert available fuel into useful energy.

In contemplation of facts like these, it is difficult to remain pessimistic, difficult to believe that, given economic stability, all there is ahead is higher and higher electric bills. The transitional storm will pass and the great drama will come to a happy ending if the participants in it play out their roles conscientiously.

"ECONOMIC GROWTH AND THE FUTURE"

THE STORM AHEAD

The world today is in the midst of a great transitional storm between two energy epochs -- the fossil-fuel age and a future energy era. The impact of this dramatic episode is being felt by all of us every time we buy a tank of gasoline or pay an electric bill.

It may not be easy for us to accept something as vague as a "transitional storm" as the real cause of high electric bills. The storm doesn't send the bills, the utility companies do. And the logical inclination, therefore, is to look to this immediate source of the pain for relief.

But the utility companies can do only so much. Our essential function is to convert raw fuel into useful energy, and if the available fuels run low in supply or high in cost, our options are no more viable than are those of the people we serve.

The inescapable fact is that significant relief from high electric costs can be hoped for only when something is done about the storm itself. The encouraging thing, not yet fully perceived by the public, is that something can be done about the storm. We can substantially lessen its intensity and shorten its duration.

The phasing in and out of fuel epochs is nothing new. It began with the phasing in of man himself. His first "fuel" was the food he ate -- the berries, roots and small animals that gave him the muscle and stamina to hunt for more food and to dig caves to live in. Then, roughly a hundred thousand years ago, a new fuel epoch was phased in when man discovered how to burn wood to cook with and to keep warm by. Next, in about 5000 BC, he learned how to use animal power to help in the growing of his crops. By 1400 AD he had learned how to burn coal, how to use the gravitational flow of water to turn waterwheels, and how to use the wind to turn windmills. And with these new energy sources, he developed an advanced agricultural society and the beginnings of commerce and industry. Finally, in the middle of just the last century, the fossil-fuel age began, and the advanced industrial society we know today was made possible.

Historically, the move from one fuel epoch to the next has always been accompanied by a marked improvement in human living conditions. It will certainly be the same when, eventually, the present transition is completed. In the meantime, the fact must be dealt with that there is one essential difference between this transition and all that have preceded it. And that is that in all the previous episodes of this type, man has moved from one fuel epoch to the next not because he had depleted his old source, but because he had found something better to take its place. Discovery of the new preceded depletion of the old. The epochs were interlocking. Man didn't run out of muscle or falling water or wind or animals or wood. He found something more efficient to replace them.

Today it is different. The fossil-fuel epoch and the next age are not completely interlocking. There is some overlap, but not enough to satisfy evergrowing demand. There is a potential gap, and we will call the gap a "transitional storm" -- the press usually calls it an "energy crisis."

In hindsight, it is clear that, from the first, man expected too much of the fossil-fuel epoch. Virtually everyone alive today was born years after it began. We were born into it, as we were into the constants of rain, sunshine and the tides. It is understandable, therefore, that without giving it much thought, we more or less expected it to go on forever. Just how unrealistic these expectations were is indicated by a paper written by Dr. M. K. Hubbert of the U. S. Geological Survey. The same King Hubbert on your program yesterday. "It is difficult," Dr. Hubbert observes, "for people who are living now and who have become accustomed to the steady, exponential growth in the consumption of energy from fossil fuels to realize how transitory the fossil-fuel epoch will eventually prove to be when viewed over a significant span of human history." Dr. Hubbert estimates that in a period of only 1300 years from the beginning to end, man will have consumed the world's entire available supply of fossil-fuels. Further, he estimates that 30 percent of that supply -- all but the first and last ten percents -- will have been consumed in the incredibly short period of only 300 years. Put another way, if we say that man's adventure on earth began some 400,000 years ago, and if that period is presented by a 12-inch rule, then 80 percent of the fossil-fuel epoch would cover only 1/9000 of an inch on the rule. Clearly, in historic perspective, it is a rather insignificant period, and it is important that we adjust our thinking to accept this insignificance lest we fall victim to the despairing notion that the world will go out of business when the last barrel of oil is pumped. The chances are excellent that it will go on lòng after it has passed through the 1/9000 of an inch.

It is also important to keep in mind during this transitional period that there is a basic difference between an energy crisis and an energy shortage. There is, in fact, no energy shortage. As Edward Teller puts it, "Thermal dynamics teaches us that unlimited energy exists. What is missing is the practical way to use this energy efficiently." In other words, the shortage is not of energy or of fuel, but of conversion technology -- the "smarts" to convert available fuel into useful energy.

Given the transience of the fossil-fuel epoch and the permanence of energy itself, the challenge of the moment comes into clearer focus. First we must do everything possible to stretch the fossil-fuel epoch to its absolute limit (thus lessening the storm's intensity) and second we must simultaneously accelerate the development of conversion technologies that will get us into the follow-on epoch as soon as possible (thus shortening the storm's duration). It sounds simple, and theoretically it is. What makes it more difficult than it needs to be is the lack of public consensus; the notion promoted by some that there are other options, most particularly that there is the option of simply bringing everything to a grinding halt.

Of course, the fact is that option simply doesn't exist. The steady increase in the world's population will steadily increase the demand for energy, and somehow or other we must find a way to meet it.

It is essential for all the players in this enormous drama to have a clear understanding of their individual roles.

The utility industry's part is relatively easy to state. It is simply to strive to meet consumer demand at the lowest possible cost and with acceptable environmental impact. It must share, with government and others, the task of seeing that the people learn how to use electricity more efficiently.

The consumers' role is in many ways the most vital one. How well the transition goes between the fuel epochs will depend largely on your performance.

Since you are the users of electricity, you are the only ones that can make the term "more efficient use" mean something. You must make it a way of life, and your must encourage your neighbors to do the same. You must support and encourage research and development that will lead to new and improved conversion technologies. But most importantly, you must take your position seriously -- as seriously as you expect the government and the utility companies to take theirs.

Neither of these roles will be as easy in the performing as in the identification. What makes the drama worth the playing, however, is the promise at its end: the discovery that things need not come to a grinding halt, and that a new, more abundant epoch will follow the old. The thrill will be in finding that there is indeed something beyond the high electric bills, and that, in fact, increases need not be eternal if other inflationary pressures are also relieved.

There are some things we already know about the transition to the new energy epoch. We know that we will move into it with increased dependence upon power generated from the one fossil fuel we have in relative abundance: coal. By the most conservative estimates, there are sufficient coal reserves in the United States to last another 250 or 300 years, a fact we must be grateful for and exploit to the fullest.

We also know that with fission, the conversion technology that takes useful electric energy from uranium, we can extract as much energy from one pound of uranium as we can from 15 carloads of coal. A new technology -- the "fast breeder" -- will make it possible to multiply that yield forty times.

And we are beginning to learn more about things like solar energy, geothermal energy and fusion. Fusion (which, as you all know, is the opposite of fission) is the conversion technology that takes energy from deuterium. It has been estimated that, if converted by the fusion process, there is enough deuterium in the world's oceans to meet all of mankind's energy needs at the present rate of consumption for 500 billion years. There is only one two-hundredths of an ounce of deuterium in a gallon of water. Yet if all the energy could be extracted from the small fraction of an ounce, it would be the equivalent of 300 gallons of high-test gasoline. Edward Teller was once asked what he thought mankind would do with the abundance of energy promised by nuclear fusion. He replied that such a question was like asking a prehistoric caveman crouched over the newly discovered miracle of fire how he intended to make a steam locomotive.

Geothermal energy is the energy below the surface of the earth. The most visible manifestations of this largely unexploited source are the volcanoes, geyers and hot springs we see in national parks. But like icebergs, these are only a tiny fraction of what lies underneath. Dependable geologists estimate that by the year 2000 geothermal sources could be developed to produce almost as much electric energy as the nation's entire utility industry is producing today. But access to it will be, for the most part, in the western part of the country.

The greatest energy source of all, of course, is the sun itself. Every day it floods the earth with a hundred thousand times as much energy as is produced in the same period by all the generating plants in the world. The inflow of its energy warms the earth and produces, through photosynthesis, all of the food, fuel and oxygen we need to sustain life. Every two hours, the sun's warmth provides the United States with enough energy to outlast all of the fossil-fuel reserves we have left. And the technologies to capture useful amounts of this energy are becoming more advanced daily.

In contemplation of facts like these, it is difficult to remain pessimistic, difficult to believe that, given economic stability, all there is ahead is higher and higher electric bills. The transitional storm will pass and the great drama will come to a happy ending if the participants in it play out their roles conscientiously.

Dr. Glenn Seaborg, Former Chairman of the Atomic Energy Commission, has this vision of the future: "The wise use of energy," says Dr. Seaborg, "can restore nature and rejuvenate man. It can help us to turn green again much of the desert wasteland that was once natural gardens. It can help us clean our man-made environment and rebuild the lives of men and the lands and cities they inhabit. It can help us build the foundation for lasting peace on this planet. And it can give us the means to explore beyond this planet -- to open new frontiers to man, physical frontiers and those of the mind and spirit. In short, the future of energy is the future of man. Without it we become nothing. With it, we become whatever we wish to be."

THE IMMEDIATE GOAL

In the first half, I outlined something of the promise that lies ahead. But what should we do to help see that promise fulfilled?

I said earlier that the thing that stands between us and the promise of tomorrow is not a shortage of energy or of fuel, but a shortage of technology. There is another shortage which may be even more serious in the long term. It is the shortage of will; the absence of public commitment either to the solving of our immediate problems or to the realization of the long-term promise. Dr. Rasmussen, the MIT nuclear engineer, says that the technological problems of nuclear fusion could be resolved before the end of the century if there were a public commitment to resolving them. "The engineering problems are simple compared to the human problems," he says.

Thus, to the imperatives of extending the useful life of the fossil fuel epoch and of overcoming the technological shortage, we must add a third; the development of a social ambience that will make it possible to approach the enormous tasks we have before us more pragmatically and with less emotional distraction. We must transmit the concept of the transisitional storm to our countrymen.

Saying that there is an absence of public commitment may not be quite right. It may be more nearly correct to say that there is a considerable presence of negative commitment; commitment that has manifest itself in dozens of ways -- shrill and almost overwhelmingly in the six or so crises the country has been struggling through these past 15 years.

We can correct this situation. We can, for example, focus more on the promise and less on the problems. It is, after all, the promise that makes the problems bearable. We can appeal more to man's deeply rooted sense of curiosity and pilgrimage. We can be less educational and more inspirational in our messages.

A committee of the Edison Electric Institute recently issued a report entitled "Economic Growth In The Future." It represented the culmination of 18 months of intensive research and analysis by expert consultants from diverse technical backgrounds. It was undertaken in recognition of the fact that economic growth which has traditionally been regarded as a fundamental social good, is being challenged by critics who hold the view that it is the cause of many of our current problems and may lead to eventual global collapse. Let me list some of the report's more important conclusions:

+ Potential limiting factors can be managed so that desirable forms of economic growth can be sustained for the foreseeable future.

+ United States growth over the next 25 years will be constrained more by shortages of capital than by shortages of energy or raw materials. Therefore, revisions in public policy will be needed to encourage capital formation and private investment in productive facilities.

+ Any attempt to arbitrarily halt growth would require authoritarian measures with a commensurate loss of individual freedom.

+ Environmental quality standards will have to continue to be enforced by regulation until an alternative system of financial incentives and "disincentives" can be developed.

+ Continuing economic growth will improve the "quality of life" as well as the standard of living. Growth is necessary to: aid in maintaining employment, improve the conditions of the poor, finance cleaning up the environment, and maintain a favorable position in international trade and balance of payments.

In sum, it is an "upbeat" report. It concludes that everything need not come to a grinding halt; that man's pilgrimage need not be ending, that we need not go back to the cave, that, indeed, the transitional storm will pass. It is, in my view, an important document filled with useful information for the American people. I would like to think that it would be made the subject of editorials in newspapers and television comments across the country -- just as was the Club of Rome study. I would like to think that columnists and TV commentators would "investigate" it and report on it with objectivity and thoroughness.

Our industry believes the "storm" will pass. We have undertaken to invent new, communication channels to locate some not-so-new to get the message through. We are not depending entirely on conventional channels simply because experience has taught us that they are not that interested in messages about "good" things from "bad" guys. It goes against the concept of dramatic conflict. So far our efforts have been at least modestly successful -- successful enough to reinforce the conclusion that further development of new channels is probably the single most important thing we can do to clear up transmission difficulties and get the message through to the receivers -- our customers.

One of the first persons to advance the constituency concept for private industry was Irving Kristol, Professor of Urban Values at New York University. Professor Kristol says: "No institution in our society can endure without a constituency -- a substantial number of people who are loyal to the institution and who will quickly rally to its defense when in trouble." That is the kind of channel we need, and that's what we have begun to build.

We've ranged afield, while sustaining the hope that we can and will sustain the promise of tomorrow. After all, if the problems are bigger than our time, and if the solutions are bigger than our time, there isn't much room left for little people. The imperatives are clear. The remaining question is, are we as big as they?

I say "you betcha!"

"THE ENERGY CRISIS: The electric utilities and the consumer"

by

M. B. Hobby

Consumer Affairs Department, Georgia Power Company
Atlanta, Georgia 30302

I think the one thing that differentiates the present energy situation from most other crises our country has faced is its permanence. Throughout history, the United States has faced many crises and each time the challenges were met in what can only be described as "The American Way." We have demanded that laws be passed to eliminate the crisis, that wars be fought to eliminate the threat, or that technologists and scientists come up with a better mousetrap or a new vaccine to reduce the impact of a particular situation. And, we have demanded that these corrective actions be taken immediately.

Unfortunately, our nation now finds itself in an energy dilemma that is both inconvenient and costly. And it will be even more so. There are no laws that can be passed which will immediately eliminate the problem. There are no wars that can be fought which will increase the domestic reserves of natural gas or oil. And, scientists and technologists have not come up with a way to make cheap natural gas out of air.

I do not want to give you the wrong impression. There are some things we can do. If government, industries, and consumers act in concert and address the problems of the energy situation, we can lessen the impact of dwindling supplies of fossil fuels. However, any action taken that will be effective will require the best efforts of all of us.

Probably the best place to start is to tell what an investor-owned electric utility is. I shall speak specifically about the Georgia Power Company but the description is basically applicable to utilities in all 48 of these United States. Tennessee and Nebraska have been excluded from the Union for this discussion.

There is nothing really so bizarre about an electric utility. It is very much like Coca-Cola or Gulf Oil Company. Brought down to the bottom line, it is in business to make money. We say we are a service company, and I sincerely believe we are. The prime motivation to be in business, however, is to make money for our owners. Let us stop making money and we will shortly be out of business.

An investor-owned electric utility has owners to whom management is responsible. In our case, Georgia Power is owned by The Southern Company, a utility holding company whose corporate headquarters are in

Atlanta. Thus, Georgia Power Company is owned by the more than 285,000 Southern Company stockholders of record plus an estimated 80,000 additional beneficial stockholders. These people scattered all over the world own some 121,954,297 parts of the company.

These stockholders have bought part of the company -- they have invested their money with us -- for only one purpose. They want to make money. If they do not, they will not buy stock in our company and consequently, we'll be out of business. That is the same as with Coca-Cola.

Like Coca-Cola, the Georgia Power Company has a product to sell. There are several differences though. One is packaging. We cannot wrap our product up in a neat little box and deliver it to the customer the way Right Guard does. Also, the amount of product one of our customers uses is deceiving. First, he uses the product before he pays for it. And he doesn't pay each time he uses a unit of our product. He is billed for his total usage once a month. Secondly, he uses our product many times without realizing he is doing so. Since so many applications for electricity are made when the customer is not at home or when the customer is asleep, and since our product when in use is not "seen," the customer is sometimes startled to learn how much he has actually used.

There is one other difference in our product that does not occur with many other products. That is, it must always be available for delivery to customers when they want it, wherever they wish it, and in whatever quantity they request. We are not allowed to backorder requests. Unlike Remington, we cannot stockpike quantities of our product for the Christmas rush.

Therefore, since the product must be produced in whatever quantities our customers demand, we are not allowed discretion in deciding upon the expansion of facilities. Of course, through various considerations, we can decide what type of facility to build and where it should be built, but we cannot decide <u>not</u> to expand if customer demand trends indicate an expansion is necessary. We must, in the public interest, project accurately what customers will demand and build to meet those demands even though the company's financial position or high interest rates might make us prefer to defer construction.

The last difference which makes an investor-owned electric utility different from other private enterprises is that we cannot charge whatever we wish for our product. We must justify to State and Federal agencies and to customers the amount which we charge. We are a regulated industry. That does not mean we are not a private enterprise, just regulated.

The reasons for the regulation of utilities are many times misunderstood and are several. The overwhelming reason is that we are such an essential industry and our product is such an essential part of everyone's life that an adequate supply of the product and the existence of the company is deemed to be in the public interest. The existence of our company and an ample supply of product could probably be assured without regulation except for one reason and that reason is what sets us apart from all other industries and is what is plaguing the electric utility industry today. That is the tremendous amount of capital required to establish and continue such a business. It costs so much money to establish an electric generating, transmission, and distribution system that almost every state recognizes it is in the consumers' best interest to not have competing companies. Each company is assigned a certain area to serve, and only they may serve in that area.

The electric utility industry gets a lot of grief about this one point. It is called a monopoly. A monopoly? Yes. But, regulated? Yes. If several companies operated within a given area with redundant lines, operating facilities, and personnel, the capital cost to each company would be so high and the return on the investment spread so sparsely among the companies, that a customer could probably not afford the product. Simply stated, our business requires such a tremendous amount of capital outlay that if competition among companies were allowed, we might find that no company could exist. We are a natural as well as a statutory monopoly.

I am sure all of this is elementary to you. But one thing that the energy crisis has done to all of us is to make us lose sight of some of the more basic facts of the free enterprise system. You let the headlines in the Atlanta Constitution state that the Georgia Power Company made a profit last month, and you will hear consumers yelling. Sure we made a profit! And the consumers should be thankful that we did, for without a profit we would not be in business very long.

If one looks at the history compiled by the electric utilities in this country, I think you will find our record unparalleled in the world. While we have been entrusted by the public with a certain amount of faith, we have acted responsibly and have done a good job. We have in this nation one of the best electric systems in the world. Traditionally, the cost of service we provide has been very reasonable and the charge each month for electric service has not been a significant part of the family budget.

However, rising fossil fuel prices, inflation, and the need for ever-increasing capital expansion have so changed the atmosphere in which we must work that the future will not be nearly as pleasant as the past. With the best efforts of us all and with the adoption of a realistic national energy policy, the best we can hope for is an adequate supply of electrical energy at higher and higher prices. While we may now think the days of cheap energy are over, in five years I am sure we will think of the current prices as the days of cheap energy.

There are several important pressures bearing on the utilities today. I would like to discuss some of these problems, how we are going to react to them, what impact they will have on the consumer, and what the consumer can do to help minimize the impact of these problems.

In other talks at this conference you have discussed load patterns of the electric utility industry. If you will remember, there is a peak hour each day. Actually there is a peak period each day when the demand is high. On our system, the peak period is usually from 10 a.m. until 10 p.m. But there is a needle peak each day, which we usually refer to as the peak demand, when during that hour the demand for electricity was the greatest. Of course, each year we have a peak -- that being the hour of the year when our customers demanded the most electricity. A utility's expansion plans or plant construction plans must be based around that peak hour of the year. On the Georgia Power system, that peak hour occurs typically in the summer time -- around the last of August. Already this year, we have reached a new peak, it was last Monday (July 12), of almost the same as last year. And, we are nowhere near the end of the summer.

This brings up the first problem pressuring electricity producers -- growth in demand for our product. In the past, our system growth rate has been at about 10.5% compounded annually. Of course, with the energy crisis, inflation, higher prices, and the economic recession, we have experienced a decrease in the historical growth rate. But we still have growth. Our growth rate now is projected to be about 7.75% annually.

While we have confidence in our projection, shortages of other fuels, or a dramatic increase in the price of oil or natural gas could stimulate additional changeovers from petroleum-based fuels to electricity which would increase our growth rate.

Let's assume a 7.75% growth rate. At the present time on our system, we have approximately 10,000 megawatts of capacity installed. If our growth rate is 7.75% annually, then next year we must have coming on line in our system an additional 775 megawatts. By 1980, if the projected growth rate continues, we must have at least an additional 1000 megawatts coming on line each and every year.

That does not sound too bad until you consider what it takes in terms of money to get an additional 1000 megawatts of capacity installed. First off, it means we had better be well on our way by now if we expect to get these plants on line by the early 1980's. As you know, it takes from 7-8 years to get a coal plant on line and from 8-10 years to get a nuclear plant on line. And for us these are currently the only two choices.

Secondly, at today's prices, the cost of a 1000 megawatt nuclear plant is in excess of $1 billion. With a coal-fired plant, the cost is not as great at this time but we do not yet know what that final cost effect will be due to additional environmental control devices. Whether we go to scrubbers, high stacks, or desulfurized coal, there will be a cost.

In the next five years, the Georgia Power Company will spend over four billion dollars on new plant construction. This may not seem to be a lot of money for a company as big as Georgia Power to raise. But consider this. We have been in business in one form or another -- I am speaking of our predecessor companies -- since before 1900, and our current worth is only $3,270,000,000. So, we are talking about doubling the worth of the company in only five years.

This is not a Georgia Power problem exclusively. Nor is it exclusively the problem of all privately owned utilities. It is a consumer problem. For if we do not have the ability to raise this money from the financial market, we simply will not have enough electricity to go around. And if customers are to have the energy needed, we are going to have to charge enough for the product to provide us a rate of return on our investment that will enable us to raise this money. And that hits the consumer right where it hurts most, in the pocketbook.

There are some things we are doing to try to keep the need for additional facilities as low as possible. For instance, in our company for many years, with the exception of a small county system and the Savannah Electric System, the Georgia Power Company was the only bulk producer of power in the state. We served about forty percent of the customers in the state from our lines. The remainder were served by rural electric cooperatives and municipal systems which bought the majority of their power from us and delivered it to their customers over their own distribution lines.

This worked fine for a while and served to the mutual benefit of each of us. However, some time ago we realized that the cost of additional capacity to serve the Rural Electric Cooperatives customers' was so great we could no longer unilaterally afford to supply the capacity they were going to demand. Thus, we agreed to sell part of our generating capacity to the Rural Electric Cooperatives. We operate the facilities and have part interest in the plants and they have part interest. By doing this we cut down on the amount of capital our company would need and still assure a dependable supply of electric power to the citizens of Georgia.

So far, the Oglethorpe Electric Membership Corporation has purchased 30% of the two-unit Hatch Nuclear Plant, 30% in the two-unit Wansley Coal Fired Plant, and has also purchased a significant portion of our transmission system. Thus far, they have invested some $483 million dollars in generating and transmission capacity. They have future projected investments of some one-and-a-half billion dollars out of which the Rural Electric Cooperatives hope to become self-sufficient capacity-wise. This has been a significant benefit to the Georgia Power Company and to our customers.

Another area where we are doing significant work is in the area of load management. As you remember, we build facilities to meet peak demand; it stands to reason that our facilities are not being utilized to their fullest advantage at all times of the year. This is called our load factor and in recent years we have experience a declining load factor. This means we have very expensive plants sitting around not producing revenue yet fixed expenses such as interest on the borrowed money to construct the plants continue daily and must be paid by the Company. Needless to say this is very costly and wasteful. We are trying to do something about it. Of course, we shall never realize a 100% load factor since outages of units are necessary for maintenance.

We are involved in several programs which in the industry is called load management. It is a two-fold effort. First, we would like to slow down as much as possible the rise in the peak each year. To lessen the increase in the peak would mean less requirements for additional capacity. The second purpose is to shift some demand away from the peak and into the valleys of the load curve. While this would cut down on the peak, it would also fill in the valleys of the curve so we would have a much better utilization of our system which would improve load factor. In terms of money, we would realize the maximum possible revenue with the minimum amount of investment. That is not what we have realized, but it is the goal of our load management program.

I will not describe all of the load management techniques we are investigating but I would like to mention a couple. First, the air conditioning load control device, (ACDC) for short. Since our peak occurs in the summer, you can well imagine that air conditioning is primarily responsible. The ACDC device is a motor driven rotary switch activated by a thermostat that senses the temperature outside a residence and controls the compressor of a central air conditioning system. When the ambient temperature outside gets above a certain point, say 88°, the ACDC device will shut off the compressor of the air conditioner for a certain time period of each hour. This procedure could be continued until the temperature outside reached a lower reading, say 80°. Given the fact that a 3-ton air conditioner while the compressor is running demands about 4 kilowatts of capacity, you can imagine the impact that such a technique could have on our peak. If such a system were employed in a large measure, we would stagger various groups of residences so not all of the residences were off or on at the same time.

A legitimate question that should be addressed is "What is the benefit to the consumer?" "Will it lower his electric bill?"

The answer is that such a device could greatly benefit customers but possibly not immediately. Last summer, 1975, we installed ACDC devices on some 300 residences. The test period lasted from June through September. The results indicated that at the time of our peak demand the ACDC devices reduced the electricity demand of each participating home by approximately 1.4 kilowatts.

If ACDC's had been on all the estimated 274,000 homes with central air conditioning served by the Georgia Power Company, the system peak demand would have been reduced by 436,000 kilowatts.

Of course, the hotter the summer, the more impact that ACDC's could have. 1975 produced a relatively mild summer. We estimate that during a hot summer, the ACDC's could reduce a customer's demand as much as 2 kilowatts which, if we had ACDC's on all 274,000 homes, would result in a system peak demand reduction of 779,000 kilowatts.

This reduction in peak demand would mean that we would not have to build as many new generating units. Thus, consumers would greatly benefit from hundreds of millions of dollars not being spent on construction.

When the tests first started, we had predicted that customers could save money on their electric bills. However, our initial summer's tests did not show this to be the case. The simple reason is that our customers continued to use approximately the same number of kilowatt-hours just at different times. But this is a step in the right direction.

This summer, 1976, we are going to test the ACDC device on centrally metered, multiple dwellings. Here the advantage to the customer becomes more obvious since these customers' bills are based upon their demand. The use of the ACDC device could reduce their demand and have a positive impact by lowering their electric bills.

A second tool we have employed is called the summer/winter rate differential. Recognizing that facilities have to be built to meet the summer peak demand with the facilities not being used as much in the winter time, in 1971 the Georgia Power Company started charging more for electricity in the summertime than in the winter months. This effort is not a punishment for persons using electricity in the summer. It is a recognition of the cost to serve. It places the burden financially on those who are responsible for the increase in demand and consequently the requirements for new facilities. A copy of our present rates is included as Attachment A.

Each of these above approaches encourages conservation -- both energy-wise and financial. And we have many other programs in effect now to encourage conservation on the part of our consumers. For instance, we have built four special houses located in different parts of Georgia experimenting with various types of construction and with solar heating facilities. It is our hope that the information from these "Answer Houses," as they are known will provide leadership and input to the building industry to encourage them and homeowners to employ energy-saving techniques in new construction. Of course, we all realize the cost of housing is so high today that additional costs for solar heating or more insulation will only be employed if we can show definite, money saving advantages. When the results of these "Answer Houses" are in, we hope to be able to do so.

For the first time this summer, we are offering to customers in three cities in the state what might be described as time-of-day rates. The program is strictly experimental in nature but we would like to see what the effect on use pattern would be of offering lower rates to customers in off-peak times. Therefore, in this experiment, we have incorporated load research meters and meters to measure KW as well as KWH. In one test town the meters have 2 KWH registers designed to measure off-peak and on-peak consumption. Customers who use electricity during the peak hours of the day will pay a higher rate for on-peak consumption than for off-peak consumption. Those who shift their household electric chores out of the peak hours will be using electricity which is priced at a lower per unit rate.

Since this program is just beginning, no results are in. While a successful participation in this venture would be most beneficial to both the company and the customers, we are not sure at this time that customers are willing to change their lifestyles as much as would be required with this new system.

But I think you can get an idea that Georgia Power Company and the electric utility industry are at the forefront in overcoming the complications that have arisen from the energy crisis. We are not content to sit back and let the other fellow do it. But, it is going to be a long climb.

One of the potential hindrances to an effective program to handle the problems of the energy crisis is the lack of confidence in big business and big government. A recent survey conducted by the Gallup Organization and commissioned by the Federal Energy Administration concluded:

> "skepticism, cynicism and ignorance concerning the energy crisis characterized all the group discussions and a general suspicion of being constantly lied to was pervasive. And while all this prevading skepticism can be interpreted as a rationalization for not conserving energy, it cannot help but impede the effectiveness of energy conserving communication."

Needless to say this is discouraging but also I do not think that such an attitude is completely unexpected or unwarranted. There are a lot of questions around for which we simply do not have the answers. When are fuel prices going down? Why doesn't someone do something about the high cost of petroleum from the Middle East? There are either no answers to those questions or the answers to the questions are distasteful.

What we at Georgia Power hope to do and what I hope my remarks to you today have indicated is to take the lead in our state in helping our customers adapt as well as possible to the changes in lifestyles that are inevitable. As energy prices go up, as fuel prices soar, electricity prices are going to increase. We feel we have an obligation to our customers to accumulate as much expertise as possible, either through our institutions of higher learning, from industries and concerns doing research in the energy field, and from our own in-house expertise, and dissiminate this information to the people who need it and who will benefit most from it.

This does not mean just the upper-class housewife on the northwest side of Atlanta. It also includes the sharecropper in South Georgia who did not have the opportunity to finish high school. All of our efforts to encourage energy conservation and energy awareness are directed at all levels of our society for those persons that might be the hardest to reach and achieve understanding might also be the people who could realize the greatest benefit from our service and who might need the assistance the most.

In conclusion, there are some things we can do to ease the strain of the energy crisis, but the electric utility industry must be alert to these opportunities and must commit itself to joining hands with its consumers in order to achieve the best possible solutions. We are capable of such action and have an obligation to act responsibly.

Georgia Power Company Residential Rates

SECTION I

(0-350 KWH/Month Consumption)

First 20 KWH or less	@	$2.50
Next 80	@	2.60¢ per KWH
Next 100	@	2.27¢ per KWH
Next 150	@	1.38¢ per KWH

SECTION II

(Over 350 KWH/Month Consumption)

WINTER - October through May

First 20 KWH	@	$3.05
Next 80	@	3.16¢ per KWH
Next 100	@	2.76¢ per KWH
Next 150	@	1.68¢ per KWH
Next 250	@	1.87¢ per KWH
Next 800	@	2.06¢ per KWH
Over 1400	@	1.31¢ per KWH

SUMMER - June through September

First 20 KWH	@	$3.05
Next 80	@	3.16¢ per KWH
Next 100	@	2.76¢ per KWH
Next 150	@	1.68¢ per KWH
Next 250	@	1.87¢ per KWH
Over 600	@	2.71¢ per KWH

Minimum Monthly Bill: $2.50

ATTACHMENT A

RESIDENTIAL ENERGY USE ALTERNATIVES TO THE YEAR 2000

Eric Hirst*

ABSTRACT

This paper describes a comprehensive engineering-economic computer model used to simulate energy use in the residential sector from 1970 to 2000. The purpose of the model is to provide an analytical tool with which to evaluate a variety of conservation policies, technologies, and strategies for their impacts on residential energy use and fuel expenditures over time. The baseline forecast developed here shows total fuel use growing from 17.6 GGJ (10^{18} joules) in 1975 to 26.4 GGJ in 2000, with an average annual growth rate of 1.7%. The percentage of household fuel provided by electricity grows from 44% in 1975 to 56% in 2000. The percentages provided by all other fuels decline over time. Alternative high and low forecasts show a range in annual fuel use growth from 1975 to 2000 of 2.1% to 0.3%.

INTRODUCTION

Between the end of World War II and the early 1970's, residential energy use grew steadily and rapidly because of growth in population, households, and income; declines in retail fuel prices; and the introduction of new household energy-using devices. The responses to these demographic, economic, and technological changes included: growth in ownership of energy-intensive household equipment (e.g., food freezers, air conditioners), shifts from small energy-efficient devices to larger less efficient units (e.g., replacement of small manual defrost refrigerators with much larger automatic defrost models that consume 50-100% more electricity), and increasing household use of energy-using equipment (e.g., taking longer hot showers, leaving lights on, setting thermostats higher in the winter). The net result of these changes was an average annual growth rate in household energy use of 3.7% between 1950 and 1974, nearly double the growth rate in household formation (2.0%). Figure 1 shows growth patterns for residential uses of electricity, gas, oil, and other fuels (coal, coke, LPG) from 1950 to 1974 [1].

During the past few years, however, a number of forces have emerged that may significantly alter these historical trends. Residential fuel prices began to increase around 1970, after two decades of declines. Because of these increases, personal consumption expenditures on electricity, gas, oil, and other

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*Research engineer, Energy Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830. The work reported here is sponsored by the Federal Energy Administration and the Energy Research and Development Administration under Union Carbide Corporation's contract with the Energy Research and Development Administration.

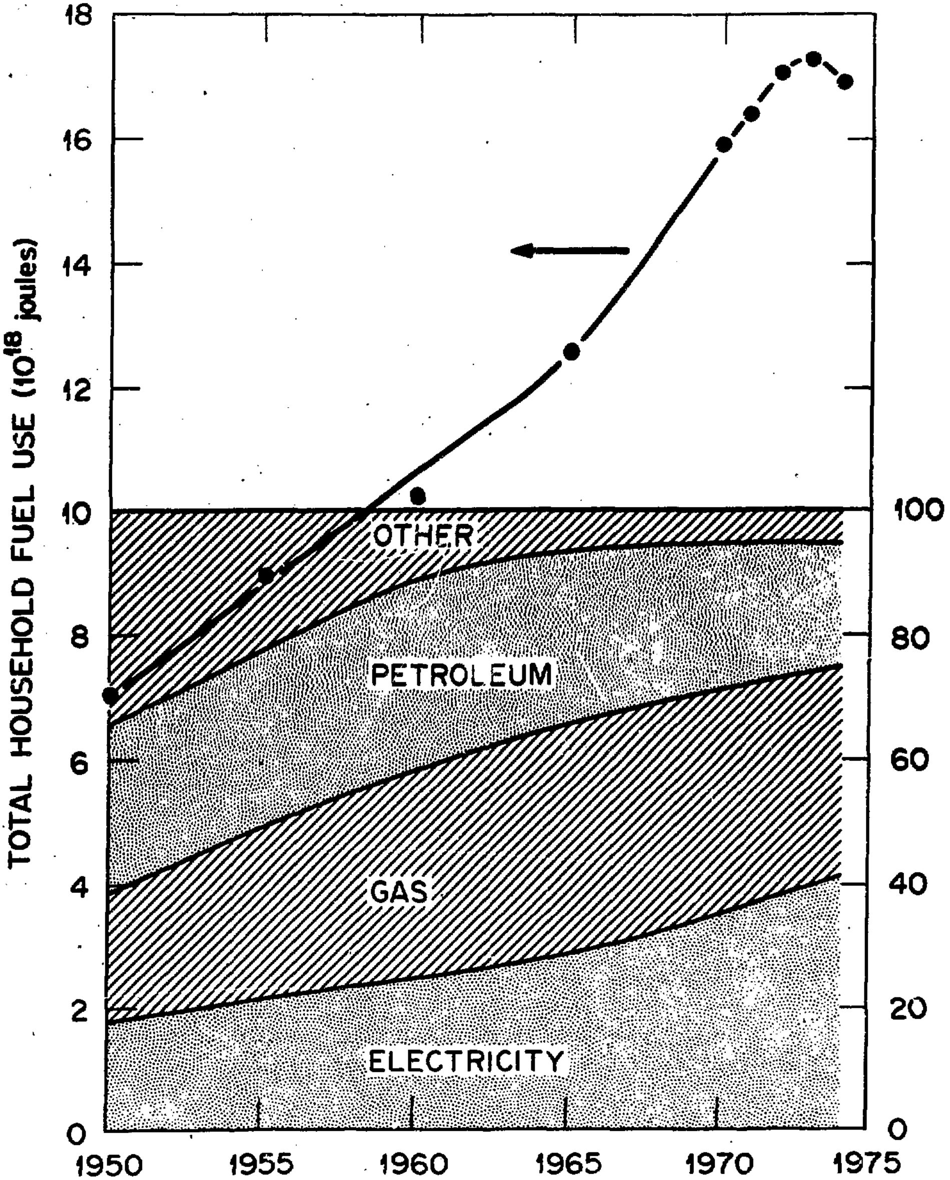

Fig. 1. Household fuel use: 1950-1974. (Electricity use figures are in terms of primary energy; that is, they include losses in generation, transmission, and distribution. Figures for gas and oil, however, do not include losses associated with refining and transportation.)

household fuels rose 27% between 1970 and 1974. In addition to the economic force of higher fuel prices, a number of institutional changes are now underway, including creation of the Federal Energy Administration, creation of the Energy Research and Development Administration, and passage of the Energy Policy and Conservation Act.

In this paper we use a comprehensive computer model of residential energy use developed at ORNL to construct and evaluate three alternative forecasts of residential energy use to the year 2000. The model, details of which are in ref. 1, simulates household fuel use at the national level for four fuels, six end uses, and three housing types. Each of these fuel use components is computed on an annual basis in response to changes in: stocks of occupied housing units and new residential construction, equipment ownership by fuel and end use, thermal integrity of housing units, average unit energy requirement for each type of equipment, and usage factors that reflect household behavior.

STRUCTURE OF THE MODEL

Figure 2 is a schematic diagram of the model. The first submodel estimates stocks of occupied housing units by type (single-family units, apartments, and trailers) for each year of the simulation. Based on calculations of household formation and retirements from the existing stock of occupied units, new construction requirements are calculated each year to ensure that the stock of occupied housing matches demand. The housing model used here was originally developed for the U.S. Forest Service [2]. It has since been modified slightly at ORNL.

The second component of the energy simulation is the elasticity estimator. This program calculates price and income elasticities* of the three major household fuels (electricity, gas, and oil) for each of the six end uses. Each elasticity is decomposed into two elements — an elasticity of equipment ownership (E_o) and an elasticity of equipment use (E_u). The first gives changes in equipment ownership in response to changes in fuel prices and incomes, whereas the second gives the responsiveness of equipment usage (with ownership held constant) to changes in prices and incomes. This submodel computes a total of 144 elasticities (short and long run for 3 fuels x 4 price and income variables x 6 end-uses).

The third submodel, shown in dashed lines, will (when complete†) calculate unit energy requirements and initial cost for residential heating-ventilating-air conditioning (HVAC) equipment, appliances, and structures. These energy and cost figures will be estimated as functions of engineering design changes to increase energy efficiency. In the present version of the model capital costs do not appear, and energy use values for each type of equipment and structure are exogenously specified.

The residential energy use simulator combines outputs from the housing, elasticity, and engineering cost submodels with appropriate initial conditions

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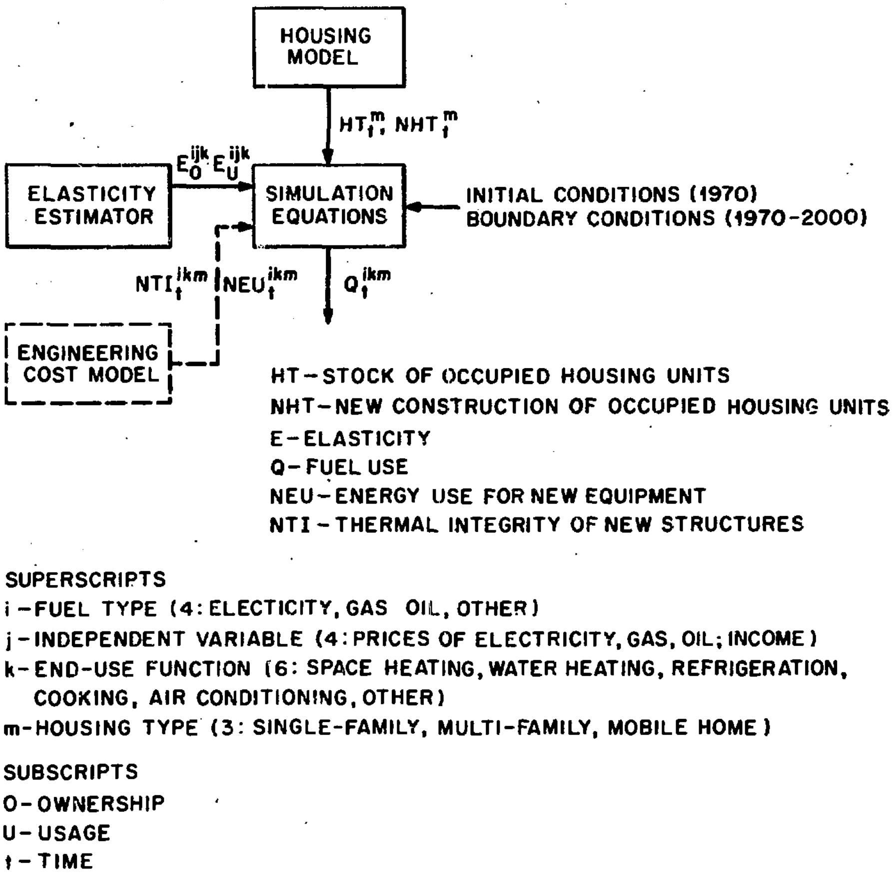
[*] Elasticity is defined as the percentage change in the dependent variable (y) due to a 1% change in the independent variable (x); that is, $E = (\Delta y/y)/(\Delta x/x)$.

[†] Energy submodels are now being developed for gas and electric water heaters, gas and electric ranges, refrigerators, and freezers.



HT – STOCK OF OCCUPIED HOUSING UNITS
NHT – NEW CONSTRUCTION OF OCCUPIED HOUSING UNITS
E – ELASTICITY
Q – FUEL USE
NEU – ENERGY USE FOR NEW EQUIPMENT
NTI – THERMAL INTEGRITY OF NEW STRUCTURES

SUPERSCRIPTS
i – FUEL TYPE (4: ELECTICITY, GAS OIL, OTHER)
j – INDEPENDENT VARIABLE (4: PRICES OF ELECTRICITY, GAS, OIL; INCOME)
k – END-USE FUNCTION (6: SPACE HEATING, WATER HEATING, REFRIGERATION, COOKING, AIR CONDITIONING, OTHER)
m – HOUSING TYPE (3: SINGLE-FAMILY, MULTI-FAMILY, MOBILE HOME)

SUBSCRIPTS
O – OWNERSHIP
U – USAGE
t – TIME

Fig. 2. Schematic of residential energy use model.

for 1970 [3,4] and boundary conditions for the period 1970 to 2000. Outputs from the simulator include 72 fuel-use components (Q_t^{ikm}) for each year (4 fuels x 6 end uses x 3 housing types).* Each fuel-use component is determined in the simulation as the product of five factors:

$$Q_t^{ikm} = HT_t^m \cdot C_t^{ikm} \cdot TI_t^{ikm} \cdot EU_t^{ikm} \cdot U_t^{ik} ,$$

where *HT* is the stock of occupied housing units, *C* is the fraction (market share) of households with a particular type of equipment, *TI* is the thermal integrity of housing units (for space heating and air conditioning only), *EU* is the average annual energy use for the type of equipment, and *U* is a usage factor (see Fig. 2).

As an example, consider consumption of electricity for space heating in single-family homes. *HT* is the stock of occupied single-family homes and *C* is the fraction of single-family homes that use electricity for heating. *TI* is

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*Many of these 72 cells are empty, for example, oil-fired refrigerators.

the average thermal integrity (scaled to 1970, $TI_{1970} = 1.0$) of single-family homes that use electricity for heating, EU is the average annual energy requirement (in J/unit) of an electric space heating system, and U is a usage factor ($U_{1970} = 1.0$) that reflects how intensely households use their electric heating systems.

Additional details concerning the structure of the model, input conditions required to operate the model, and comparisons of model outputs with historical data can be found in ref. 1.

FORECASTS

Boundary Conditions

The Bureau of the Census [5] developed three sets of household projections from 1975 to 1990. We extended their high and low forecasts to the year 2000 by fitting regression equations to their 1975 to 1990 age-dependent headship rate estimates (see Table 1). The Bureau's household forecasts are nearly independent of population forecasts, because almost all of the potential 1990 heads of households are already born; the range of populations consistent with the household forecasts is also shown in Table 1.

Table 1. Alternative forecasts of U.S. households and residential construction

	Resident population (10^6)	Households (10^6 units)		New construction[a] (10^6 units)	
		Low (C)	High (A)	Low	High
1970	204	63.4			
1975	213	71.5		2.2	2.5
1980	219-224	78.2	80.0	2.0	2.3
1985	227-240	84.7	88.5	1.9	2.4
1990	234-256	90.2	96.3	1.3	2.4
2000	244-285	100.3	108.5	1.8	2.2

[a] The construction figures given here account only for growth in households and replacement of scrapped occupied housing units; vacancy requirements are not included.

We selected the low household forecast (series C) for the baseline. However, we shall later evaluate the impacts on energy use of the series A forecast.

The housing model also requires, as input, a housing choice matrix for the year 2000. We assumed that trends between 1960 and 1970 [4] would continue to the year 2000; that is, we linearly extrapolated changes in housing choice by age of household head from 1960 through 1970 to the year 2000. The percentage of households in single-family units declines from 69% in 1970 to 61% in the year 2000; the percentages in multi-family and trailer units increase over time.

We reviewed several fuel price forecasts and selected two sets of Anderson's [6] forecasts to use with our model: a low price series (equivalent to a $5/bbl crude oil price in 1972), and a pessimistic high price series of $11/bbl (Table 2). We selected the low price series for the baseline. Later we will examine differences in fuel uses between the two.

Table 2. Assumed real fuel price and per-capita income trajectories to 2000[a]

	Electricity[b]		Gas[b]		Oil[b]		Income[c]	
	Low	High	Low	High	Low	High	Low	High
1970	1.00		1.00		1.00		1.00	
1975	1.09		1.17		1.49		1.06	
1980	1.17	1.29	1.22	1.44	1.26	2.02	1.14	1.29
1985	1.27	1.41	1.32	1.39	1.36	2.02	1.23	1.48
1990	1.41	1.57	1.43	1.55	1.47	2.02	1.32	1.71
2000	1.67	1.88	1.68	1.83	1.70	2.02	1.53	2.28

[a] The values shown here are normalized to 1970 data. Residential fuel prices in 1970 were (in 1970-dollars/GJ): electricity, 1.73; gas, 0.98; oil, 1.26. Per-capita income was $3970 in 1970.

[b] The high fuel price forecasts are based on the $11/bbl pessimistic scenario of ref. 6; the low fuel price forecasts are based on the $5/bbl scenario.

[c] In the high growth case, real per-capita income is assumed to grow at 2.9%/year; and at 1.5%/year in the low growth case.

Projections of per capita income are available from a number of large macroeconomic models: we used the BEA forecast [7] (real growth of 2.9%/year) for the baseline. We also will simulate the energy consequences of a 1.5%/year growth (Table 2).

The final sets of boundary conditions required for the baseline include changes in unit energy requirements of new residential HVAC equipment and appliances and changes in thermal integrity of residential structures. Although these values are certain to decline over the next 25 years, we assume in the baseline run that there are no technical improvements in the design and production of new equipment and structures. Another run, discussed later, shows the energy impacts of improvements in equipment and structural efficiencies.

Baseline Forecast

Figure 3 summarizes results of the baseline run from 1970 to 2000, using the boundary conditions discussed above. The model estimates that household fuel use will grow from 15.9 GGJ in 1970 to 17.6 GGJ in 1975, 19.5 GGJ in 1980, and 26.4 GGJ in 2000. The average annual growth rate from 1975 to 2000 is 1.7% (compared with 3.7% from 1950 to 1970 and 1.5% from 1970 to 1974). Energy use per household during this 25-year period is projected to grow at 0.3% annually (compared with 1.7% from 1950 to 1970 and -1.0% between 1970 and 1974).

Thus household fuel use is projected to grow more slowly than it did during the past 25 years but more rapidly than during the past few years. The growth in energy use forecast to the year 2000 is slower than the 1950 to 1970 historical trend because of higher and rising fuel prices and slower growth in household formation assumed for the forecast period.

Figure 4 shows changes in the distribution of fuels from 1970 to 2000. Electricity consumption grows at 2.7% annually, while gas and oil grow at only 1.0 and 0.5% annually. Thus the percentage of total household fuel provided by electricity grows from 35% in 1970 to 56% in 2000. The percentages provided by all other fuels decline over time.

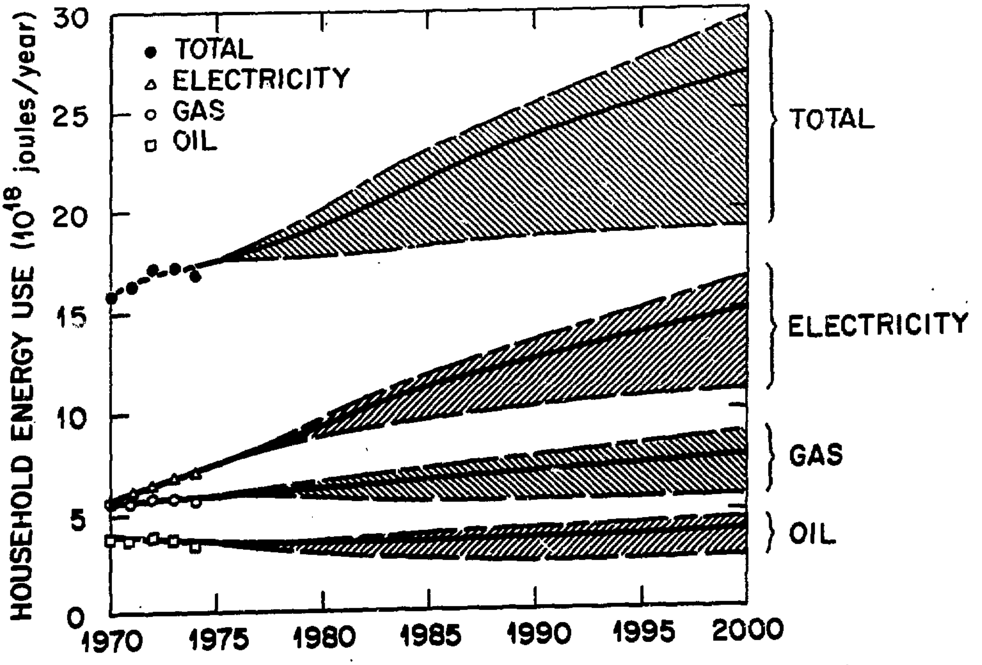

Fig. 3. High, baseline, and low forecasts of household fuel use.

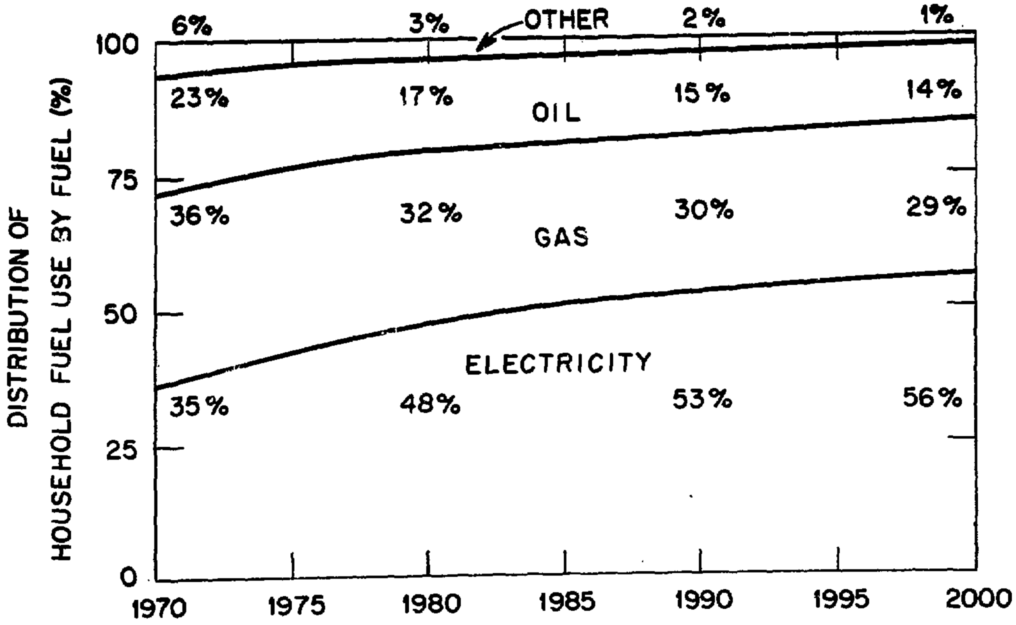

Fig. 4. Baseline forecast distribution of household fuel by fuel.

The distribution of fuel use by housing type changes slightly during this period. The percentage consumed in single-family units declines from 78% in 1970 to 71% in 2000. The percentages consumed in multifamily units and trailers increase from 19% and 3% respectively in 1970 to 23% and 6% in 2000.

The distribution of household fuel by end use also changes over time (Fig. 5). Space heating (the largest end use during the entire 30-year period) declines from 56% to 49% of the total. Air conditioning, on the other hand, increases its share of the total from 4% to 11%. Other end uses remain fairly constant as percentages of the total.

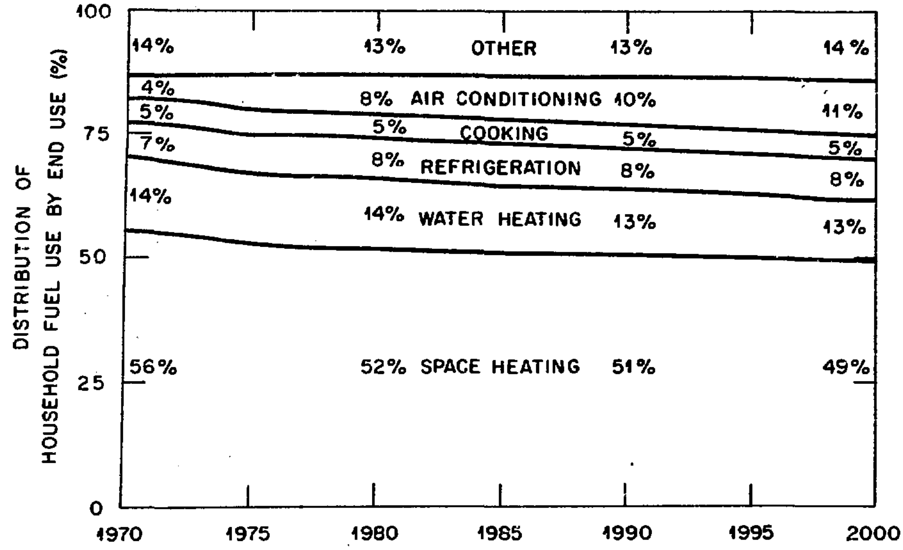

Fig. 5. Baseline forecast distribution of household fuel by end use.

Figure 6 shows the baseline forecast of residential fuel expenditures (in terms of constant 1970 dollars). Total expenditures grow from $21 billion in 1970 to $29 billion in 1975 and $65 billion in 2000. The annual growth rate in household fuel expenditures averages 3.3% between 1975 and 2000, less than the 3.8% average annual growth in total personal income. Thus the impact of rising incomes more than offsets the impact of rising fuel prices on overall household fuel expenditures.

Alternative Forecasts

A forthcoming ORNL report will present detailed analyses of several energy conservation policies and programs and their impacts on residential fuel use and expenditures to 2000. For this paper, we present only two alternative forecasts. The "high" forecast uses the same boundary conditions as does the baseline, except that household growth is assumed to increase according to the census series A forecast (see Table 1). Also, the high forecast assumes that the housing choice matrix remains unchanged from its 1970 values. Thus the fraction of households occupying single-family structures is greater in the high forecast than in the baseline.

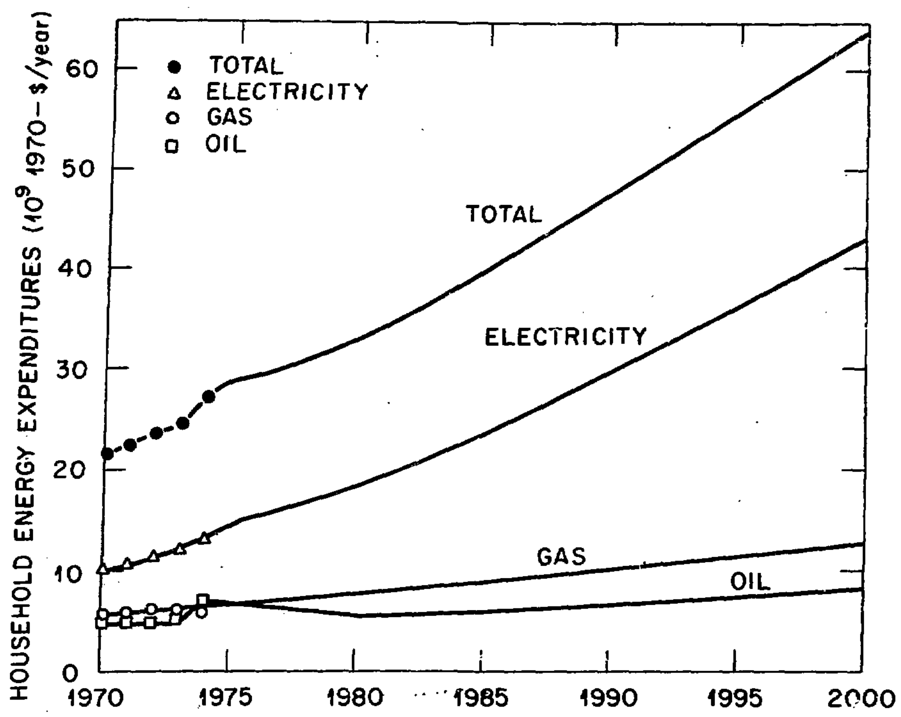

Fig. 6. Baseline forecast of household energy expenditures.

The "low" forecast uses the same inputs on household formation and housing choice as the baseline does. However, it assumes that per capita income grows at only 1.5%/year from 1975 to 2000 and that fuel prices grow more rapidly than in the baseline (see Table 2). The low forecast also assumes that unit energy requirements for all new equipment decrease over time. The schedule chosen roughly approximates the 1975 Department of Commerce voluntary targets [8] for 1980 with continued, but slower, improvements from 1980 to 2000 (see Table 3). Thermal integrity of all new structures is assumed to improve as shown in Table 3, roughly corresponding to implementation of the ASHRAE 90-75 standards [9] in 1980. Finally, retrofit standards are assumed to start in 1976, applied to all single- and multi-family housing units constructed before 1973; 10% of the single-family and 5% of the multifamily units still in use and not yet retrofitted are affected by the standards each year. The standards are set at half their values for new construction. No retrofit standards are applied to mobile homes because of their short lifetime.

Major outputs from the high, baseline, and low forecasts are shown in Fig. 3. Growth in total household fuel is positive in all three forecasts; however per household fuel use declines in the low forecast by about 1% annually. The high forecast of 29 GGJ in 2000 is 11 GGJ (58%) higher than the low forecast for that year. Thus the range of forecasts due to different boundary conditions is considerable. Cumulative fuel use between 1975 and 2000 is 603 GGJ in the high case and 456 GGJ in the low case; thus the high forecast requires 32% more fuel (in aggregate) between now and 2000 than does the low forecast. In the high forecast, household fuel expenditures reach $72 billion (1970-dollars) in 2000, almost 40% more than the $52 billion in the low forecast. Differences among forecasts in distribution by fuel and by end use are insignificant.

Table 3. Assumed improvements in energy requirements for new equipment and thermal integrity for new structures (1970 = 1.0)

	1975	1980	1990	2000
Space heating equipment				
Electric	1.0	0.90	0.85	0.80
Gas	1.0	0.75	0.65	0.55
Oil	1.0	0.75	0.65	0.55
Water heating equipment				
Electric	1.0	0.90	0.86	0.82
Gas	1.0	0.75	0.65	0.55
Oil	1.0	0.85	0.79	0.73
Refrigerators	1.0	0.70	0.58	0.46
Cooking equipment				
Electric	1.0	0.90	0.86	0.82
Gas	1.0	0.70	0.58	0.46
Air conditioning equipment	1.0	0.80	0.72	0.64
Other equipment	1.0	0.90	0.86	0.82
Single-family units				
Space heating	1.0	0.84	0.84	0.84
Air conditioning	1.0	0.95	0.95	0.95
Apartments				
Space heating	1.0	0.54	0.54	0.54
Air conditioning	1.0	0.85	0.85	0.85
Trailers				
Space heating	1.0	0.84	0.84	0.84
Air conditioning	1.0	0.95	0.95	0.95

Figure 3 shows that high growth in personal income, rapid household growth, continued patterns of household choice that favor single-family units, and no improvements in either technical efficiency of household equipment or thermal integrity of residential structures are likely to yield a growth in total household fuel use of at least 2%/year; thus, household fuel use in 2000, under these assumptions, will be approximately two-thirds greater than 1975 fuel use.

Slower growth in personal income, higher increases in fuel prices, slower household growth, continuation of the 1960 to 1970 trends in housing choice (shifts to apartments and trailers), significant improvements in technical efficiencies of household equipment, and improvements in thermal integrity of both new and existing structures are likely to yield only a slight growth in total household fuel use (and a decline in per household fuel use); under these assumptions, fuel use in 2000 might be no more than 10% above 1975 household fuel use.

CONCLUSIONS

The model discussed here provides detailed forecasts of national annual energy use in the household sector for four fuels, six end uses, and three housing types. To calculate each of these fuel use components, the model computes stocks of occupied housing units (and new construction) by type, equipment market-shares by fuel for each end use, average thermal integrity of occupied housing stocks, average unit energy requirements by type of equipment, and usage factors that reflect household behavior. Thus the model is sensitive to the major demographic, economic, and technological determinants of household fuel use.

The baseline forecast developed here shows aggregate household fuel use growing from 17.6 GGJ in 1975 to 26.4 GGJ in 2000, with an average annual growth rate of 1.7%. Demand for electricity grows at 2.7%/year during this period, while demands for gas and oil grow at only 1.0% and 0.5%/year respectively. Fuel expenditures grow from $29 billion in 1975 to $65 billion in 2000 (in 1970 dollars), with an average annual growth rate of 3.3%. The high forecast shows fuel use growing at an average annual rate of 2.1%, while the low forecast shows a growth of only 0.3% annually. This dramatic difference in fuel use — 29 and 18 GGJ in the year 2000 — is due to the differences in the assumed boundary conditions regarding household growth, housing choice, fuel prices, incomes, equipment efficiencies, and structural integrities.

Table 4 shows the influence of the demographic, economic, and technological factors discussed here on differences between the high and low forecasts. Energy use in the low case is 36% less than in the high case for the year 2000, and 24% less in terms of cumulative (1976-2000) energy use. These numbers show that the dynamics of residential energy use are such that responses to exogenous changes take many years to reach their full values. These lags are due to the long lifetimes for residential structures, appliances, and equipment.

Table 4. Contributions to residential energy use reductions

	Change in energy use	
	2000	cumulative
Slower household growth	18%	19%
Changes in housing choices	8	8
Fuel price increases	11	16
Slower income growth	18	15
Thermal integrity increases	7	9
Improvements in equipment efficiencies	38	33
Overall change in household fuel use: low/high forecasts	36%	24%

Demographic factors (household formation and housing choices) account for slightly more than 25% of the overall difference in energy use between the high and low cases. Economic changes (fuel price increases and slower growth in per capita income) account for about 30%. Improvements in thermal integrity for new and existing structures account for less than 10%; and improvements in equipment efficiencies account for about 35% of the total change in fuel use.

These three forecasts suggest the following general conclusions concerning residential energy use growth to the year 2000:

1. Residential energy use will almost surely grow at a slower rate during the fourth quarter of this Century than it did during the third quarter. The high forecast produced here shows a growth of 2.1%/year, compared with a growth of 3.7%/year from 1950-74 (Fig. 1). Thus, energy use in the year 2000 is likely to be less than 30 GGJ, about 14 GGJ less than would occur if residential energy use continued to grow at 3.7%/year.

2. Residential energy use is likely to grow at an even lower rate than the high forecast considered here. Slower growth in household formation and a continuation of the 1960-70 trend in housing choices might yield a fuel use growth of 1.7%/year (our baseline forecast). In this case, energy use in the year 2000 will be 26 GGJ. This baseline forecast suggests that energy use might grow at about half its historical rate. Thus a great deal of energy will be "conserved" because of projected changes in demographic conditions and increases in fuel prices (relative to trends from 1950-74).

3. Implementation of energy conservation programs to increase efficiency of new household equipment and improve thermal integrity of housing units can have significant energy impacts. A vigorous conservation program — including such technical improvements plus higher fuel prices — might yield a growth in fuel use of only 0.3%/year to 2000, as shown in the low forecast. These changes yield an energy use in the year 2000 that is only slightly higher than present energy use, less than half the value that would be obtained if energy use grew at its 1950-74 historical growth rate.

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GLOBAL ENERGY DEMAND AND RELATED CLIMATE CHANGE

Ralph M. Rotty

Institute for Energy Analysis
Oak Ridge Associated Universities

It is relatively obvious that climate fluctuations and longer-term climate changes affect energy-use patterns, but it is perhaps less obvious that the energy use by man may be having, and in the future is almost certain to have, far-reaching consequences on the climate itself. These changes in climate will be on local, regional, continental, and global scales.

Because climate is the result of energy exchange between the sun and the earth, the earth and outer space, and of the interchanges of energy between parts of the earth, it is necessary to understand how anthropogenic releases of energy from long-term storage might influence and alter the natural exchanges in sufficient magnitude to cause an observable change in climate. I believe, and most climatologists seem to agree, that there are four ways that the natural energy transfer system can be perturbed and thus initiate climate changes. These are:[1]

1. A change in the total amount of energy being exchanged - either that coming from the sun (probably not controllable by man) or that leaving the earth (which is augmented by man).
2. A change in the albedo resulting from changes in atmospheric aerosols and particulate loading.
3. A change in the albedo resulting from changes in cloud cover.
4. A change in the optical properties of the atmosphere with change in carbon dioxide.

In connection with the first of these - increasing the total energy flux from the terrestrial system - it is instructive to note the magnitude involved. Current global consumption of commercial energy is about 200 quads/yr (1 quad = 10^{15} BTU). The solar energy impinging on the top of the atmosphere is 5 x 10^{21} BTU/yr, and the amount reaching the earth's surface is about

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Given as testimony before the Subcommittee on the Environment and the Atmosphere of the House Committee on Science and Technology (Hearing on H. R. 10013), Washington, D. C., May 19, 1976

2.5×10^{21} BTU/yr. Thus, the anthropogenic release (at the earth's surface) is one hundredth of one percent (10^{-4}) of the natural energy exchange at the surface. This seems to be insufficient to disturb the quasiequilibrium state of "climate". However, if one considers past and anticipated global energy growth patterns, the picture may not offer much grounds for complacency. For more than one-hundred years, the global use of commercial forms of energy has been growing at an annual rate of over 5 percent. The recent slackening of this growth rate is much less than other temporary interruptions during the past 100 years, and continued growth is <u>almost</u> certain. Assuming an average future growth rate of 4.5 percent - which is perhaps too high for the developed countries of the world, but probably low for the developing ones - the present 200 quads/yr would grow to 20,000 quads/yr (2×10^{19} BTU/yr) in the next 100 years. If the energy growth rate is less, it takes longer to reach 20,000 quads/yr level - 3 percent annual growth requires 150 years. Increasing global population will demand increased energy use, and whether demand levels off below 10,000 quads/yr or continues exponentially indefinitely, man-released energy will reach levels which will influence the natural energy exchange at the surface.

Assuredly a one percent increase in the <u>average</u> energy flux at the earth's surface would cause very significant changes in global climate. Before that, quite major changes in local and regional climate can be expected. The nature of these changes, their magnitudes, and their impacts on the capacity of the world to feed the human population are unknowns. Until we have a better fundamental understanding of climate, the questions suggested by changing the flux of energy in the atmosphere will remain unanswered.

The problem of aerosol effects on global climate[1] can be looked at this way: considering the earth as a whole, the warming effect of the sun is a function of the reflectance (albedo) of the earth at solar wavelengths. A black earth would reflect little solar radiation, and the climate would be relatively warm, a white earth would reflect a great deal of solar radiation, and the climate would be relatively cool. Now, if a white aerosol cloud is injected into the atmosphere above a black earth, it is clear that the effective brightness (albedo) of the earth-aerosol system would be increased and the overall planetary temperature would be lowered. Conversely, if a black aerosol is injected above a white earth, the effective brightness of the system would be decreased and the overall temperature raised. In the case of real aerosols injected into the real atmosphere above the real earth, there is, of course, no black or white but various shades of grey. When greay aerosols overlie a grey earth, their thermal effects are obviously smaller and not necessarily discernable except through very careful measurements.

The direct influence of energy demands on the concentration of atmospheric particulates and aerosols is probably less than that of other anthropogenic activities, such as forest clearing, modern agriculture, and urbanization. With the possible exception of dust from strip mining activities, most of the particulates and aerosols associated with energy industries do not remain in the atmosphere very long nor are they transported over great distances. To be sure, the oxides of sulfur, the unburned hydrocarbons, the partically oxidized combustion products, and particulates from power plants and industrial boilers cause pronounced and unpleasant local consequences, especially under certain atmospheric conditions. Although these present problems require intensified study of a type which could be included under the proposed "climate program", they are not of the type that greatly influence the natural energy transfers in the global system.

Requirements for energy in particular forms may influence the amount and type of cloudiness, but the physical details of these processes and their effects on the fundamental global energy balance, and hence climate, are not understood. Enhanced fog and cloudiness from evaporative cooling of energy systems appear now on a local scale, but predictions of changes in the amount and distribution of global cloudiness and the nature and magnitude of the resulting climate change are beyond present understanding. Some scientists have suggested that effects of changes in cloud type and amount will be more important than those from any other man-induced change, but this remains a major unknown.

The fourth way climate can be influenced by global energy demand depends on the capacity of carbon dioxide to absorb long wave length terrestrial radiation - the "greenhouse effect". Fossil fuel deposits provide energy used in the past century, that being used today, and that which probably will be used during the next century. When fossil fuels are burned, carbon dioxide is produced. The increasing use of fossil fuels and the consequent carbon dioxide releases are indicated in Figure 1.[2,3] (About 2 percent of the total is from cement manufacture.) Evident in the figure is the slowing of global industrial growth during the periods of the world wars and the great depression of the early nineteen-thirties. It is remarkable that the slope of the line fitting the points has remained nearly constant before and after the interruptions. How long can the production of carbon dioxide continue to grow at 4.3 percent per year?

Of greater importance in the present context is the question: what is this growth doing to the concentration of carbon dioxide in the atmosphere? Beginning in 1958 observers at the Mauna Loa Observatory in Hawaii have monitored atmospheric carbon dioxide content. According to the 1975 measurements, the average CO_2 concentration in the atmosphere is now about 330 ppm, compared with the pre-industrial value of 290-295 ppm[4]. These measurements show annual increases for each year during the period of record, averaging about 0.7 ppm during the later 1950s and early 1960s and up to 1.0 ppm or more in recent years. Recent analyses of the data at the Institute for Energy Analysis (as yet unpublished) suggest the observed increases show exponential growth similar to the CO_2 production from fossil fuels.

The Mauna Loa data are not alone in showing this buildup of atmospheric carbon dioxide. Figure 2 shows measurements made at four different locations, from 73°N to 90°S.[5,6,7,8,9,10] There are differences in the measuring instruments and in calibration techniques, so one cannot compare absolute concentrations between these series to deduce a variation with latitude; but in all cases the upward trend is strongly evident.

Seasonal variations are also clear with the amplitude larger at the most northern stations. Growing seasons and the melting cycles of sea ice have been suggested to explain the cycles and the larger amplitudes in the north compared to the south.

About 54 percent of the carbon dioxide produced from fossil fuels (Figure 1) is accounted for in the atmospheric increases of Figure 2. The record from 1959 through 1974 shows considerable variation in the fraction of produced CO_2 that remains in the atmosphere with a slight tendency toward larger fractions remaining airborne in the later years. These year-to-year fluctuations in airborne fraction indicate that the effectiveness of natural reservoirs (which exchange CO_2 with the atmosphere) fluctuates as other conditions change, e.g., quality and length of growing season or abnormal temperatures and currents in the upper layers of the ocean.

Because of the fluctuations, it is informative to look at the cumulative effect. In Figure 3 the cumulative production of CO_2 is plotted.

The upper curve indicates the increase in the carbon dioxide fraction of the atmosphere that would have occurred if all CO_2 produced since 1957 from fossil fuels and cement had remained airborne. The lower curve represents the observed increase in atmospheric CO_2 concentrations at the Mauna Loa Observatory. On the average about 54 percent of the CO_2 produced from fossil fuels since 1957 remained airborne.

As indicated above, CO_2 in the atmosphere affects the thermal radiative balance of the planet and therefore the global climate. This effect has been incorporated into models of the climate developed by Rasool and Schneider,[11] Manabe and Wetherald,[12] Ramanathan,[13] Sellers,[14] and others. Although the predictions of the models vary, critical examination by Schneider[15] of the existing models suggests "a global average surface temperature increase of 1.5 to 2.4°K" if the CO_2 concentration in the atmosphere doubles. However, Schneider conceded that "This estimate may prove to be high or low by severalfold". <u>This uncertainty must be reduced</u>.

An increase in average temperature of 1.5 to 2.4°K represents a major change in the global climate, but with largely unknown details. For example, more significant than the average temperature is the distribution of atmospheric temperature changes (Figure 4 from Manabe and Wetherald[12]) determined by a general circulation model, but without including cloud feedback and atmosphere-ocean interactions. The cooling of the stratosphere and especially the pronouned warming near the surface in higher latitudes are highly significant. The effects of warming the earth's surface north of 70°N by more than 7°K will be extreme. The model shows that the sea ice would retreat and the warming effect in this region would be reinforced because open water absorbs more of the incoming solar radiation than ice does.

Can we predict when the CO_2 concentration might reach alarming levels? The definition of "alarming levels" will depend heavily on greater climatological knowledge than we now

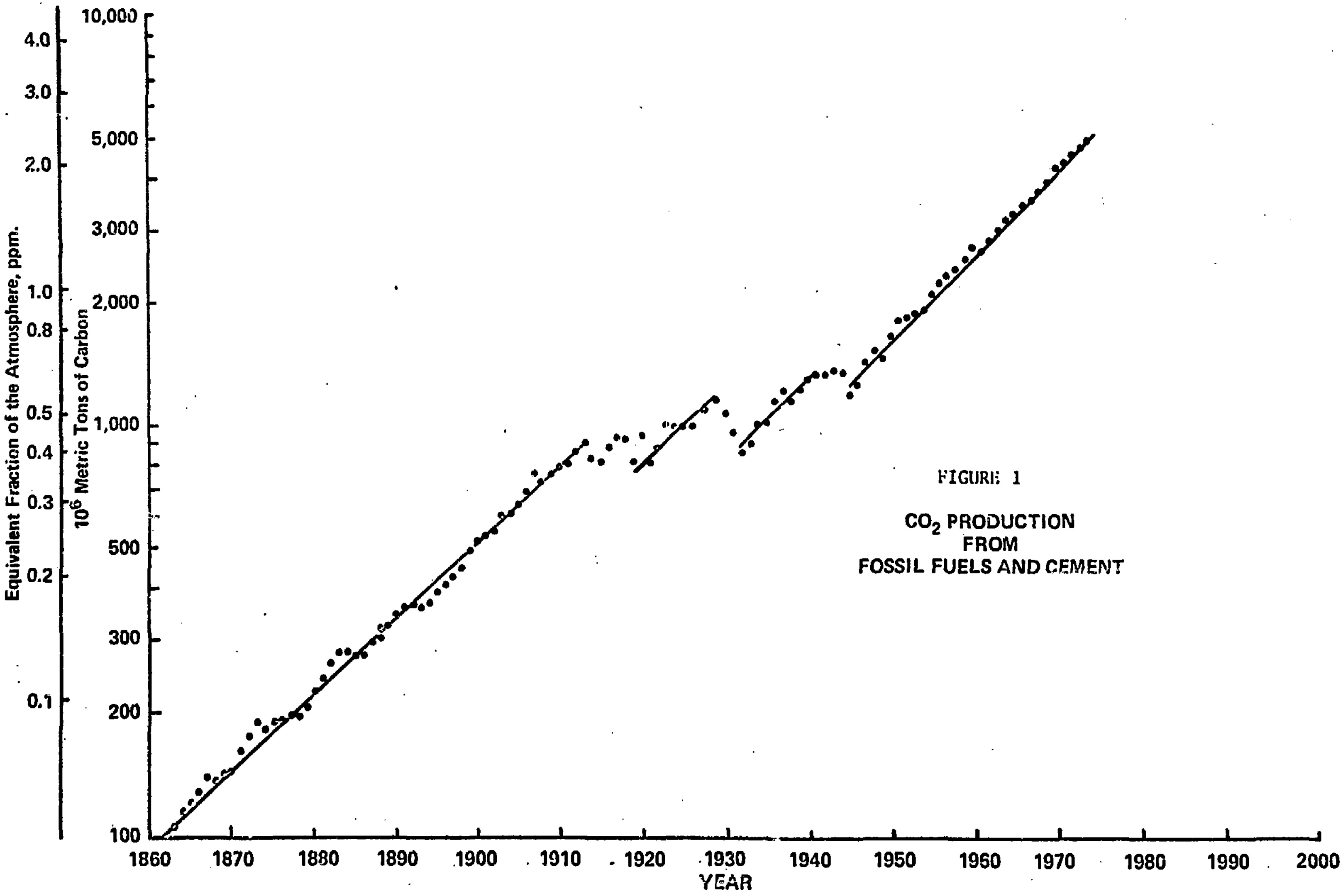

FIGURE 1

CO$_2$ PRODUCTION
FROM
FOSSIL FUELS AND CEMENT

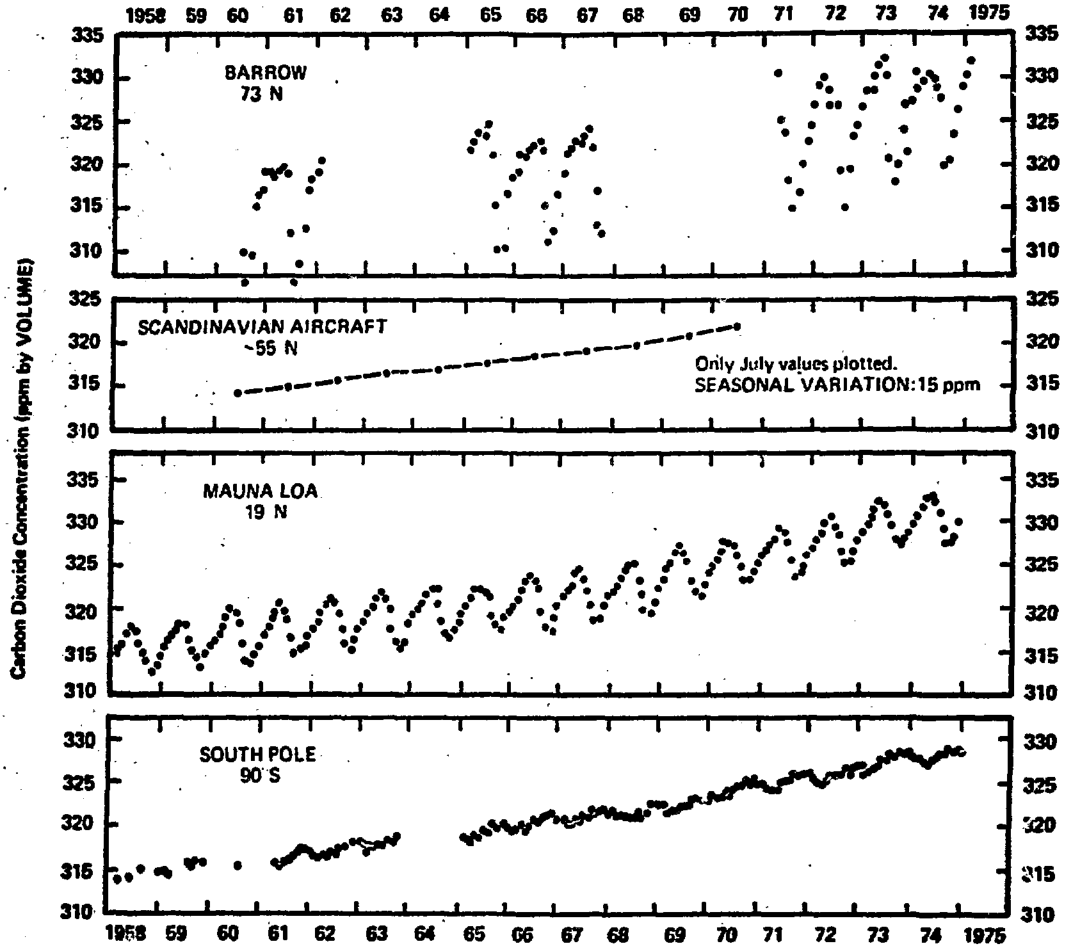

Figure 2

ATMOSPHERIC CONCENTRATION OF CARBON DIOXIDE

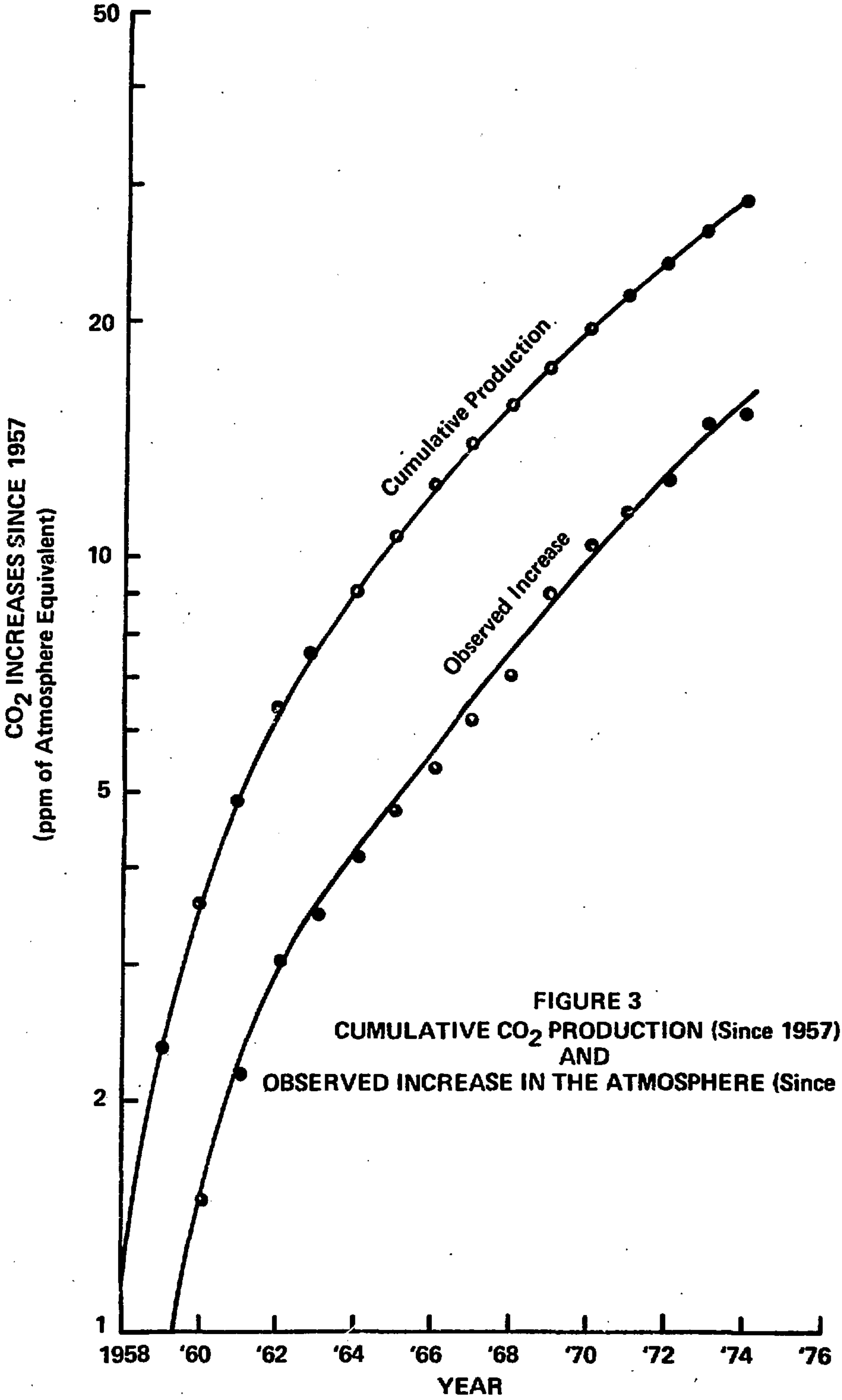

FIGURE 3
CUMULATIVE CO_2 PRODUCTION (Since 1957)
AND
OBSERVED INCREASE IN THE ATMOSPHERE (Since 1957)

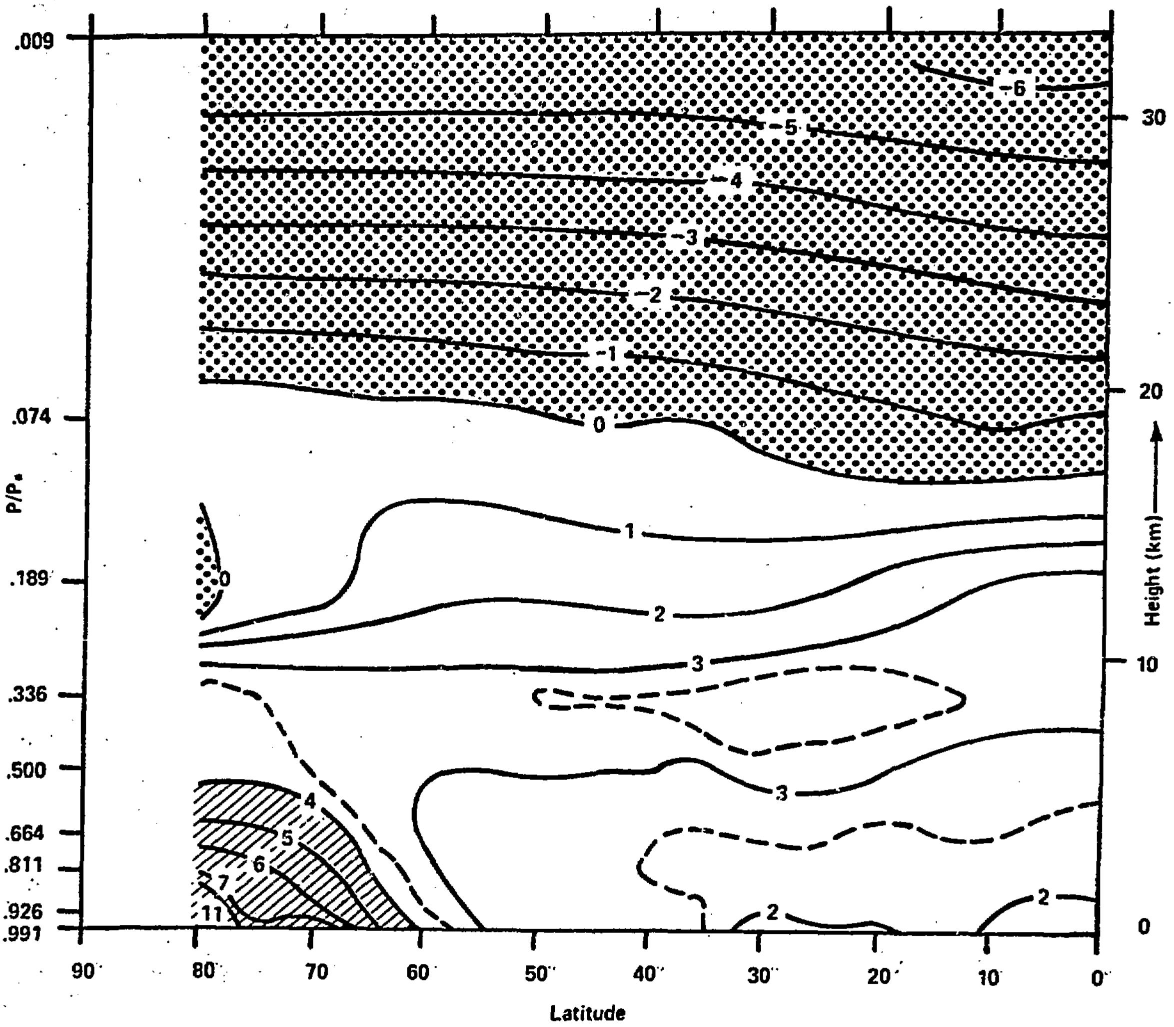

Figure 4
TEMPERATURE CHANGE DUE TO DOUBLING CO_2 CONCENTRATION IN AIR
(Data from Manabe.)

have, and the time of reaching a given concentration of CO_2 in the atmosphere will depend heavily on future fossil fuel use.

Figure 5 indicates possible future CO_2 production from fossil fuel use patterns as determined from an assumed mathematical expression:

$$\frac{1}{N}\frac{dN}{dT} = 0.043 \left(1 - \frac{N}{N_\infty}\right)^A$$

where: N is a function of time t and represents the total amount of CO_2 produced from fossil fuel use up to that time.

N_∞ is the quantity of CO_2 which would be produced from all of the fossil fuel ultimately recoverable. ($\approx$3500 ppm).

A is a variable quantity to place more or less emphasis on the fraction of recoverable fossil fuels remaining (to be used).

The quantity, $(1 - \frac{N}{N_\infty})^A$, which is always between 0 and 1, enables the cumulative use function to reflect reduced rate of use as the resource is depleted and the costs rise. The historical fossil fuel use (indicated by the open circles) falls on the curve; since $(1 - \frac{N}{N_\infty})$ is so nearly equal to 1.0 up to 1975 the exponential fit is excellent. The curve with A = 1 might represent "free and easy" access to remaining reserves along with early exhaustion of those readily available. The curve with A = 4 might represent lowered demand scenarios for fossil fuels resulting from early extensive reliance on solar, nuclear, and other sources, or on high prices resulting from governmental actions, (cartels, etc.).

Also indicated in Figure 5 by the shaded area is the range of CO_2 production between now and 2025 as predicted by scenarios of future energy demand developed at the Institute for Energy Analysis. The lower limit of the shaded band assumes low energy growth in the U. S. and other highly developed countries and also assumes a high fraction of global energy demands (35%) are met by nuclear (or other non-fossil) sources. The upper limit assumes heavier reliance on fossil fuels (only 5% of total global energy from nuclear sources) and a higher U. S. demand for energy. (In general, the IEA energy projections for the U. S. are lower than those of most others, hence the shaded area of Figure 5 might be regarded as "conservative.")

The projected cumulative production of CO_2 along with the resulting increase in the observed atmospheric concentration is shown in Figure 6, which should be considered as a continuation of Figure 3. The curves labeled A = 1, A = 2, A = 4 in Figure 6 are based on the corresponding curves of production rate shown in Figure 5, but Figure 6 gives the cumulative amount of CO_2 released from fossil fuel storage since 1957. The indicated points are actual amounts produced and observed (same as Figure 3)

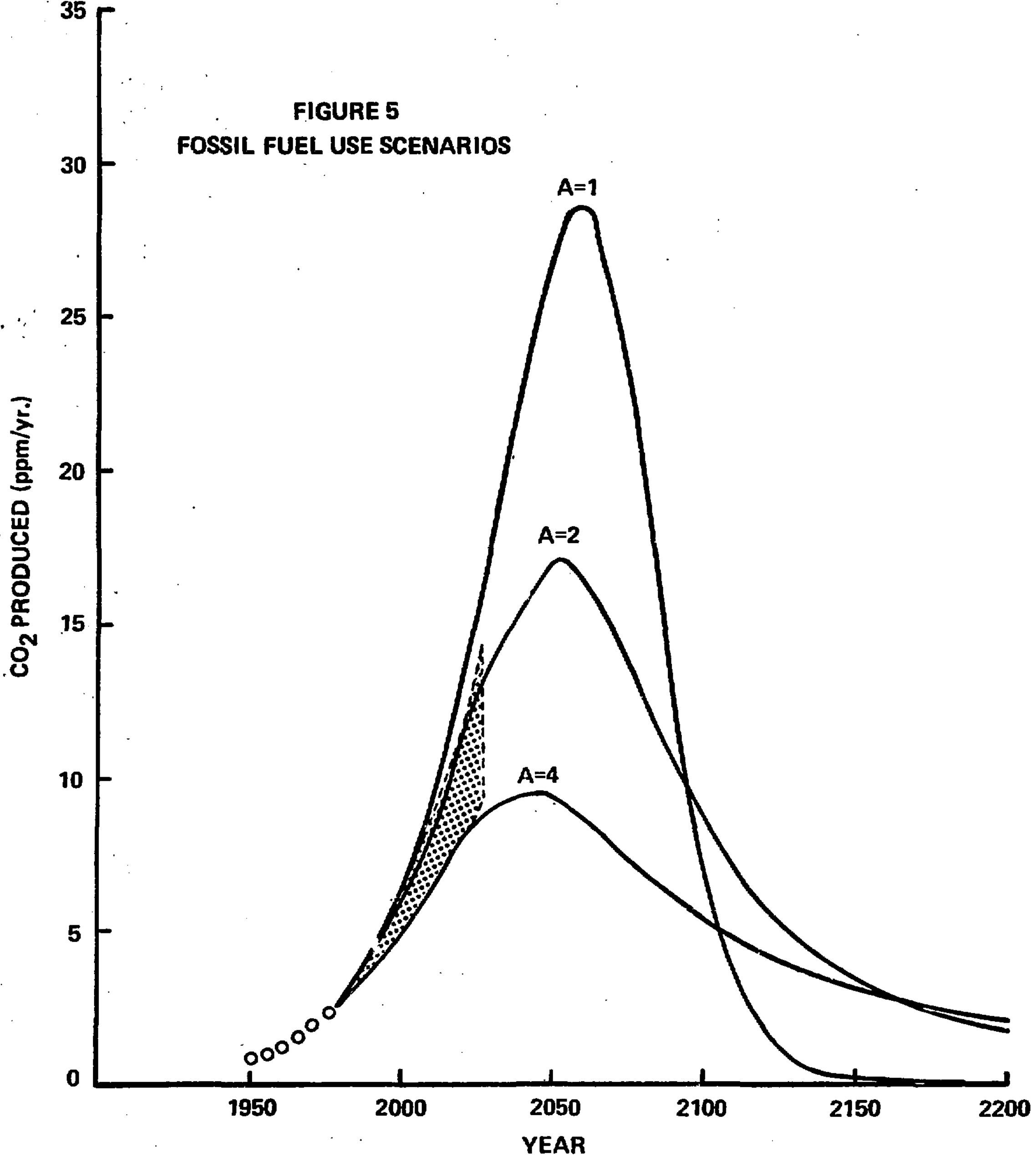
FIGURE 5
FOSSIL FUEL USE SCENARIOS
A=1
A=2
A=4
dN/dt
CO₂ PRODUCED (ppm/yr.)
35
30
25
20
15
10
5
0
1950
2000
2050
2100
2150
2200
YEAR

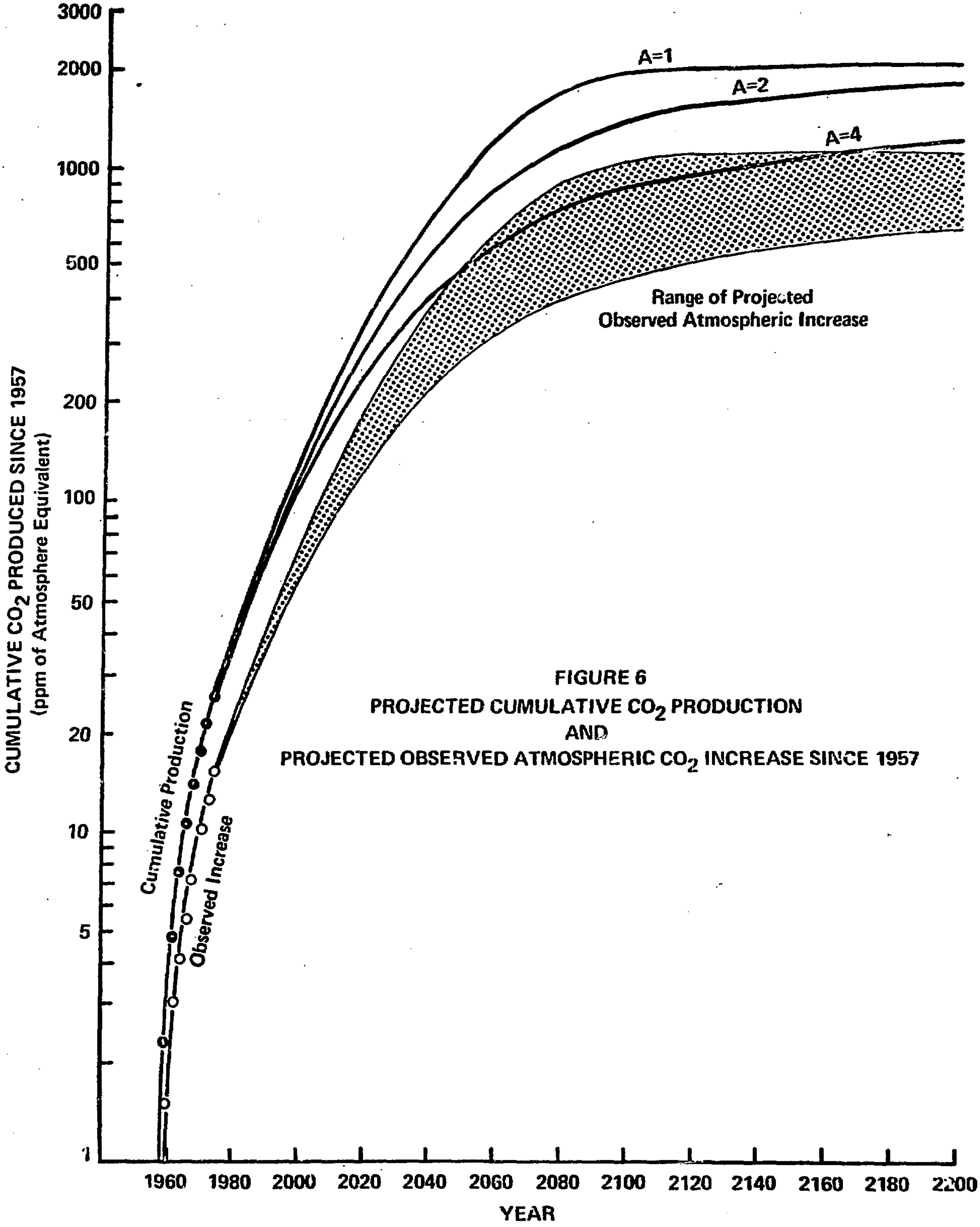

FIGURE 6
PROJECTED CUMULATIVE CO_2 PRODUCTION
AND
PROJECTED OBSERVED ATMOSPHERIC CO_2 INCREASE SINCE 1957

while the lines for years subsequent to 1975 are based on the use of patterns of Figure 5. The shaded area represents an extrapolation of the observed atmospheric CO_2 increases (based on the continuing 54 percent atmospheric retention of that produced).

Figure 6 suggests that the time when the atmospheric CO_2 concentration will become crucial is early in the twenty-first century. The figure suggests for AD 2000 an increase of 62 to 73 ppm over the 1985 value of 315 ppm. Atmospheric concentration of 375 to 390 ppm may well be a threshold range at which climate change from CO_2 effects will be separable from natural climate fluctuations; increases of 150 to 225 ppm by 2025 (concentrations of 465 to 540 ppm) should certainly result in recognizable climate changes. Even with the larger uncertainty in estimating the climate change attendant with CO_2 increases, it is evident that the increase in average global temperature from CO_2 will be 20 to 30 times greater than the warming required to eliminate the additional heat flux by radiation to space.

A better understanding of climate is required decades in advance of the possible climatic consequences to permit the orderly shift to energy systems not heavily dependent on fossil fuels. At least two decades lead time is required for effective transition to alternative energy forms in transportation, electric generation, residential and commercial space heating, construction and other industries, etc.

In summary, these are four ways in which growth in energy demand will affect the climate, but of these four the probable increase in concentration of atmospheric carbon dioxide from the burning of fossil fuels has by far the most severe global implications for all of mankind. The immediacy of the problem and the formidability of evaluating the climatic implications require major action.

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SOME GEOLOGICAL AND POLITICAL CONSIDERATIONS REGARDING FUTURE PRODUCTION OF DOMESTIC FOSSIL FUEL ENERGY RESOURCES

by

Serge Gonzales

Institute of Community and Area Development and Department of Geology

The University of Georgia
Athens, Georgia 30602

Abstract

This paper summarizes the current contribution of domestic crude oil, natural gas and coal to the production of energy in the United States. It also discusses the economic, political and societal climate which has emerged in reference to energy since the 1973-74 crude oil embargo.

Also considered is the future potential of domestic, conventional petroleum resources with an emphasis on measures to promote more aggressive exploration in frontier areas and more application of enhanced recovery. The natural gas situation receives treatment in regard to declining reserves, pricing problems, inadequate foreign supplies and several unusual, potential sources such as coal-seam bleedoff and the artificial fracturing of shales. The potential and problems confronting coal development are also reviewed, and the possible production of synthetic hydrocarbons from coal is discussed.

Comments on the status of oil shale and tar sands development conclude the paper. Recommendations for both economic and political policy changes are made throughout the discussion, and include support for various mandatory conservation measures.

Introduction

Less than two years ago, the United States was in the midst of a major energy crisis, largely precipitated by the embargo on imported crude oil as rendered by the Middle East nations of the Organization of Petroleum Exporting Countries (OPEC). In the intervening time, there has been a measurable increase in our national interest about energy and energy resources. Conferences devoted to every conceivable aspect of energy have proliferated; the revamped federal Energy Research and Development Administration has moved forward on a variety of energy-research fronts; and, much political rhetoric, advertising and industry pleas have been directed toward increased efficiency in energy use and energy conservation. At the midpoint of 1976, exactly where does our supposedly increased concern about this country's energy posture stand? Although there certainly are some rays of encouragement, the picture remains largely pessimistic.

Within that context, this paper considers the role that geological energy resources presently play in our domestic energy situation, and the possible impact that these same resources may be expected to have in our future energy picture. Closely related to these geological considerations are several important energy policy issues which must be addressed within the near term if the United States can ever hope to become less energy consumptive and less reliant on foreign sources of petroleum.

Current U. S. Energy Situation

A review of the status of energy use in the preceding year of 1975 and certain trends and projections for 1976 is instructive at this point. Compared to the pre-embargo year of 1973, energy use within 1975 was clearly less, especially in the industrial sector (Table I). This overall reduction can be jointly attributed to the higher costs of fuels, especially those based upon crude oil, the general economic downturn experienced by the nation, some conservation efforts and improvements in energy-use efficiency, especially within industry, and to a lesser degree in automotive based transportation.

Table I. Principal U. S. Energy Markets Expressed In Millions of Barrels of Daily Oil Equivalent

Sector	1973	1974	1975
Transportation	9.2	9.0	9.1
Residential-Commercial	6.4	6.1	6.1
Electric Utilities	9.2	9.2	9.4
Industry	11.3	10.9	9.7
Totals	36.1	35.2	34.3

(after Emerson and Shuttlesworth, 1976)

Nevertheless, the national use of energy still heavily relied upon geologically formed "fossil fuels." Of all the energy consumed in the United States during 1975, some 75 percent was derived from petroleum (crude oil and natural gas), while another 19 percent was attributable to coal. Hydroelectric stations provided another 4 percent, and nuclear-electric plants fueled with uranium recovered from geologic deposits accounted for only 2+percent.

Casting an ominous tone over these statistics was a continuing and expanded dependence on foreign sources of petroleum, namely crude oil and products refined from it. Foreign supplies accounted for 37 percent of our national oil demand, while 4 percent of the natural gas consumed came from either Canada and Mexico via pipeline or from Algeria in the form of liquefied natural gas (LNG). Even though the usage of energy in 1975 had declined nearly 5 percent compared to 1973, our national dependency upon imported oil had risen 2 percent. Also of significance was the fact that more than 30 percent of all imported crude oil and oil products came directly or indirectly from the Middle East sector of OPEC.

Data and projections for 1976 are even less reassuring. Although total demand for all liquid petroleum during the first six months of 1976 was less than the same period in the peak year of 1973, the consumption of gasoline reached an all-time high. Usage of this product in 1976 reflected nearly a 3 percent increase over 1973 levels. A projection for the total 1976 demand of liquid petroleum, as made by the Chase Manhattan Bank, suggests a level equal to that experienced in 1973. An additional forecast is that foreign supplies will account for 42 percent of this demand. In a similar manner, the EXXON Company (1975) has predicted that imports of foreign oil would reach 44 percent of demand. Based upon preliminary statistics compiled by the U. S. Federal Energy Administration, imported oil has accounted for 40 percent of domestic consumption through the first six months in 1976. Data published in the Oil and Gas Journal (1976a)indicate that nearly 36 percent of the crude oil imported directly into this country originated from Middle Eastern and North African members of OPEC. These figures are of course underscored by the continued decline in the domestic production of liquid petroleum. Industry figures suggest that domestic crude oil production will decline more than 3 percent compared to 1975. If realized, this will mark the fourth consecutive year in which domestic production of crude oil has decreased.

Production of natural gas in the United States apparently reached its peak in 1973, following several prior years of increasing production. For the first time since 1970, however, domestic production and consumption each declined below 20 trillion cubic feet in 1975 (U. S. Bureau of Mines, 1976). These trends can be explained by declining productive capability, curtailments to industrial users, conversion to coal for some industrial and electric-utility boilers and relatively mild winter weather. Because of highly publicized and in part realistic concerns over natural gas shortages, especially as related to the interstate market, there has also been a tendency to suppress the installation of gas-fired heating units in new construction.

Natural gas remains for the most part a domestic based energy source. Imports have totalled less than one trillion cubic feet in each of the last two years. Canada is still the major source of imported natural gas, but recent governmental policy decisions in that country have both restricted the volume to be exported and significantly increased the price. By the end of 1976, natural gas imported into this country from Canada will cost 3.5 times what it did in 1974 (U. S. Bureau of Mines, 1976).

Imports of liquefied natural gas, whose unloaded price has been approved by the Federal Power Commission at a figure nearly four times the historical average wellhead price of pipelined interstate gas, can be expected to account for only a few hundred billion cubic feet per year. Although various contracts for long-term supplies of LNG have been negotiated, the levels of such imports can be expected to increase only slightly. Dupree and Corsentino (1975) estimate that, even by 1980, the amount of imported LNG will not exceed 300 billion cubic feet of re-gasified product. Even if these figures are conservative, which other estimates such as that by the Federal Power Commission suggest they may be by a factor of ten, the degree of reliance upon foreign LNG will indeed be small compared to our present large-scale dependence upon foreign crude-oil sources.

Despite the reduced consumption of natural gas in 1975 and forecasts for 1976 that probably no more than 20 trillion cubic feet will be consumed, other statistics indicate the severity of the natural gas situation. As shown by Risser (1973), new discoveries of natural gas (exclusive of the Alaskan North Slope in 1968) from 1968 through 1971 failed each year to match annual production. Data for the years 1972 through 1975 extend this discouraging trend. Based upon reserve calculations released by the American Gas Association (1974), proven reserves, less those in Alaska which cannot be produced before the mid 1980's, are estimated at 218 trillion cubic feet. If an average annual consumption of 20 trillion cubic feet is assumed, the current national reserves-to-production ratio is slightly more than 10, or the lowest figure since natural gas became a significant energy source in this country!

Consumption of electricity is the only market sector which demonstrated an increase in 1975 over 1973 levels, and this trend is projected to continue into 1976. According to the Edison Electric Institute, electric power usage in the first quarter of 1976 was 6 percent higher than the same period in 1975. Sixty percent of all electricity is now consumed in the residential/commercial sector, and 1976 use in this area is expected to be 12 percent greater than in 1973. The annual rate of growth in the usage of electrical energy remains nearly 7 percent.

Although coal's share in producing electricity has now risen to nearly 60 percent, and nuclear energy may approach 10 percent by the end of 1976, the reduction in the availability of natural gas, greatly increased costs for fuel oil, limited hydropower expansion and increased delays for new nuclear plants due to capital and environmental constraints continue to make the electric utility industry vulnerable to power insufficiencies. When considered in league with the increasing rate of usage, this energy industry is probably deserving of as much concern as the natural gas situation.

Geothermal steam used to generate electricity and solar power as a substitute for electricity contributed an insignificant amount in 1975. A similar picture can be forecast for 1976, and the remainder of this decade. In fact, Pollard (1976) has argued strongly against the high hope held by many that solar produced electricity will make a significant long-range contribution to this nation's large-scale energy needs.

In 1975, the production of bituminous and lignitic coal reached an all-time high of 637 million short tons, slightly exceeding the previous record set in 1947 (U. S. Bureau of Mines, 1976). Preliminary production data for 1976 suggest that, unless a major labor problem were to arise, this total will be matched and probably slightly surpassed. Despite the nearly 7 percent increase in production over 1974 levels, use of coal as an energy source in the United States remains troubled by many factors. Some of the latter include continued environmental problems in regard to mined-land reclamation and acid-mine drainage, uncertainty over federal leasing, reclamation legislation and mining requirements in western coal lands, more stringent underground-mine safety regulations, problems in achieving air-quality standards on sulfur-oxide emissions and impasses about the use of stack-gas abatement systems. Heavily involved too are the vast capital requirements confronting this industry as it is faced with renewed calls for significantly enlarged production in the near term.

These are some, but certainly not all, of the technical-resource facets of the current energy situation in the United States in 1976. Also of considerable impact is the political-citizen response to energy as an issue of national significance.

Political-Citizen Attitudes About Energy

In January of this year, Mr. C. C. Garvin, Chairman of the Board of the EXXON Corporation, spoke of "the new energy complacency," and the evidence already presented tends strongly to support this view. But, sadly, there is considerably more disturbing information. The great concern and near-panic of less than two years ago have been replaced, now that OPEC oil is freely flowing into this country and certain overrated federal legislation has been enacted, so that the American citizen no longer need worry about adequate energy. Supporting this contention are the results of a recent Gallup poll in which energy as a national concern was relegated to an extremely low priority behind national economic growth, cost of living, crime and drug abuse and other societal problems. Only 2 percent of the surveyed voter group ranked energy as our most pressing national problem.

Voluntary conservation in the public sector has returned to its pre-embargo state of near non-existence. The nationally legislated 55 mile per hour speed limit is neither enforced, nor adhered to by an ever increasing motoring public. Electric utilities, especially those in the Southeast, have been taxed to their limit to supply enough electricity with the increased usage of air conditioning during the hot summer being experienced there. The resurgence in the nation's economic vitality has of course precipitated sharply increased usage in energy.

A careful review of the political commentary recently espoused by presidential candidates of both parties clearly shows a dearth of remarks about energy as a national problem. For more than two years there has existed a virtual impasse between the Republican Administration and Democratically controlled Congress over many critical issues bearing upon our national energy situation. Much of the legislation that has emanated from Washington has, moreover, tended to be punitive toward the petroleum industry rather than to address sensitive and vital energy issues at a time when the economy had to be treated delicately and election-year politics were at stake. The fact of the matter is that most politicians are essentially reticent to really address energy problems because they either do not have the answers, or they realize that many of the answers require drastic measures which they are fearful either to propose or implement.

Despite the considerable progress made between ERDA and industry in cooperative energy research efforts to date, the United States still today lacks a comprehensive, forceful energy policy for the future. No knowledgeable authority on energy now really believes that Project Independence will be successful by 1985, a view this author has held since the inception of that goal. To many, it is even extremely doubtful if the United States can truly become non-reliant on foreign petroleum within the next two decades. In one such forecast, the EXXON Company (1975) suggests that as much as 50 percent of this nation's oil will have to be obtained from overseas sources through the year 1990.

Despite its many individual and collective problems, there is also a growing body of opinion that supports the continual existence and pronounced influence of the OPEC oil cartel. This view can be readily joined by another tenet, namely that the price of energy in any form or from any source will not revert again to the extremely low levels so long experienced in this nation.

The continued "wait and hope for the best" approach now being taken by federal legislators and agencies has only furthered the vulnerable position of the United States in regard to energy. More than two years of failure to act decisively in the field of conservation, despite the increased attention this subject has received in ERDA's newly released National Energy Research and

Development Plan (Energy Research and Development Administration, 1976), has added to this vulnerability. With payments for foreign oil expected to cost more than $35 billion in 1976, expanded reliance on this source also carries potentially adverse implications for the nation's economic status.

What can this country expect in the way of relief from our existing geological energy reserves and those untapped resources such as oil shale and tar sands? What potential is there for conversion of vast coal reserves into synthetic hydrocarbons? What government policies deserve to be considered and enacted to stimulate energy conservation and to improve more domestic energy production? Some of these vexing questions are discussed next, but admittedly not every element can be considered.

Future Role of Conventional Petroleum Resources

Although the preceding commentary has portrayed a serious short-term situation with certain longer range implications, and the projected cycles for domestic natural gas and crude oil production both appear to be on the downward side as predicted by Hubbert (1969), this nation and its great reserve base of geological energy resources retain one significant advantage. Of the World's three centers of major energy consumption, i.e., the United States, the Western European community and Japan, only this country possesses sizeable reserves of still untapped geological energy resources. Stated another way, Japan and Western Europe both remain much more reliant upon foreign petroleum, in spite of the large petroleum discoveries recently found under the North Sea, and do not possess the huge deposits of coal, oil shale, tar sands and yet undiscovered conventional petroleum.

Even if prudently developed under acceptable environmental circumstances, these vast domestic energy resources probably will never completely eliminate the nation's need to import some foreign petroleum, but they can give us the necessary lead time to technologically discover alternative energy sources not based upon depletable fossil fuels. Such options simply do not exist over the next three or so decades for Japan and Western Europe, as well as for the great majority of lesser developed nations in Asia, Africa and South America where the pressures for increased food production and better living conditions are already being translated into greater demands for energy. With the possible exception provided by the North Sea, most of these areas will continue to rely heavily on expensive foreign petroleum. Only the Soviet Union, now the World's largest oil producing nation on an annual basis, and the actual member nations of OPEC seem immune to the need to rely on petroleum from overseas sources.

The problem of adequately assessing undiscovered petroleum hydrocarbons is indeed difficult and has been the subject of much recent debate (National Petroleum Council, 1973; Hubbert, 1974; National Research Council-National Academy of Sciences, 1975). Limitations in the scope of this paper preclude discussion of the variation among estimates by different authorities or the reasons that future resource calculations vary so decidedly. Data from Miller and others (1975), however, would appear to provide a moderate assessment for the onshore and offshore portions of the United States, including Alaska. In addition to the 35.4 billion barrels of crude oil and natural gas liquids listed as proven reserves, another 33.3 billion barrels of estimated reserves are believed potentially recoverable from extensions of existing fields, deeper reservoirs, etc. Depending upon economic and technologic considerations, between 50 and 127 billion barrels of undiscovered resources may also be found. Comparable figures for natural gas are: (1) proven reserves of 266.1 trillion cubic feet; (2) 202.5 trillion cubic feet of estimated reserves; (3) a range of 322 to 655 trillion cubic feet of undiscovered resources.

Although Hubbert's repeated prophecy that the influence of domestic petroleum as an energy source will endure for only a few more decades, these data, even if only partly accurate, indicate that a sizeable volume of conventional hydrocarbons remains to be produced, provided there is vigorous exploration by the American oil industry. This is especially true of the so-called "frontier areas" such as the Atlantic Coast, the Bay of Alaska and portions of the California offshore. Exploration and production, under prudent environmental constraints, should be allowed to proceed in these areas, but not solely with short-range goals in mind.

Although relevant to all energy resources, the role of conservation merits special consideration in regard to our declining domestic petroleum productivity. Heretofore, either concern for the economy's recovery or political expediency prevented meaningful conservation measures to be enacted. The time has arrived to seriously move toward mandatory conservation measures in areas such as automobile weight, automotive engine displacement, construction insulation, standards for appliance-equipment efficiency and incentives for solar heating and cooling systems. Experience to date has shown that voluntary conservation has only "worked" within the industrial sector where such measures and various negotiated provisions of the Energy Policy and Conservation Act have resulted in financial savings for the firms involved. Legislation to outline means to accomplish mandatory conservation in non-industrial sectors as well as to establish various tax incentives must be implemented because voluntary energy conservation simply will not accomplish the desired savings in crude oil or natural gas. The onus for moving aggressively in this area rests squarely with President-elect Carter and the Congress. To accomplish certain conservation goals, it may even be necessary to enact some highly unpleasant and controversial legislation.

A second area of great significance is the enhanced recovery of crude oil from already discovered reservoirs. Government research funding in this area should be markedly increased over the $33 million allocated for the current fiscal year. The trend established within the U. S. Energy Research and Development Administration to rely more heavily on private industry's expertise in this area should be continued. Financial incentives instead of price rollbacks are needed to stimulate more production by these more expensive secondary and tertiary recovery methods. If crude oil price control cannot be accepted, legislation should be formulated to establish more favorable tax credits for crude oil production derived by enhanced recovery. With many fields still holding today more than 70 percent of their in-place oil, advances in both recovery technology and associated financial incentives can do much to get more of this oil into production.

The short and intermediate-term availability of natural gas, in my opinion, constitutes our nation's most severe domestic energy-resource problem. Data from the Federal Power Commission as cited by Regeimbal (1976) have shown a steady increase since late 1972 in curtailments of interstate-pipeline gas sold under firm contracts (as opposed to interruptible-service contracts). Curtailments from September 1974 to August 1975 amounted to 2.4 trillion cubic feet. Should winter weather continue to be severe into early 1977, a volume of 3.6 trillion cubic feet in curtailments has been projected.

Since 1954, the wellhead price of natural gas allocated to interstate pipeline supply has been regulated by the Federal Power Commission. Prior to 1972, the average price per 1000 standard cubic feet annually has been less than $0.20. Natural gas which is consumed within producer states is unregulated except where the gas is used by electric utilities, and then state agencies are involved. This so-called intrastate gas has recently averaged $1.59 per 1000 scf. In the past four years, these circumstances have precipitated much Congressional debate about deregulation legislation, as well as pressure on the FPC to raise the regulated price. Through late 1976, the wellhead price had gradually increased to $0.52; however, the Commission issued a November 5th opinion which elevated the price for gas discovered in 1973-74 to $0.93, and approved a price of $1.42 for gas discovered since 1974. No distinction was made about the source of this higher priced gas, i.e., from gas or oil wells, or from onshore or offshore fields.

In the event that the Commission's decision, now under litigation, is eventually allowed by the Courts, major impacts will be higher costs to consumers and the provision of sizeable longer-term financial resources to producers for additional exploration and drilling. The second aspect has been a lobbying goal by the petroleum industry in regard to deregulation legislation.

Even with the additional capital, it seems doubtful that much short-term relief can be obtained through new discoveries. Should large reserves be found in the Atlantic OCS for example, their delivery to consumption centers is unlikely to occur before 1982 or 1983. As an advocate of price deregulation, I believe that price increases can, hosever, at a minimum prevent a worsening of the natural-gas supply picture into the 1980's, and can result in increased new discoveries. Undiscovered reserves are estimated to range from 360 to 880 trillion cubic feet (Potential Gas Committee, 1973; Hubbert, 1974; Miller and others, 1975; National Research Council-National Academy of Sciences, 1975). Inasmuch as much of this undiscovered natural gas lies in deeper reservoirs, under "frontier" OCS acreage and in smaller or more marginal deposits, additional revenues must be provided to encourage exploration for these higher risk prospects.

Although the recent FPC ruling has clouded the deregulation issue, I still hold to the view that incrementally phased deregulation, with some form of mandatory exploration reinvestment clause, is a preferable pricing solution in the longer term. Already imported oil costs $2.30 for a thermal output equivalent to a standard volume of natural gas; imported LNG is priced between $2 and $3 per regasified standard volume; and, cost estimates for synthetic gas from coal (assuming $8.00 per ton coal) vary between $3 and $4 (in 1975 dollars) per 1000 cubic feet (Swinney, 1975; Hammond and Baron, 1976). When the planned coal-synthesis plants announced to date become operative in the late 1970's and early 1980's, it is reasonable to assume that the product price could be even higher due to such factors as inflation, loan interest and higher construction costs.

Some intermediate-term relief could be realized, especially in the Midwest, if action can be taken before 1980 on the best means to deliver natural gas from the Prudhoe Bay field in northern Alaska to the so-called "lower 48." According to the American Petroleum Institute (1976), this field contains 26 trillion cubic feet of proven reserves. A consortium of Canadian and American firms, amid controversy over exact routes and Canadian export policy and public opinion, has proposed a 2600-mile pipeline to handle gas from both the Prudhoe Bay field and several large fields in Canada's Mackenzie Delta. Although this project has already escalated in cost to nearly 9 billion dollars, any resolution lies first in the political arena. If a decision can be made there, a related point must consider the cost of the delivered gas. There appears no way in which that gas can enter domestic markets for less than $2 to $3 per 1000 scf. When and if this Arctic gas is produced, a likely corollary is that the price may require special economic arrangements, regardless of the future status of natural gas pricing in terms of deregulation.

According to Maugh (1976), four largely untapped sources of domestic natural gas worthy of future consideration are: (1) methane bleedoff from coal seams prior to mining, especially in the Appalachian Region; (2) recovery through artificial fracturing of several widespread, Paleozoic-age black shales;

(3) improved production from "tight," or low permeability gas-bearing sandstones in the Rocky Mountain Region by means of artificial stimulation; and, (4) development of geopressured sand reservoirs along the Gulf Coast. Some successful efforts have recovered small volumes of gas from each of the first three, while only speculation at this time surrounds the fourth. Natural gas from coal, fractured shale and low permeability reservoirs collectively have significant potential, provided improved extractive technology, especially artificial fracturing, can be successfully developed. The volumes of gas are appreciable; although widely distributed, black shales alone may contain up to 500 trillion cubic feet of potential reserves. One aspect common to each of these unique sources is the clear need for the price of natural gas to rise, either through FPC edict or deregulation. Unless prices can increase to above $2 per 1000 scf, production of gas from these undeveloped deposits cannot be economical. Inasmuch as the coal seams and shales under consideration to a large degree lie near centers of high natural gas consumption, their possible development is additionally intriguing.

One related problem in the use of natural gas deserves comment. Although the percentage of contribution has steadily declined since 1970, natural gas still accounted for 15.8 percent of the fuel used to produce the nation's electricity in 1975. This usage amounted to more than 3 trillion cubic feet, or 15 percent of all natural gas consumed. While it raises many other difficult questions such as the economics of plant retrofitting, the availability of coal and the quandary over flue-gas desulfurization technology, the gradual phasing out of natural gas as an electric-utility boiler fuel is of paramount importance. The value of natural gas as ammonia-fertilizer feedstock and a clean-burning fuel for household and commercial applications is too great to allow the consumption of it in producing electricity at thermal conversions which do not exceed 40 percent.

Future Role of Coal Resources

Averitt (1973) estimated that the amount of coal of all ranks remaining in the ground within the United States (including Alaska) as of January 1, 1972, totalled 3.22 trillion tons, and that approximately half this total, or 1.58 trillion tons, were in seams shallower than 3000 feet in depth, and thus classified as identified resources. In a more recent assessment, Averitt (1975) has estimated total coal currently in the ground to be 3.97 trillion tons, but has indicated that only 25 percent of this can be considered as economically recoverable resources. Based upon the economics in the mid-1970's, Simon and Malhotra (1976) consider the actual reserve base at 217 billion tons, a figure which is barely 6 percent of the resource base.

Nevertheless, that volume of coal is a tremendously valuable energy source if the many problems posed by its extraction and use can be overcome. Much of these 217 billion tons is too high in sulfur to be acceptable under existing air quality standards. Expanded use of medium to high sulfur coal for industrial and electric-utility boiler fuel is further compounded by technical and economic problems, as well as differences of opinion about flue-gas desulfurization methods. Controversies in both the East and West rage over the recovery of coal by strip mining and the related problems of mined land reclamation, the adequacy of water, and state versus proposed federal legislation.

Although the domestic production of coal in 1975 was a record-setting 637 billion tons, calls for expanded production in the future will not be easily met. Inasmuch as the short-term expediency of more efficient surface mining can be expected to persist, the passage of strict, yet realistic federal legislation on surface mining is needed now to insure acceptable environmental conditions. Moreover, this measure is considered a necessary first step to insure prudent leasing of federally-owned coal lands, and a preliminary move prior to any government support for synthetic-hydrocarbon production from coal.

The historical emphasis in this country in regard to making synthetic hydrocarbons from coal has been gasification into either SNG for substitution of declining natural gas or lower-BTU gases for power production (Perry, 1974; Squires, 1974). As reviewed by Swinney (1975), a very small amount of SNG from coal, using a modified Lurgi method, could enter the marketplace in the late 1970's. El Paso Natural Gas Company and Texas Eastern Transmission Company combined with Pacific Lighting Company are close to construction of plants having output capacities of 250 million cubic feet per day. Both plants are planned for New Mexico, relying upon mine-mouth coal. Each has, however, encountered problems and activity to install these facilities has been largely stalled. The gas to be produced is expected to cost close to $4 per 1000 scf; how this problem relates to the deregulation/FPC price picture remains unknown at this time.

The many, highly publicized gasification techniques being developed by American firms working with various federal energy agencies appear to have a definite measure of uncertainty about their eventual application (Hammond, 1976a). While the conversion efficiencies are commonly superior to the Lurgi method, other technical problems, competition for funding and industry/agency impasses have collectively prevented these domestic gasification techniques from moving past the pilot plant stage.

Critics of gasification also cite two other obstacles or objections, namely the high cost of the products and the significant demand for water. The latter problem is compounded by the additional water needs in reclamation of the coal-mined lands. The factor of water clearly appears to be the most limiting element to much larger scale energy development in the Rocky Mountain-Northern Great Plains region, where much of the nation's coal and all of the high-grade oil shale are to be found.

The production of liquid hydrocarbons, such as syncrude, gasoline and methanol, and numerous byproduct chemicals from coal has also received considerable attention in recent years (Mills, 1975; Squires, 1976). A detailed review of the process technologies for both liquifaction and gasification of coal was recently prepared by the University of Oklahoma Science and Public Policy Program (1975); these specific techniques will not be discussed here.

As with gasification, liquid products will prove to be expensive, even though the processes are less demanding of water. Swinney (1975) has indicated costs between $16 and $20 per barrel, while Clewell (1976) has cited figures as high as $24 per barrel. Both these estimates assume moderate priced coal at less than $10 per ton. Although the South African Sasolburg plant currently produces synthetic liquids from coal by the Fischer-Tropsch method, more efficient, newer technology is still some distance from success (Hammond, 1976b).

Despite the sizeable coal reserve base, and numerous research and development efforts to perfect hydrocarbon/synthesis techniques, it seems extremely doubtful if coal synthetics will make any impact on the domestic energy situation before 1990 (Simon and Malhotra, 1976). Even if the restraining economic pricing conditions are removed and technologic-environmental problems solved, the lead times for plant construction, etc. are such that this writer agrees with that assessment. Thus, the promise of coal to replace the United States' dwindling deposits of hydrocarbons appears decidedly less than one might expect, considering the magnitude of coal reserves and the increasing severity of declining petroleum production.

Future Role of Non-Coal Synthetic Sources

The United States possesses the World's largest known deposits of oil shale as developed within the Green River Formation of western Colorado, eastern Utah, and southwestern Wyoming. As well, the nation possesses the World's third largest concentration of heavy oil or tar sands in several widespread deposits within the Vinta Basin and southeastern corner of Utah. Efforts to recover syncrude from these two unique occurrences have met with some success, but not enough to date to stimulate commercial production.

Although the Green River shales contain an estimated 2 trillion barrels of oil as a solid hydrocarbon called kerogen, estimates of what may be economically recoverable vary between 600 billion barrels (Dinneen and Cook, 1974) and 200 billion barrels (Risser, 1973).

In 1974, when the federal government offered for prototype leasing two tracts each in the Western states, a record per acre bid was received for the Colorado C-a tract. Four of the six tracts were leased, advances in extractive technology seemed to be weekly announcements and expectations ran high that shale oil would be produced in commercial quantities before 1980. Since then, development of a viable shale oil industry has been dealt a series of reversals which makes it appear doubtful that syncrude from oil shale can make much of an impact before the mid to late 1980's, if then (Oil and Gas Journal, 1976b; Pforzheimer, 1976). The two most pressing aspects involve economics and environmental considerations. In order for syncrude from oil shale to be competitive, it must command a price between $15 and $19 per barrel (Clewell, 1976). Furthermore, the energy industry firms engaged in shale oil operations want some form of financial incentive through loan guarantees, long-term contracts or other subsidies. Environmental problems embrace air pollution from processing, acceptable disposal of the spent shale and adequate water for processing and land restoration. The question of water availability in Western energy resource development is a topic worthy of discussion by itself; over the long term, water will prove to be more limiting than favorable economics.

This writer does not favor any form of subsidy/guarantee program for oil-shale ventures. Risk ventures and potential high profits are basic ingredients in the petroleum industry; the latter should not have to resort to outright federal aid. Essential economic incentives that can stimulate oil-shale development are: (1) removal of federal price controls on <u>all</u> domestic crude oil; (2) assured direction to federal leasing of oil-shale acreage; and, (3) more favorable tax credits for the infancy period (first 5 years) of the industry. Price decontrol would give industry more than adequate profits to develop oil-shale leases without federal government assistance.

Despite the various impasses experienced to date, considerable hope has been expressed that the Paraho process, which utilizes little water and handles lump oil shale, can make a significant breakthrough (Pforzheimer, 1976). Success in retorting and acceptable use of the product for military fuels have already been demonstrated at the Anvil Points, Colorado test facility. Confidence is also high that the Occidental Petroleum Company's in-situ process, in which some mining is done prior to the production of a rubble zone (chimneys) where the in-place retorting takes place, can become commercial. Test results to date from small chimneys have been good, and larger-size operations are underway. Occidental has recently become a participant in one of the Colorado federal lease tracts, and speculation is that their process may be applied to recovery efforts (K. S. Johnson, 1976, personal communication).

According to Ritzma (1973), tar sand deposits in Utah may contain as much as 25 billion barrels. Unlike the sizeable Athabasca deposits in Alberta, production, if successful, may well involve in-situ thermal recovery. The

U. S. Energy Research and Development Administration has a research effort utilizing this approach presently underway at the large Asphalt Ridge deposit near Vernal, Utah. Although the volume of heavy oil in sand deposits is sizeable, it is premature to estimate what the ultimate effect may be. Development of tar sands, with the exception of the Canadian example, is less advanced in this country than several other potential sources of crude oil.

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SOME FUSION PERSPECTIVES*

by

J. Rand McNally, Jr.

Thermonuclear Division, Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830

ABSTRACT

This paper presents a review of fusion concepts including possible fuel cycles for both magnetic and inertial confinement. A discussion of mirror reactor possibilities is included.

I. INTRODUCTION

At the first Atoms for Peace Conference held in Geneva in 1955, the Conference President, Homi Bhabha of India, stated, "The historical period we are just entering in which atomic energy released by the fission process will supply some of the power requirements of the world may well be regarded one day as the primitive period of the atomic age. It is well known that atomic energy can also be obtained by a fusion process as in the H-bomb, and there is no basic scientific knowledge in our possession today to show that it is impossible for us to obtain this energy from the fusion process in a controlled manner. The technical problems are formidable, but one should remember it is not yet 15 years since atomic energy was released in an atomic pile for the first time by Fermi. I venture to predict that a method will be found for liberating fusion energy in a controlled manner within the next two decades."[1]

Today, 21 years later, this method has not been found — or if it has been found, it has not gained acceptance by the total fusion community. Yet, news reports still glow with the prospect of unlimited energy — clean, non-polluting, safe energy — from nuclear fusion. Having been associated with the controlled thermonuclear research (CTR) program during these 21 years, I have seen new hopes arise and then dim, but there has been a steady progression in our knowledge of and ability to handle increasingly hotter, denser, and better confined plasmas. On the other hand, this knowledge has made clearer that nuclear fusion has its own set of problems such as radioactivity, after-heat, neutron damage, and gamma (γ) rays, and therefore the glamour of benign fusion has dimmed somewhat.

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*Research sponsored by the U. S. Energy Research and Development Administration under contract with Union Carbide Corporation.

The fact that different fusion fuels can be ignited on planet earth has been demonstrated[2] in the 1951 U.S. Greenhouse test of DT burning, the 1952 U.S. Ivy-Mike test of DD burning, the 1953 Soviet "Joe-4" test of LiD burning, and the U.S. Bravo and other tests of the Castle series in 1954 (LiD, LiD-U). Whether any of these fuels can be burned in a controlled manner for peaceful applications, such as in limited micro-explosions after the fashion of the automobile combustion chamber or in steady-state nuclear burners using magnetic fields for confinement, remains to be determined. Fusion-fission hybrid reactors had their progenitor in the Castle series of explosive fusion-fission.

In this paper we shall explore some of the concepts of nuclear fusion reactions, advanced fusion fuels, environmental impacts etc., using the following general outline: I. Principles of Fusion (Nuclear Fuels and Reactions, Lawson Condition, nτ vs T, Nuclear Burn Characteristics); II. Magnetic Mirror Possibilities (the Ion Layer and Electron Layer, Exponential Build-up at MeV energies, Lorentz trapping at GeV energies); III. Pellet Fuel Fusion Prospects (Advanced Pellet Fuel Fusion Prospects, Burn Characteristics and Applications, Excitation-heating Prospects for Runaway Ion Temperatures).

II. PRINCIPLES OF FUSION

A. Nuclear Fuels and Reactions

The "classical" fusion fuel for fusion reactors is DT (all others are called advanced fuels), which reacts much faster at low temperatures than any other charged particle combination. It involves a highly excited compound nucleus $^5He^*$ and reacts best at a deuteron bombarding energy of 0.107 MeV (see also Fig. 1):

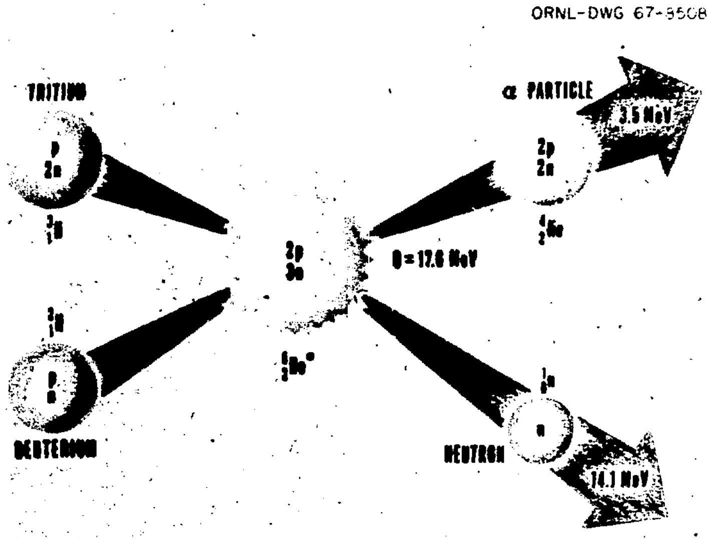


Fig. 1. The D + T → n + α + 17.6 MeV reaction branch which has a mass-energy resonance with the compound nucleus $^5He^*$ at E_d = 107 keV.

$$D + T + 0.107\ \text{MeV} \rightarrow {}^5\text{He}^{**} \begin{cases} n(14.1\ \text{MeV}) + \alpha(3.5\ \text{MeV}) + 0.1\ \text{MeV} & (1) \\ \gamma(16.8\ \text{MeV}) + {}^5\text{He}^{**} & \\ \qquad\qquad \downarrow & \\ \qquad\qquad n(0.7\ \text{MeV}) + \alpha(0.2\ \text{MeV}). & (2) \end{cases}$$

1 MeV energy release is equivalent to 1.6×10^{-6} ergs. The cross section for the 14.1 MeV neutron branch is 5.0 barns ($1\text{b} = 10^{-24}\ \text{cm}^2$) at the peak of the nuclear resonance whereas the second, energetic gamma producing branch is about 1/5000 as probable. Thus, in a 5000 MW(th) DT fusion reactor, there would be about 1 MW of 16.8 MeV gamma rays emitted and extensive shielding would be required. The 14 MeV neutron poses important radiation damage problems (helium void formations, atom displacements, etc.) as well as radiological problems (radioactivity and after heat). Steiner has discussed these problems and, though important, they are expected to be less severe than in a fission reactor.[3] Tritium is radioactive (18 keV maximum β energy, 12.3 year half-life) and must be well contained — a 10 kg inventory of tritium in a DT reactor (plasma, Li blanket, separation and storage systems) amounts to 100 million curies of activity which must be secured to about one part in ten million per day. DT reactors would necessitate a thermal recovery of ∿90% of the energy and possibly up to 10% via direct electrical conversion. The thermodynamic efficiency would be 30-40% (possibly less) and hence waste heat problems must be resolved. Metz has discussed some of these problems recently.[4]

Since tritium is almost non-existent in nature, it must be regenerated by means of the 14 MeV neutrons interacting in a Li blanket (see Fig. 2) in the following reactions:

$$n_{\text{fast}} + {}^7\text{Li} \rightarrow n' + t + \alpha - 2.5\ \text{MeV} \qquad (3)$$

$$n' + {}^6\text{Li} \rightarrow t + \alpha + 4.8\ \text{MeV}. \qquad (4)$$

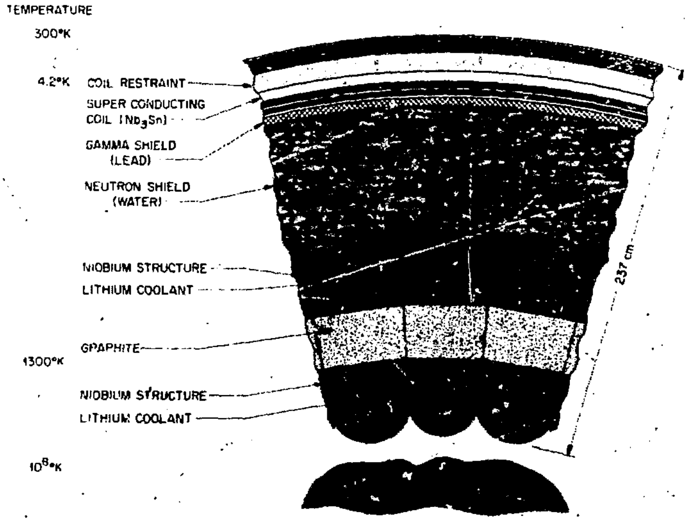


Fig. 2. Artist's conception of possible blanket structure region for a DT-Li reactor.

Thus, with a tritium generation factor of about 1.2, the DT reactor is essentially a D(T)-Li reactor, and although deuterium is abundant in water (∿1/6500 of ordinary hydrogen), the lithium must be obtained economically from the earth's crust (20 ppm), from salt brines (∿50-300 ppm), or from the sea (∿0.2 ppm).[5]

The practical advanced fusion fuels include DD and D^6Li (both of which appear to be suitable fuels for steady-state magnetic containment reactors)[6] and the more exotic and potentially much "cleaner" fuel D^3He which is dependent on an excess T inventory from DT reactors ($T \rightarrow {}^3He + \beta + \nu$) or on DD or D^6Li reactors which can breed ^3He and T. The fuels p^6Li, p^9Be, and $p^{11}B$ do not appear to be practical either because they probably won't "ignite" at all or because their ignition temperature is too high and energy return too low (e.g., $p^{11}B$).[6] One might visualize a large, advanced fuel DD reactor operating in a reactor park and providing ^3He and T as source material for several urban-sited "clean" D^3He reactors.[7]

The DD reactor involves the two almost equally probable branches (see also Fig. 3):

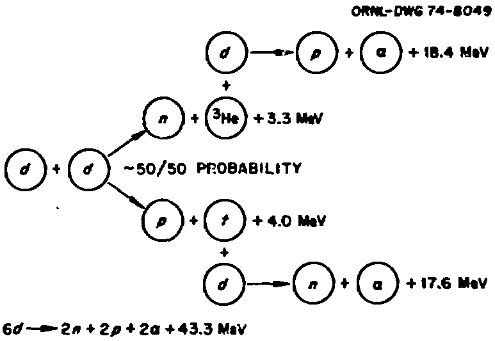
$$d + d \rightarrow \begin{cases} n(2.5\ \text{MeV}) + {}^3\text{He}(0.8\ \text{MeV}) & (5) \\ p\ (3.0\ \text{MeV}) + t\ (1.0\ \text{MeV}) & (6) \end{cases}$$

with the following second generation reactions:

$$t + d \rightarrow n(14.1\ \text{MeV}) + \alpha(3.5\ \text{MeV}) \qquad (7)$$

$$^3\text{He} + d \rightarrow p(14.7\ \text{MeV}) + \alpha(3.7\ \text{MeV}). \qquad (8)$$

Auto-catalytic or <u>in situ</u> burning of t and ^3He may occur with about 50% probability if the ion temperature exceeds 100 keV.



Breeding Reactions in D-D Fueled Plasmas (The Reactions are Auto-Catalytic in Nature Inasmuch as the t and ^3He Lead with High Probability to a Second Generation Reaction).

Fig. 3. The DD first and second generation nuclear reactions.

In a driven, catalyzed DD burner, the unburned T and ^3He would be isotopically separated from the p and α ashes and returned with D as fuel make-up to the reactors or would be transported to storage areas for T decay to ^3He in the reactor park for subsequent transport of the ^3He to urban-sited relatively "clean" D^3He reactors. Preliminary indications are that t in the plasma, 14 MeV neutrons, and the power output from neutrons all can be reduced by at least two orders of magnitude in a D^3He reactor compared with an equivalent power DT reactor.[7] The DD reactor (catalyzed or non-catalyzed), on the other hand, is only marginally (by a factor of 2 or more) better than the DT reactor except that the tritium abundance in the plasma is down by about a factor of 20–30. Non-T-catalyzed DD burners would require the cumulative storage of very large quantities of the excess tritium — but this would be stored in cold, static systems for ^{3}He production.

The cross sections (σ) as a function of bombarding energy are given in Fig. 4 for several light element reactions. The σ for DT is larger by a factor of at least 100 for energies up to 100 keV; however, when this is multiplied by the velocity v and Q_+ (the energy release in charged particles) and averaged over a Maxwellian distribution of ion velocities at temperature T_i, this factor of 100 decreases significantly — especially for DD and D^3He (see Fig. 5). The expression $\langle \sigma v \rangle Q_+$ is a measure of the ability to deposit energy in the plasma. (See also notes on Fig. 5 which indicate expected enhancement of the effective reactivity of a DD plasma.) A T and ^{3}He catalyzed DD plasma is within a factor of 2 of the reactivity of a DT reactor at T_i = 100 keV and even closer at $T_i >$ 100 keV; the environmental gains of the catalyzed DD reactor may more than offset the slight reduction in reactivity provided such high temperatures can be attained. Total tritium in the DD system may be only about 10^4 curies.[6]

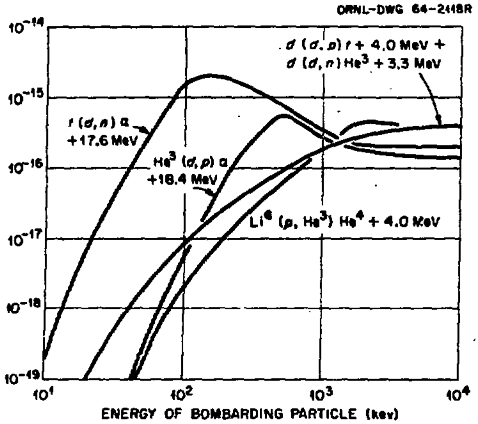
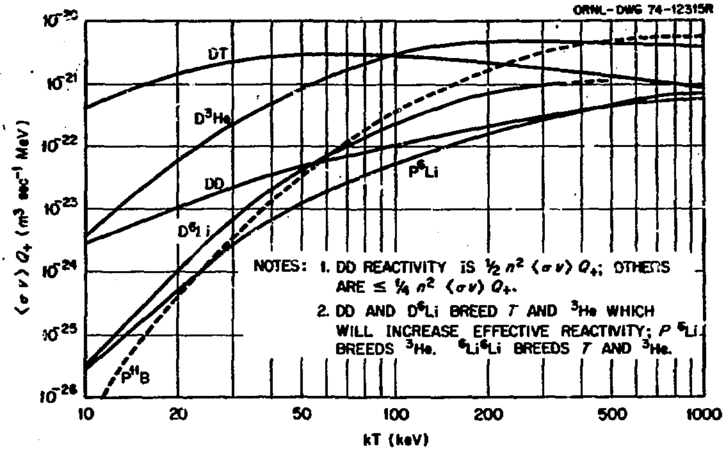


Fig. 4. Cross sections of several light element reactions vs energy.



NOTES: 1. DD REACTIVITY IS $\frac{1}{2} n^2 \langle\sigma v\rangle Q_+$; OTHERS ARE $\leq \frac{1}{4} n^2 \langle\sigma v\rangle Q_+$.

2. DD AND D^6Li BREED T AND ^3He WHICH WILL INCREASE EFFECTIVE REACTIVITY; $P\,^6Li$ BREEDS ^3He. $^6Li^6Li$ BREEDS T AND ^3He.

Plasma Reactivity of Various Fusion Fuels vs Kinetic Temperature.

Fig. 5. Relative reactivities, $\langle\sigma v\rangle Q_+$, for several light element reactions vs ion temperature.

B. Lawson Criterion, $n\tau$ vs T

J. D. Lawson developed a criterion for ignition of DT and DD plasmas against bremsstrahlung radiation losses.[8] A modified simpler expression for an ignition $n\tau$ can be readily derived. If we define Q_p as the ratio of power deposited in the plasma to the plasma energy throughput (for $T_i = T_e$), then:

$$Q_p = \frac{\frac{1}{4} n^2 \langle\sigma v\rangle Q_+}{3\ nkT/\tau_E} \geq 1 \quad , \tag{9}$$

where τ_E is the energy containment time. One obtains for $n\tau_E$:

$$n\tau_E \geq \begin{cases} \dfrac{12\ kT}{\langle\sigma v\rangle Q_+} & \text{for DT} \quad (10) \\[2em] \dfrac{6\ kT}{\langle\sigma v\rangle Q_+} & \text{for DD} \quad , \quad (11) \end{cases}$$

since for like particles the reaction power goes as $\frac{1}{2} n^2 \langle\sigma v\rangle Q_+$. The required experimental values of $n\tau_E$ to obtain an ignited plasma must at the least exceed the value appropriate to the plasma temperature. Figure 6 illustrates $n\tau_E$ vs T_i (expressed in keV) for DT. Thus, at 6 keV a DT plasma must have $n\tau_E \geq 8 \times 10^{14}$ cm^{-3} sec. If the plasma has a density of 10^{14} cm^{-3} it must have an energy containment time of at least 8 seconds. The minimum $n\tau_E \sim 1.6 \times 10^{14}$ cm^{-3} sec occurs at $T_i \sim 20$ keV.

No present day plasma is within a factor of about 1000 of these scientific feasibility requirements. Different magnetically confined plasmas have exhibited maximum values of about 10^{19} cm^{-3} for the density (LASL plasma focus); 300 keV, 150 sec (ORNL DCX-1), or 10^{14} cm^{-3}, 12 keV (LLL 2 X IIB) — but never all three parameters at once in the same device. On an $n\tau_E$ vs T_i plot the experimental points for any given experiment are about a thousandfold or more away from the goal of scientific feasibility, i.e. if a DT plasma were present as fuel.

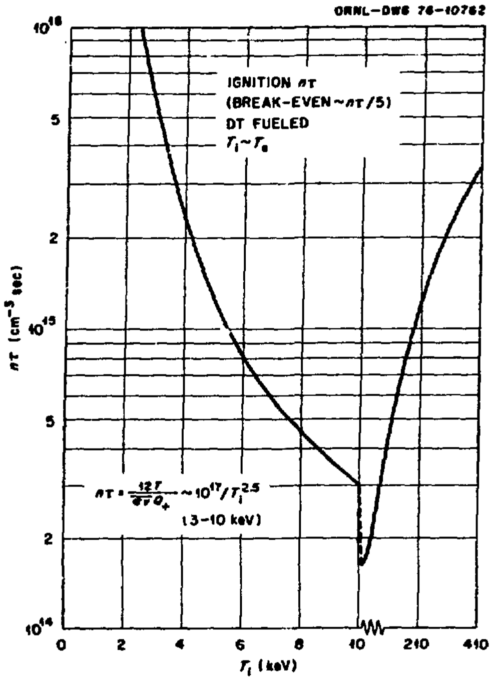


Fig. 6. Modified Lawson criterion $n\tau$ vs ion temperature for DT plasma.

C. Nuclear Burn Characteristics

Figure 7 shows schematically the burn sequence of a DT plasma as a function of ion temperature. Below about 6 keV the power expended in radiation losses (bremsstrahlung and synchrotron) exceeds the power deposited in the plasma by the alpha particles (see Eq. 7); thus, once the externally supplied energy

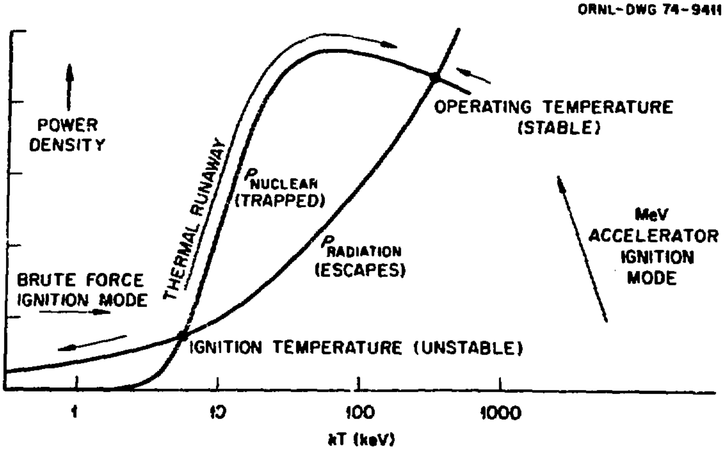


Fig. 7. Schema of burning characteristics of a DT plasma.

source is removed the plasma will quench. At the ignition temperature the plasma is unstable, and a slight increase in temperature will lead to a thermal runaway to a high temperature (possibly 300 keV) independent of whether or not the external energy source is active. The steepness of the radiation power loss curve at 300 keV is due mostly to synchrotron radiation losses (which vary about as $T_e{}^3$).

At the operating or burning temperature the plasma exhibits a stable behavior provided the fuel mix does not change (such as due to build-up of fuel or ashes). This operating point has a characteristic negative temperature coefficient like that of a fission reactor — if the temperature is perturbed the plasma tries to stabilize itself and will do so provided the perturbation is not too large.

On the other hand, if the fuel density or mix changes, the plasma will seek a new operating point. Increase of fuel density leads to more reactivity and, since the synchrotron radiation is better absorbed in denser plasmas, the temperature increases. Thus, the plasma has an undesirable property — a positive density coefficient — which must be controlled by fuel feed or ash control or by manipulation of the magnetic field. A negative feedback control must be introduced to stabilize the nuclear burn. An increase of ash in the plasma will cool the plasma.

The presence of still other losses (particles or energy) in addition to radiation will lower the operating temperature point shown in Fig. 7. Most of these losses (e.g., pseudo-classical diffusion across the magnetic field) are rather modest; however, if severe temperature dependent losses like the dissipative trapped ion (DTI) loss mode predicted for tokamak fusion reactors[9] occur, the operating temperature may shift down to the T_i = 10-20 keV range. The DTI has not yet been observed experimentally so it may not be operative in a tokamak or in other potential fusion devices. If it is not present in tokamaks the possibility of a high beta ($\beta = 8\pi\Sigma nkT/B^2$), flux conserved tokamak may be a real tokamak option,[10] even permitting the prospect of burning advanced fuels. Instability of the plasma-magnetic field configuration can also lead to severe losses.

A computer evaluation of the burn of a DT plasma ignited at 6 keV and density $n_e = 10^{14}$ cm^{-3} in a reactor having a radius of 5 m and effective wall reflectivity (for synchrotron or magnetic radiation) of 90% is shown in Fig. 8. In this hypothetical pulsed, closed burn the ion temperature escalates to about

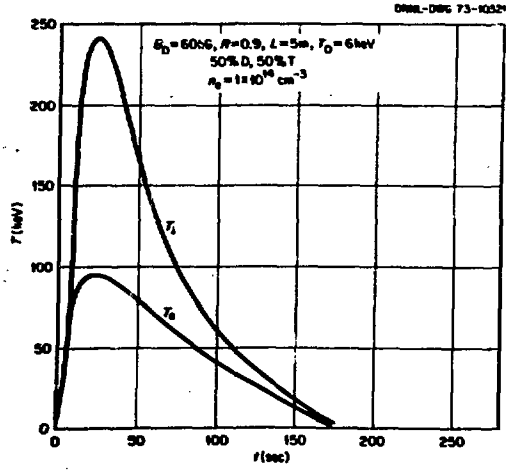


Fig. 8. Thermal runaway and quench of a DT plasma ignited at $T_i = T_e$ = 6 keV.

250 keV but the alpha ashes build up and quench the plasma in about 150 seconds.[6] The temperature characteristics of a pulsed, closed DD plasma burn ignited at $T_i = T_e \approx 50$ keV are illustrated in Fig. 9. The slight dip in Te is due to the lack of a nearly equilibrium amount of t and ^{3}He in the plasma at start-up. Priming the plasma with a few percent of these energy-rich, reactive nuclei enhances the burn and the small dip in Te disappears.

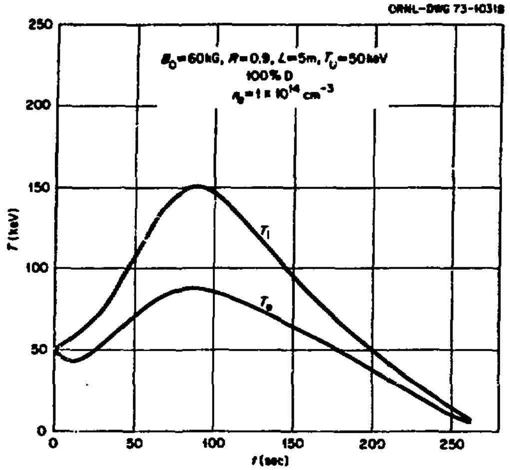


Fig. 9. Temperature — time variation of a DD plasma ignited at 50 keV.

Plasmas containing ^{6}LiD fuel permit upwards of 80 exothermic reactions among the fuel and reactant products (p,d,t,^{3}He,α,^{6}Li,^{7}Li,^{7}Be), but based on the seven first generation reactions between DD (Eqs 5 and 6) and D^{6}Li[^{6}Li(d,n)^{7}Be + 3.4 MeV, ^{6}Li(d,n)^{3}He + α + 1.8 MeV, ^{6}Li(d,p)^{7}Li + 5.0 MeV, ^{6}Li(d,p) t + α + 2.6 MeV, ^{6}Li(d,α) α + 22.4 MeV], plus DT and D^{3}He reactions they can ignite at T_i ∿90 keV. The presence of Li and Be in a magnetically confined reactor could lead to difficult problems associated with their deposition on cooler parts of the internal vacuum chamber. This could eliminate ^{6}LiD as a really practical fuel for magnetically confined fusion reactors; however, it should be recognized that sputtered wall materials in any fusion reactor may also deposit in undesirable spots. Further evaluation of all the light element fuel cycles seems desirable.

Figure 10 illustrates some of the output power features of a steady-state catalyzed DD fusion reactor. (Note the positive density coefficient effect of P increasing as the fuel density increases.) Figure 11 illustrates some of the burn properties of a steady-state catalyzed DD reactor for various relative abundances of deuterium. It should be emphasized that the particle and energy confinement times in such evaluations are only mathematical solutions of a steady-state condition; realistic fusion reactors will have their own natural confinement times and source feed rates which may require larger or smaller nτ values than indicated by Fig. 11.

The transport of particles and energy (radiation, conduction, convection) is one of the most challenging experimental and theoretical problems in the CTR efforts; it must be answered definitively to ensure working, controllable fusion reactors.

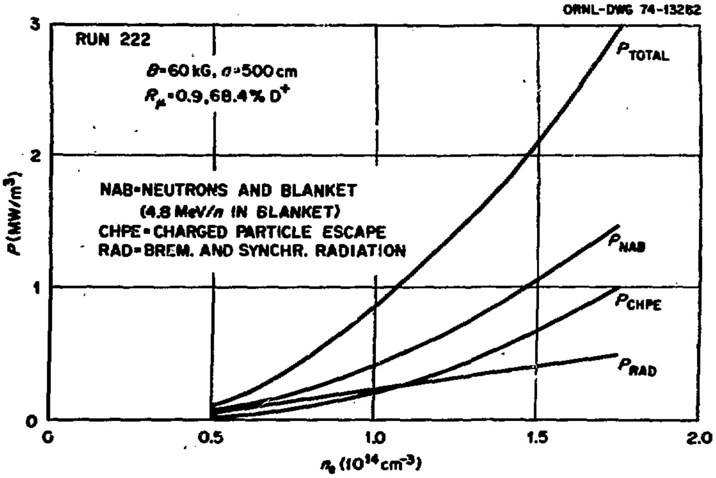


Fig. 10. Power output characteristics of steady state catalyzed DD reactors vs density, P_{NAB} = neutron and blanket power, P_{RAD} = synchrotron and bremsstrahlung radiation power, P_{CHPE} = power in escaping charged particles.

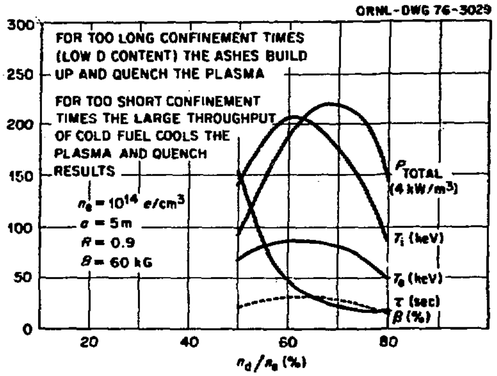


Fig. 11. Properties of steady state catalyzed DD reactors for various deuteron concentrations.

Figure 12 shows the fractional burn-up of t, ^{3}He, d and p [via the $t(p_{fast},n)^3$He-0.8 MeV reaction] in the possible steady-state catalyzed DD reactors. Note that at low deuteron concentrations for which τ is long (see Fig. 11), very high burn-up of T and ^{3}He occur. An approximate expression for T burn-up is[11]

$$FBT = 1/(1 + 1/n_d\tau\langle\sigma v\rangle_{DT}) \qquad (12)$$

and high temperatures and large $n\tau$ values ensure high burn-up fractions.

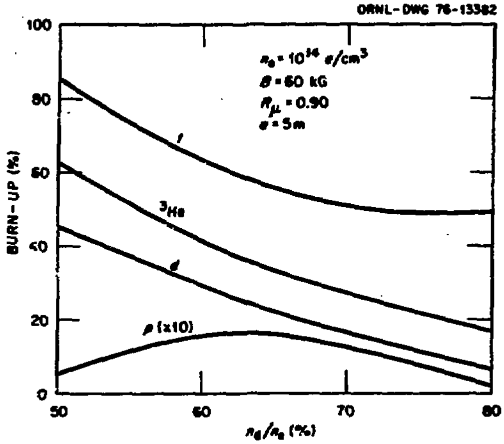


Fig. 12. Percentage burn-up of p, d, t, ^{3}He in steady state catalyzed DD reactors for various n_d/n_e.

III. MAGNETIC MIRROR POSSIBILITIES

A. The Ion-Layer and Electron-Layer

The magnetic mirror configuration (illustrated in Fig. 13) is the simplest of all magnetic field designs for fusion reactors. It would be most practical

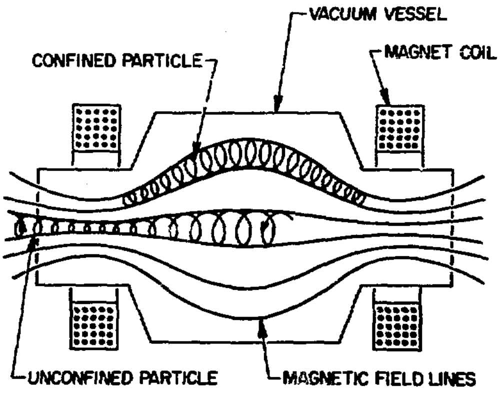


Fig. 13. Confinement of charged particles in a magnetic mirror.

from the utility viewpoint because of its compactness, simplicity, steady-state capability, and ease of maintenance. Unfortunately, ions and electrons having too much of a velocity component in the axial direction "leak" out of the mirror instead of being totally reflected at the strong field regions in the coil throats.

The DCX-1 mirror experiment at ORNL, which attempted to reduce these end losses by using very high energy protons, trapped 300 keV protons by dissociation of 600 keV H_2^+ ions in a long carbon arc (Fig. 14).[12] The trapped ring of protons is exhibited by the incandescence of carbon particulates which pass through the proton ring. Attempts to build up a high density of fast protons by this approach were hampered by rapid charge exchange losses in the carbon arc ($H^+_{fast} + C^{2+} \rightarrow H^\circ_{fast} + C^{3+}$) with the ensuing fast neutrals escaping across the magnetic field. Elimination of the carbon arc, despite its very efficient dissociation ability, led eventually to confinement times of 150 seconds for the 300 keV protons, but only at very low proton density ($\sim 10^8$ cm^{-3}).[13] Charge exchange of protons on the background gas was the major loss factor after the injection beam was turned off. (Beam-on characteristics involved a severe instability driven by the highly ordered recently trapped class of protons, which increased the containment volume for the protons.) The plasma was essentially quiescent shortly after beam turn-off.

Fig. 14. Photograph of long carbon arc and incandescent carbon particulates passing through the 300 keV proton ring of the DCX-1 device.

Many years ago Christofilos proposed closing the leaky magnetic mirror with a large internal current of relativistic electrons (E-layer).[14] Such electrons would not suffer from charge exchange and would be only affected by Coulomb scattering collisions plus any instabilities which might be present. Fleischmann and co-workers at Cornell University eventually succeeded in producing an Electron Layer or ring current which actually reversed the magnetic field on axis and gave rise to a closed toroidal magnetic bottle.[15] Figure 15 is a photograph

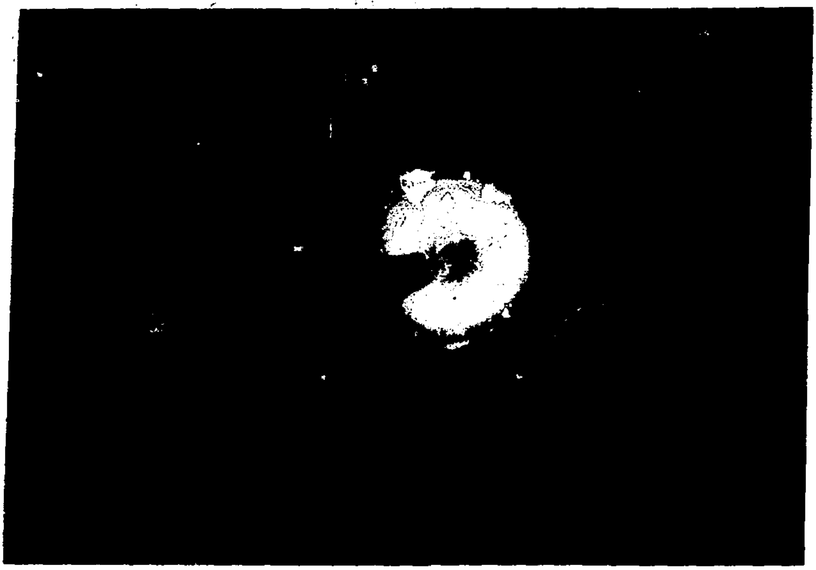


Fig. 15. Field reversing Relativistic Electron Coil Experiment (RECE) showing E-layer.

showing the Cornell E-Layer; the current-carrying stuffing bar along the axis was used to generate a toroidal magnetic field for stability studies.

The possibility of producing an Ion Layer or Ion ring reversed field condition with fast ions generating the ring current was proposed in 1962.[16] The Ion Layer or proton E-Layer is depicted in Fig. 16. To eliminate proton charge exchange losses one would perhaps need for start-up MeV or GeV energy protons for which the charge exchange and scattering cross sections are comparable to or less than the nuclear reaction cross sections. Electron cyclotron heating (ECH) would also probably be required to keep the electrons hot and thus reduce their effectiveness in slowing down the ions at least until ignition occurred.

The Ion Layer or proton E-Layer has a number of prospective advantages over toroidal devices: 1) economical design, 2) compact plasma, 3) ease of maintenance, 4) utility appeal, 5) efficient use of magnetic field, 6) high burn-up of T and ^{3}He, 7) steady state catalyzed burner, 8) axial fuel feed to negatively charged plasma core, 9) irreversible trapping of fuel ions (e.g., $D_2^+ \rightarrow D^+ + D^+ + e$ in a negati~~ve~~ potential well), 10) natural divertor action outside closed field lines, 11) direct electrical conversion due to charge separation in escaping plasma, 12) propulsion or thrust. It also has a number of problem areas: 1) can a small scale "proof in principle" experiment be done? 2) stability and equilibrium problems are not well known,[17] 3) the transport loss mechanisms are unknown; is it too good a "black hole"? 4) can a reactor size Ion Layer be produced?

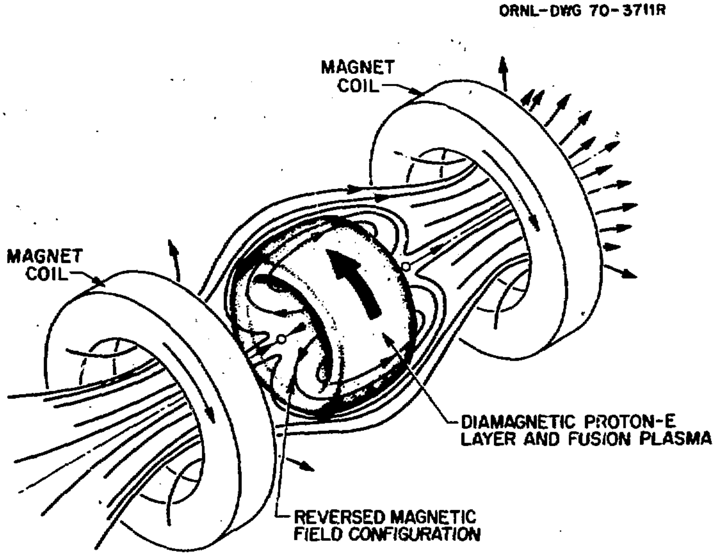


Fig. 16. Schematic Ion-layer or Proton E-layer.

B. Exponential Buildup at MeV Energies

Exponential buildup is a process whereby energetic ions are trapped in a plasma faster than they are lost by charge exchange so that the hot ion motions are dominated by Coulomb scattering collisions. The $n\tau$ value achievable in a magnetic mirror is then inversely proportional to $\sigma_{sc}v$, which varies as $E^{-3/2}$; thus one has for the numerical relation (for $T_e \sim T_i$):

$$n\tau \sim 6 \times 10^{10} E_0^{3/2} \log R \qquad (13)$$

where E_0 is the injection energy in keV, R=mirror ratio=B_{max}/B_{min}=2 for a 2/1 mirror. At E_0=1 MeV $n\tau$ would exceed 10^{14} cm^{-3} sec. If the magnetic mirror could be closed the effective R and $n\tau$ values would become very large since $R \rightarrow R_{vac}/\sqrt{1-\beta}$. However, this assumes charge exchange and instabilities are not significant loss processes.

Charge exchange losses can be overcome in the case of exponential buildup.[18] In the equation for density buildup by injecting a current density J one has

$$\frac{dn_+}{dt} = J\alpha + Jn_+\beta' - n_+\overline{n_0}\,\sigma_{cx}v_+ - \tfrac{1}{2}n_+^2\,\sigma_{sc}v_+ \ . \qquad (14)$$

If the plasma trapping rate $Jn_+\beta'$ exceeds the charge exchange loss rate $n_+\overline{n_0}\,\sigma_{cx}v_+$, the plasma density will grow in time to a Coulomb scatter-limited plasma. The value of $\overline{n_0}$ will also decrease as the plasma density grows as a result of ionization of the background neutrals. Exponential buildup has apparently been definitively observed in a recent Lawrence Livermore Laboratory 2 X IIB experiment using 15 keV H° injection at 310 A (equivalent).[19] The plasma β reached about 0.4 so that $n\tau$ attained a value of about 10^{11} cm^{-3} sec. If a reversed field or Ion Layer condition could be attained, $n\tau$ would increase further; this will be attempted at Livermore using 40 keV H° injected into the present dense 2 X IIB plasma.

An outline for buildup via exponentiation at MeV energies has been proposed. It would use only modest injection currents (few mA of H_2^+) but with resonance cyclotron heating of the electrons present to cut down scatter losses.[20] Figure 17 illustrates the dominant trapping and loss processes as a function of density buildup; should instabilities be non-limiting, nτ values in excess of 10^{14} should be achievable.

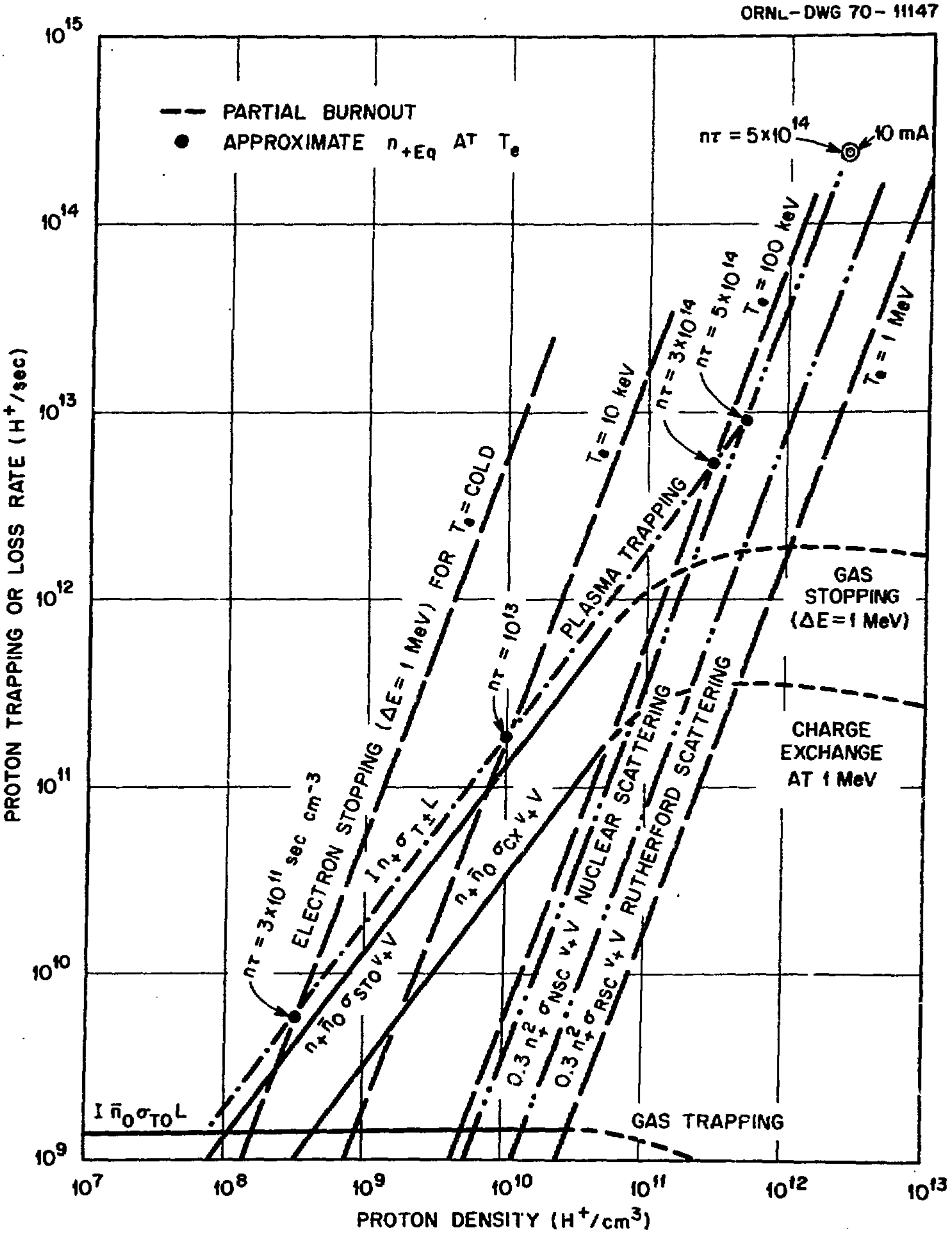


Fig. 17. Proton trapping and loss rates vs proton density using 2 mA, 4 meV H_2^+ ions injected into 20 kG 2/1 magnetic mirror field.

C. Lorentz Trapping at GEV Energies

An excited atom or molecule moving across a magnetic field B experiences a Lorentz or electrostatic force ($qv \times B$) which tends to separate the positive nucleus from the electron. At very high energies this Lorentz force is very strong and ionization of H^{o*} ($\rightarrow H^+ + e$) or dissociation efficiencies for H_2^{+*} ($\rightarrow H^+ + H^0$) may be several percent. Christofilos estimated the efficiency α_L to be about 20% for 2 GeV H_2^{+*} injected into 100 kG fields.[21] He estimated that a 100 mA beam current would be required to produce a dense DT reacting, proton E-Layer under these conditions.

A more gentle approach using only 1 mA at 0.8 GeV H_2^{+*} injected into a 20 kG field has recently been suggested.[22] After producing an Ion Layer in high vacuum with the trapped 0.4 GeV protons, a controlled feed of DT or D^3He might give an ignition condition and eventually the few megawatts of supplemental electron cyclotron heating power for heating the electrons could be turned down or even off. The energetic charged reaction products could sustain the Ion Layer condition as a result of the energetic ions' nutational motions in the Ion Layer.[23]

III. PELLET FUEL FUSION PROSPECTS

A. Advanced Pellet Fuels

The "classical" pellet fusion fuel is solid DT ($\rho = 0.213$ g/cm^3). Other DT-enriched chemical compounds have much higher initial densities (up to ~ 1 g/cm^3) so that the compression required for ignition of the pellet is significantly relaxed, i.e., $C = (\rho R/\rho_o R_o)^{3/2}$. ρR is the analogous Lawson condition and $\rho R = n_e \tau \, v_s M_e$ expressed in g/cm^2 (v_s is the sound velocity $\simeq \sqrt{5nk(T_i+T_e)/3\rho}$ and M_e is the mass per electron). The value of ρR need be of order 1 g/cm^2 for ignition so that if $R_o = 0.3$ mm, for which $m \sim 22$ microgram of DT, ρR need be about 150 times larger than $\rho_o R_o$ and the required compression is about 1800. By using the advanced pellet fuels at much higher initial densities, the compressional requirements are relaxed by $(5)^{3/2}$ and C need be only 160. Already $(CD_2)_n$ pellet experiments have given compressions of thirty-fold.[24] Thus, a slight increase in core radius (say to $R_o = 1$ mm) would reduce the required C to the experimentally achieved value of about 30.

It should be noted that solid DT ignites at 3 keV provided the ρR condition is achieved. The advanced pellet fusion fuels — $LiD_{0.5}\,T_{0.5}$, Be DT, $BD_{1.5}\,T_{1.5}$, $(CDT)_n$, CD_2T_2, $ND_{1.5}\,T_{1.5}$, ODT — will have higher bremsstrahlung losses because of the high Z of the carrier element, so that some increase in ignition temperature is to be expected. If we define Q_p to be

$$Q_p = \frac{P_+}{P_{Brem}} = \frac{n_D n_T \langle \sigma v \rangle Q_+}{\alpha n_e \Sigma n_i Z_i^2 \sqrt{T_e}} \geq 1 \qquad (15)$$

for ignition (α = numerical constant), then the density coefficient K is

$$K = \frac{n_D n_T}{n_e \Sigma n_i Z_i^2} \qquad (16)$$

and is given in the Table:

Pellet	State	ρ_o (est.)	K
DT	Solid	0.213g/cm^3	0.25
$^6LiD_{0.5}T_{0.5}$	Solid	0.83	0.006
^9BeDT	Solid	0.97	0.009
$^{11}BD_{1.5}T_{1.5}$	Solid	0.77	0.010
^{12}CDT	Solid	1.16	0.003
$^{12}CD_2T_2$	Liquid	0.57	0.010
$^{14}ND_{1.5}T_{1.5}$	Liquid	1.03	0.004
^{16}ODT	Liquid	1.16	0.0015

B. Burn Characteristics and Applications

The relative reactivity coefficient K is 25 times larger for DT than for DT — enriched, liquid methane (CD_2T_2); however, $\langle\sigma v\rangle / \sqrt{T_e}$ varies as T^3 in the range T = 3-10 keV. Thus, the ignition temperature for CD_2T_2 is only about 3 times higher than that for solid DT. In fact, the degree of difficulty as measured by the product $T_{ign}C$ favors some of the advanced fuels compared to solid DT. Figure 18 shows the ignition of dense CD_2T_2 plasma using an ignition temperature of T_{io} = 10 keV, T_{eo} = 2 keV, and assuming a closed pulsed burn. No neutron energy deposition is assumed. In an actual pellet the initial compression will lead to a faster reactivity response whereas subsequent expansion of the pellet will give reduced reactivity.

At an electron density as low as 10^{14}e/cm^3 The CD_2T_2 plasma will still burn at $T \gtrsim 50$ keV, so that if additional DT fuel can be added to the plasma and the carbon and ashes gradually flushed out, one can visualize igniting and perhaps sustaining a magnetically confined plasma. Eventual feed of DD, D^{6}Li, or especially D^{3}He would ensure a somewhat "cleaner" burn. The exploding pellet plasma

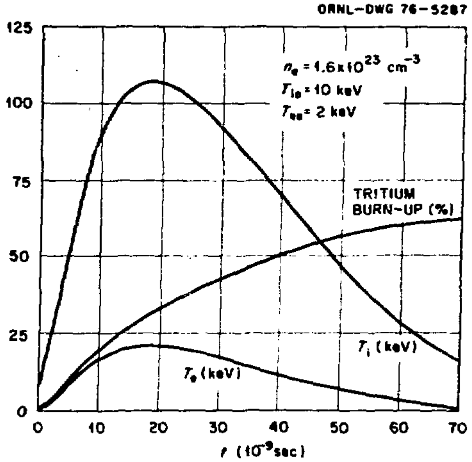


Fig. 18. Burn properties of dense CD_2T_2 pellet in a closed, pulsed burn (assumed constant density).

would introduce a large — scale diamagnetism of the hot plasma if located in a magnetic mirror field and this may permit development of a natural Ion Layer configuration. Thus, pellet fusion microexplosions could serve as the "match" to ignite steady state fusion reactors.

C. Excitation-heating Prospects for Runaway Ion Temperatures

Some years ago a 6 m long, magnetically confined carbon arc was found to have ions 100 times hotter than the electrons ($T_i \sim 500$ eV, $T_e \sim 5$ ev).[25] An hypothesis called "excitation-heating" was proposed to explain this unusual phenomenon. It involved the transfer of electron kinetic energy to excitation energy of doubly ionized carbon ions to form metastable ions (C^{2+*}). At 5-10 eV an inverted population of C^{2+*} ions is produced and most ionic collisions occur between two highly excited C^{2+*} ions. These collisions would be superelastic and the stored energy converted to kinetic energy of the ions; multiple cyclic processes lead to runaway ion temperatures. The individual steps in the cycles are:

$$\text{Excitation:}\quad e + C^{2+}\,({}^1S_o) \rightarrow e + C^{2+*}\,({}^3P^o_{2,1,0}) - 6.5\ \text{eV} \qquad (17)$$

$$\text{Heating:}\quad 2C^{2+*}({}^3P^o_{2,1,0}) \rightarrow 2C^{2+}({}^1S_o) + 13.0\ \text{eV} \qquad (18)$$

A dense pellet plasma containing carbon may prove even more efficient as a catalyst for promoting runaway ion temperatures in the dense pellet for three reasons: 1) the slowing down of fast ions in dense, low temperature plasmas decreases markedly because of the density effect on the effective stopping power[26,27], 2) the electrons form a degenerate Fermi gas [$T_{F(keV)} = 2.4 \times 10^{18}\, n_e^{2/3}$] which reduces the stopping power, and 3) excitation-heating might occur very efficiently provided T_e could be maintained at 10 eV.[28]

Whether such catalytic ignition of DT enriched polyethylene or liquid methane could be induced is a problem for the future. Suffice it to say that special care will have to be exercised in view of the hazardous nature of pellet microexplosions — a 1 mg D T burn is almost equivalent to 0.1 ton of TNT.

IV. CONCLUSION

This brief paper outlines some new perspectives and prospects for controlled nuclear fusion. Inasmuch as the outline is very skeletal, a significant research and development effort may be in order to evaluate these prospects in more detail and hopefully "harness the H-bomb" for peaceful applications.

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THE LONG-RANGE PROSPECTS FOR SOLAR ENERGY

By

William G. Pollard

Institute for Energy Analysis
Oak Ridge Associated Universities
Oak Ridge, Tennessee

There is, in the United States and many other countries today, a rapidly developing conviction among the public at large that energy from the sun can and will ultimately replace fossil fuels and nuclear electricity in meeting mankind's energy needs. This conviction expresses itself in almost every public discussion of energy problems and at the Congressional level in increasingly vehement demands that federal agencies sponsor major research and development programs on solar energy. The public at large has an implicit faith in the capability of science and technology to achieve any desired end if only adequate funding is provided. This faith has been amply justified by the dramatic successes of radar and atomic energy during the war and the space program after it. These scientific achievements are not, however, appropriate models for solar energy research because none of them involve considerations of cost or competitive merit with respect to alternative ways of achieving the same desired end.

The problem in using the sun to meet mankind's energy needs is not primarily scientific or technological. Solar energy systems can, without question, be developed and made to work from an engineering standpoint. Rather, the central issue is whether once achieved they would have the possibility of commercial adoption as a practical component of the nation's energy system in competition with alternative means for providing the same energy. It is from such an economic and commercial standpoint that an effort is made in this article to evaluate the long range potential of various ways of using solar energy. In effect, any desired degree of success in research and development is assumed and the evaluation carried out here then tries to visualize the resulting system in operation by industry in the normal business of selling electricity, fuel, or equipment to customers. This type of evaluation is carried out in the first two sections of the article according to whether solar radiation is used directly or indirectly, and these sections are followed by a third section devoted to solar-derived fuels from agriculture or forestry.

Direct Solar Energy

Systems designed for the direct use of solar radiation can be broadly grouped into those for solar heating and those for solar electricity. Only the latter will be considered here, since solar heating systems have been developed and are presently available on the market and their long-range potential is already assured (1).

There are two major approaches to the direct generation of electricity from solar radiation presently under vigorous research and development: solar-thermal and photoelectric systems. Solar-thermal systems use mirrors or lenses to concentrate the solar radiation on a receiver or receivers where its energy is absorbed as heat in a working fluid such as steam. The hot working fluid then drives a turbine or some other form of heat engine to generate the electricity. Photoelectric systems use silicon, germanium, cadmium sulfide, or some other photosensitive material in thin sheets to convert some fraction of the solar spectrum directly into electrical energy.

Either of these systems, or any other which might be developed in the future, will be constrained by certain limitations imposed by the nature of solar energy as such which cannot be circumvented by any amount of research and development of any particular system. The long-range outlook for commercial electricity generated directly from the sun is governed largely by these limitations rather than by the success of solar energy research. There are four categories of such constraints: the efficiency of the system in converting solar radiation into electricity, the low intensity of solar radiation coupled with the resulting land area requirements, and the intermittency of supply of solar energy. Any conceivable land-based direct solar electric system ever to be developed can be evaluated under these four headings. In carrying out such evaluations it is useful to refer them to a reference system of more or less standard size and cost. For this purpose a coal-fired or nuclear electric plant with an installed capacity of 1,000 megawatts generating 5 billion kilowatt-hours per year (corresponding to a capacity factor of 57 percent) will be used. An arbitrary figure of $1,000/kW(e) in 1975 dollars, or $1 billion, will be used for its cost. In specific applications the actual values could, of course, deviate considerably from these, but they are used here only as rough guides to assist the reader in visualizing the scope and cost of substitute solar electric plants.

1. Conversion Efficiency

The simplest measure of the conversion efficiency of any solar electric system for the purpose of this analysis is the amount of heat, measured in British thermal units, received from the sun from all directions on the solar collectors of the system for each kilowatt-hour of electricity generated. This measure is the annual average gross heat rate, $\underline{H}$, of the system in Btu/kWhr. In solar-thermal systems the instantaneous heat rate is subject to daily and seasonal variations with solar elevation and intensity which are not nearly as pronounced in photoelectric systems. In both cases, such fluctuations are averaged over a full year. The smaller the value of H, the more efficient the system is in converting solar radiation into electricity.

One of the more promising of the solar-thermal systems under active development consists of a tall tower on which is mounted a solar radiation receiver with a field of heliostats spread out from its base, each of which reflects an image of the sun into the receiver. For such a system the minimum achievable value of H is 15,000. This value could only be realized on a site at which over 80 percent of solar radiation throughout the day is direct from the sun, over 85 percent of that falling on the heliostat mirrors over long periods is reflected into the tower-receiver, and at which the loss in the receiver in converting received heat into high pressure steam was less than 5 percent. In that case the product of these factors allows two-thirds of the 15,000 Btu received on the solar collectors, or 10,000 Btu, to be retained in high pressure steam. The steam pressure and temperature contemplated for such systems is sufficient for the generation of 1 kWhr of electrical energy from this 10,000 Btu of thermal energy. On other sites with a higher percentage of diffuse radiation not reflectible by mirrors - or with systems of lower continuous reflectivity, greater receiver heat loss, or lower efficiency of steam-electric conversion - the heat rate could easily be double this minimum value or 30,000 Btu/kWhr. We will assume that, in the long range, research and development on systems of this type will succeed in achieving a gross annual average heat rate of 30,000 or less but no smaller than 15,000.

Photoelectric cells convert a fraction of the solar spectrum directly into electricity. At a heat rate of 15,000 this fraction would be 23 percent, which is probably more than can be achieved by even the most optimistic research breakthrough. At a heat rate of 30,000 the fraction is 11 percent, which is now realized and somewhat exceeded in present photoelectric cells. Thus, an annual average minimum heat rate of 15,000 and maximum of 30,000 can be taken to bracket both systems, and probably any solar electric system which might be developed in the future.

2. Low Intensity of Solar Energy

The total amount of solar radiation received per year on a unit area of the earth's surface varies considerably over the United States. We designate this annual insolation per unit area by J and measure it in Btu/ft^2 yr. In the deserts of the American Southwest there are sites for which J is 750,000 (2) but this is a maximum value for the country. In the lower Midwest and the Southeast a typical value of J is 525,000. Other areas with a value of J less than 500,000 have so many sunless days that even a premium solar electric system would probably not be practical.

A solar electric plant with a heat rate H built on a site with annual insolation J will generate J/H kilowatt-hours of electricity annually for each square foot of solar collector. Thus a plant of maximum efficiency on a Southwestern desert site might deliver 750,000/15,000 or 50 kWhr/ft^2 of electricity annually while the same plant on a Midwestern or Southeastern site would deliver only 35 kWhr/ft^2 annually. A plant with a heat rate of 30,000 would deliver only half as much electricity or 25 and

18 kWhr/ft^2 respectively.

In order to match the output of the reference plant (5 billion kWhr/yr.) with a system heat rate of 15,000, 100 million ft^2 or 2,300 acres of solar collectors would be required on the most favorable site and 140 million ft^2 or 3,300 acres on the less favorable site. The least efficient systems considered in this analysis would require double these areas of solar collectors. Assuming the capital cost of the reference system is $1 billion, and that it is desired that the solar electric plant be no more costly, then the cost of the most efficient plant should not exceed $10/ft^2 of solar collector on the desert site or $7/ft^2 on other sites. These costs limits become $5 and $3.50 per ft^2 respectively when the system heat rate is 30,000.

For the tower-heliostat plant about half the cost is for heliostats and the other half for the tower, receiver, steam lines, turbine, generator, cooling towers, and land. Thus the heliostats should not cost more than $5/ft^2 of mirror area even on the best site. For the photoelectric cell system the facilities other than solar collectors (consisting of electrical collection network and DC-AC converters) are considerably less costly, so that the solar cells could cost perhaps $9/ft^2 in the best case.

The heliostats might consist of a 25 ft^2 mirror on a suitable foundation and mounting, and be equipped with an accurate two-axis tracking mechanism responsive to a central control continuously monitoring the position of the sun. Protection of the mirrors against damage by storms, hail, and windblown sand would be necessary. They should have a long, trouble-free life expectancy over which high mirror reflectivity would be maintained. For the reference system, on the sunniest site with premium efficiency, 4 million of them would be required. The cost limitation of $5/ft^2 of collector area requires that they be manufactured, delivered, and erected on the site (on an adequate foundation) for no more than $125 each. Meeting these requirements within this cost limitation certainly calls for great ingenuity and inventiveness but does not constitute research in the usual sense of the term. In the case of the photoelectric system the requirement is for 100 million square feet of solar cells manufactured and installed on the site for $9/ft^2 or less. This requirement does call for the highest order of research in solid state physics combined with cost saving mass production techniques, since present solar cells cost several hundred dollars per square foot at best.

If the best heat rate achievable turned out to be 30,000 Btu/kWhr for either system, and it was built in the Midwest or Southeast, 11 million 25 ft^2 heliostats would be required at a maximum cost of under $2/ft^2 or $50 each, or 280 million square feet of solar cells at a maximum cost of $3.50/ft^2.

3. Land Requirements

The low intensity of solar energy results in very large areas of land being needed for the construction of a solar electric system. In order to provide maintenance access to heliostats or solar cell panels and to avoid shading of one set of either by an adjacent set, a land area of over twice the area of solar collectors is required to accommodate a solar electric system. At a heat rate of 15,000 this means a requirement of seven to ten square miles of land for the reference system, the smaller area being for the Southwestern desert sites. At the 30,000 heat rate, double this amount of land would be required.

Considering that a 1,000 MW plant is a relatively small component in most electric utility systems, these large land areas constitute a major barrier to a future large-scale deployment of solar electric plants. In the long range we are considering here - when larger populations lead to increased competition for land for agriculture, forestry, recreation, wilderness preservation, and community development - the procurement of such large blocks of land for electric power generation is likely to be a severe problem in most parts of the country other than some desert sites. There is also the environmental and aesthetic problem of covering hundreds of square miles of American deserts or the lower Midwest and South with mirrors or photocells.

4. Intermittency of Solar Energy

Any direct solar electric system can, of course, generate electricity only when there is sun. No generation can take place between sunset and dawn on any day, and even in the Southwestern desert there can be periods of bad weather of from four to five days duration during which the system would be inoperative. The result is that even on the sunniest sites electric generation can occur only 40 percent of the time, and on most other sites for 30 percent of the time, or less annually.

One way to deal with this intermittency of solar energy would be to use solar electricity to supply an industry which would operate only when the sun was out. Some industrial processes requiring large amounts of electricity could be designed to operate intermittently. At night and during periods of bad weather or sunless days the plant would simply close down and the employees, like farmers, would occupy themselves in other pursuits. Such applications are, however, clearly very limited. The major portion of the demand for electricity must be met in more continuous and dependable ways.

A second alternative would be to operate the solar electric plant in conjunction with other electric generation facilities in such a way that the output of the combined system can match the demand for electricity at any time. A particularly attractive system of this type is that being planned for the Salt River Project of Phoenix, Arizona (3). Here, a 100 MW(e) tower-heliostat system is to be built adjacent to the Horse Mesa Dam. The solar plant would have eight tower receivers receiving concentrated solar heat from eight fields of heliostats covering the steep slope of the mesa. The calculated heat rate for the system is 16,100 Btu/kWhr. The Horse Mesa hydroelectric facility would be operated for electrical generation only when the solar electric plant was not operating. The effect of the solar plant is to conserve water for the hydroelectric plant. In this case the land area is available and the practicality of the project depends on holding the cost of the heliostats to $\$5/ft^2$, keeping the gross heat rate down to the target 16,000, and assuring the security of the investment in the system against weather damage for 20 years or more. If these conditions can be met, combined solar electric and hydroelectric systems might prove attractive elsewhere in conjunction with impoundment dams of sufficient excess storage capacity, although the maintenance of an adequate water supply for downstream run-of-the-river dams might be an added problem.

Another way would be to build a coal-fired steam generator which would feed the steam lines of the generating plant when steam was not being supplied by the adjacent tower receivers. In this mode of operation, the amortized capital cost of the heliostats and tower receivers would have to be less than that of the coal-fired steam generator plus the cost of the coal consumed to make the combined system economic. In view of the cost constraints on the heliostats which have already been discussed, this condition seems unlikely to be achieved. The same cost criterion would apply to any solar facility integrated into a utility network primarily using fuels for electric generation.

The only other way to deal with the intermittency of the solar supply is to store large amounts of the energy produced either as heat or as electrical or mechanical energy. A variety of both types of energy storage facilities are the subject of active research and development; a few examples will serve to clarify the problem. A high temperature heat storage system developed by the Phillips Company uses fused flouride salts as the storage medium. For a tower-heliostat system the salts could be fused directly in the solar receiver or indirectly with an intermediate heat transfer medium such as a molten metal. The fused salts would later give up their stored energy to generate high temperature steam. Another storage method which could be used with either solar-thermal or photoelectric systems, in areas where the terrain was suitable, would use 60 to 70 percent of the electrical output to pump water from a depressed reservoir into an elevated reservoir. From this reservoir, electrical generation could take place as required to meet demand as with any hydroelectric power plant.

In both of these storage modes the efficiency is presently about 75 percent, so that if 70 percent of the direct solar energy goes temporarily into storage, the area of solar collectors must be increased about 20 percent to yield the same annual output of electricity. The capital cost of either type of storage facility, with a capacity for storing eight days output from the system, is about $800 million for the reference system assuming $6 per kilowatt-hour stored. This means that the capital cost of the reference system with this amount of storage and the additional collectors is double that of the system without storage.

Since photoelectric cells generate low voltage electricity, this type of system is particularly suitable for storage batteries or the electrolysis of water to produce hydrogen. The efficiency of battery storage is about the same as that of pumped hydro storage but the cost of providing any given storage capacity is presently about five times as great, although present research can be expected to lead to higher efficiencies and lower costs per kilowatt-hour stored. In the other method of storage, part of the photocell output is used to electrolyze water, the hydrogen produced is liquefied and stored, and fuel cells are then used to generate electricity on demand. However, when the energy losses in electrolysis and liquefaction are combined with the 50 percent efficiency of fuel cells, the electricity recovered from the latter is only 30 percent of that originally supplied by the photocells. Thus if 70 percent of the photocell generation went through this storage mode the area of photocells would have to be doubled to maintain the same annual output of electricity. The capital cost of electrolytic cells, liquefaction equipment, and fuel cells would be at least as great as that of storage capacity. Even allowing for improved efficiencies of batteries, electrolytic cells, and fuel cells, and for lower costs for the same capacity as a result of present and future research, the capital cost of a solar system with either method of storage would be from three to five times that of the same system without storage.

It should now be evident from this analysis that the direct use of the sun is simply not a very suitable way to provide electricity in utility systems designed to supply it on demand. Any one of the factors discussed in the foregoing might well support this conclusion by itself, but all of them taken together are rather decisive. It seems quite unlikely that it will ever be possible to manufacture and install adequate 25 ft^2 heliostats for as little as $50-125, or to provide adequate maintenance of mirror reflectivity and tracking accuracy for millions of them spread out over several square miles without excessive costs for operation and maintenance. It seems equally unlikely that photocells with an efficiency of 23 percent can ever be produced and installed for as little as $9 per square foot. If this is the case, then the initial investment in a reference solar electric plant would probably be considerably more than the $1 billion assumed in the foregoing analysis. Moreover, such an investment would have to be made in delicate equipment spread out over 10 to 20 square miles which, during a 30-year life expectancy, would be subject to massive losses through storm damage. For the utility investing in it, sufficient energy storage to make such a system equivalent to a 1,000 megawatt coal-fired or nuclear reference plant would at least double - probably quadruple - the total capital investment required. Taking all these factors into consideration, it seems clear that electric utilities in the business of generating large blocks of central station electricity will almost certainly not decide to invest in a solar power plant, no matter how well engineered, as long as any other alternatives are available. To the utility making it, the investment would appear excessive for the expected return and the assurance of its surviving a normal 20-30 year operation period without major loss would be dubious.

Indirect Solar Energy

For thousands of years man has been using water and wind power for mechanical work. Both are, of course, derived from the sun either through lifting vaporized water to high altitudes or through the atmospheric turbulence which accompanies the maintenance of thermal equilibrium between the earth and the sun. Water power has long been a major source of electricity at modest cost and the further development of hydroelectric resources will certainly occur as world populations and their need for electricity increase in the decades ahead.

Wind power was extensively used for pumping water in Holland until cheaper, less demanding and more convenient ways to do so became widely available. In rural America in the 1920's and 1930's, windmill electrification systems were common but were abandoned when central station power became available through the Rural Electrification Program. Now, impending energy crises have reawakened interest in wind power as a source of electricity.

The NASA-Lewis Laboratory at Cleveland, Ohio has built a prototype test unit which utilizes a two-bladed propeller, each blade of which is 62-1/2 feet long. Mounted on a high tower and turning at 40 revolutions per minute, it generates 100 kW of electrical power when the wind speed is above 18 miles per hour. It is structurally strong enough to withstand occasional gale force winds. The initial test unit is quite expensive, but it is hoped to substantially reduce this cost as the program proceeds and production models are built in quantity. In areas of frequent wind such as Oklahoma and West Texas, wind speeds above 18 mph may occur up to 30 percent of the time. An actual unit tested in Vermont generated electricity 14 percent of the time, and one in Denmark generated electricity 23 percent of the time. If electrical generation occurred 20 percent of the time on an annual basis, the output of the NASA-Lewis generator would be 175,000 kWhr/yr. It would require nearly 30,000 of such installations to equal the electrical output of the reference plant used in the solar electric analysis.

The intermittent nature of wind leads to much the same problems for wind electric systems as for the solar electric systems already discussed. The addition of large capacity energy storage facilities to an already large capital investment in wind machines and generators would militate against their commercial adoption. Among the various ways in which wind-generated electricity might be incorporated into existing electric utility systems, there are three which seem the most promising. In conjunction with hydroelectric dams, large wind machines might be used to pump water into existing impoundment reservoirs whenever wind is available, with corresponding increases in the hydroelectric generating capacity. In the second mode, wind electric generators could be built along utility transmission lines with line control of the frequency and phase of the electricity generated so that the output could be fed into the line at selected points by matching transformers. The third method would use wind machines to compress air in the vicinity of utility peaking power gas turbines. The compressed air would be stored and drawn upon for injection with fuel to the turbine when needed, with corresponding major reductions in the turbine heat rate by which the stored energy would be recovered.

In any of these ways of utilizing wind-generated electricity in an electric utility system, the amount so generated would simply replace what the system would have supplied without it by burning more fuel. The economics of any such application is therefore dependent on whether the annual costs of capital recovery and operation and maintenance of the wind system are less than the annual cost of the fuel which it saves. At present fuel costs and expected capital costs of wind systems this would hardly be the case. But in the long range, when fuel costs are much higher than now and the cost of manufacturing and installing reliable wind machines in quantity production has been substantially reduced, this situation might be reversed. In that event one could anticipate some use of wind electricity in utility systems but it seems doubtful that it would ever constitute more than a minor fraction of the total electrical output of the country.

None of the considerations advanced so far in this analysis are intended to apply directly to combined solar heating and photoelectric and wind electric or pumping systems supplemented with solar-derived fuels for rural areas in the U.S. and developing countries or remote applications throughout the world. Such small total energy systems using local wastes to supplement solar heat, combined with wind or photoelectric generation with limited storage and no transmission costs, seem destined to play an increasingly important role in the total world energy system. There are attractive possibilities in such applications, and their economic and practical evaluation rests on quite different criteria than those for central station power. The conclusions drawn from the foregoing evaluations of direct and indirect solar electricity are not intended to apply to such small, self-contained total energy systems.

Two other solar electric systems which have been proposed should be described here briefly. The one under most active development at present uses the difference in temperature between warm surface water and cold deep water in the tropical oceans. A system designed to recover useful energy from this solar-maintained thermal gradient is called an Ocean Thermal Energy Conversion (OTEC) system. Active engineering design and component testing for such systems is presently underway by several contractors of the Energy Research and Development Administration.

Such a plant would be hung from a large, moored platform floating on an appropriate site in the tropical ocean. The working fluid would be pressurized ammonia gas driving a turbine generator. The exit gas would be condensed in a large area condenser cooled by water drawn by marine propellers through a concrete pipe some 40 feet in diameter, from a depth of 1,000 feet or greater. The cool liquid ammonia would then go to a similar evaporator heated by surface water fed through a similar but shorter pipe. Electric power generated in this way would either be transmitted to land by submarine cables or used to produce electrolytic hydrogen from seawater followed by shipment of the liquefied hydrogen to land in tankers. About 30 percent of the power generated is used to operate the system, mainly for cold and hot water circulation. If hydrogen is generated, another 40 percent would be used in electrolysis and liquefaction.

A design by Lockheed of a 160 MW(e) OTEC calls for 235,000 tons of concrete and 26,000 tons of steel for the platform; 8,700 tons of cold-rolled steel and 1,800 tons of titanium for the power system; 11,000 tons of steel for the mooring line; and 32,000 tons of concrete for the cold water pipe. The capital investment in such a system for each net electrical kilowatt it could generate would be very large. Moreover, the problems of repair and maintenance of such an installation over a 20- to 30-year lifetime seem formidable. The titanium heat exchanger elements have a surface area of over 150 acres and any fouling of them by growth of biological organisms would make the system inoperative.

The research and development program now underway on OTEC doubtless constitutes a very interesting challenge for engineers, heat transfer scientists, marine biologists, and others engaged in it. It seems very doubtful, however, that such a system would ever attract the massive private investment required to construct it or ever actually be deployed commercially by electric utilities. A non-solar application of the same system might, however, develop marginally out of the R&D program on OTEC. This would use the waste heat from large nuclear power plants, gas diffusion enrichment plants, or other plants yielding large amounts of waste heat for a land-based, ammonia cycle electric generation system using similar 40-50^{o}F temperature differentials. Heat exchangers would be of aluminum rather than titanium, and a total system of the same electrical output would cost only about one-fifth that of the OTEC system and considerably less in annual costs for operation and maintenance.

The other solar electric system which has been proposed would mount the mirrors or photocells of the system on a satellite equipped with an electric generation system and a power converter to microwave radiation beamed to earth, with the whole unit placed in a stationary earth orbit. Microwave energy would be continuously beamed to a receiver on earth, converted to 60 cycle power, and fed into a utility grid. In such an orbit, solar energy would be converted continuously at a constant rate, except for an hour and ten minutes each day around midnight when the satellite passed through the earth's shadow. The annual collection of solar energy would be much higher than that for any land-based system, since J would be 3,600,000 Btu/ft^{2} yr. Because of the microwave conversion and transmission to earth, the heat rate would be considerably larger. Even 30,000 Btu received on the solar collectors in space for each kilowatt-hour delivered into the utility grid on earth seems optimistic. With this value of H, the annual electrical yield would be 120 kWhr per square foot of solar collector. Using the reference system in the preceeding section for comparison, 42 million square feet or one-and-a-half square miles of solar collector would be required. However, if serious consideration were given to the assembly of such a satellite in space it would doubtless be for a much greater installed capacity. The equivalent of 50,000 megawatts of nuclear capacity at a 60 percent capacity factor would require 75 square miles of solar collectors on the satellite. Even with a fully developed space shuttle, the assembly of that area of solar collector (together with associated energy collection and generation facilities and microwave conversion and beaming equipment) in a satellite 22,000 miles above the earth's surface represents a monumental task. As long as electricity can be obtained in simpler ways, it is a task not likely to be undertaken.

It is unfortunate that so many people continue to entertain such high hopes for satisfying all our needs for electricity through direct or indirect means of generating it from the sun. In remote locations, where cost is not a factor, a small amount may be produced with wind or solar cells and battery storage and the potential for small, self-contained total energy systems for rural homes and farms is significant. But for any appreciable contribution to future national requirements for central station electricity, neither direct nor indirect solar energy (other than hydroelectric) is really suitable. There is practically no chance of realizing such a contribution regardless of how vigorously it is promoted and funded by the Congress in response to public aspirations.

Solar-Derived Fuels

The fuel which man has used since the most primitive periods of his evolution as a species is wood. This fuel, in turn, is directly derived from the sun through the process of photosynthesis which converts carbon dioxide and water into carbohydrates through absorption of energy from sunlight in chlorophyll. This ancient fuel is the prototype of all solar-derived fuels. In this section the potentiality of utilizing photosynthesis on a large scale to generate solar-derived fuel in sufficient quantities to ultimately replace man's dependence on fossil fuels is considered. In contrast to the largely negative evaluations of the preceeding sections, the evaluation here of the prospects for solar-derived fuels is quite positive, as will be seen. Unfortunately, such fuels are not generally considered "solar energy", so a certain degree of public education will be required to persuade people that research and development carried out in this area properly falls within the category of a national solar energy program.

In one sense the fossil fuels - coal, oil, and natural gas - are also properly called solar-derived fuels: however, they were all produced from solar energy received by the earth many million years ago. In the sense used here, solar-derived fuels are those produced annually by the sun in plant material growing now.

If it should prove possible to largely replace fossil fuels with solar-derived fuels, there would be two advantages of considerable importance. The first is that the burning of solar-derived fuels, in contrast to burning fossil fuels, does not add to the accumulation of carbon dioxide in the atmosphere. The reason for this is that all of the earth's biomass, whether converted into solar-derived fuels and burned or left to decay naturally, is soon converted back to CO_2. On the other hand, when fossil fuels are burned they release to the atmosphere CO_2 which had been removed from it many millions of years before. Thus solar-derived fuels share with uranium and thorium the property of yielding energy without adding to atmospheric CO_2. Insofar as atmospheric build-up of CO_2 may, in time, lead to large planetary changes in climate, this is obviously a vitally important property of solar-derived fuel.

The other advantage of great significance is that the potential production of solar-derived fuels is an order of magnitude greater in the humid tropics lying between latitudes ± 20° than it is in temperate zones at much higher latitudes. This means that in the long-range future, if and when solar-derived fuels have largely replaced fossil fuels, the tropics will have developed a large and lucrative export market for them. Since the countries lying in this tropical belt are now the most impoverished and suffer from the highest rates of population increase, this could represent a major contribution to world economic welfare in the future. If the countries of tropical Latin America, Africa, and Malaysia could, by the end of this century, begin supplying the rest of the world with a major portion of its demand for essential liquid fuels (and so acquire ample trade balances for the import of food and other goods) the result would be a contribution to world stability of the very highest importance. Such a "project interdependence" should be a top priority for solar energy research.

The world dependence on gasoline, jet fuel, and fuel oil is massive, growing, and essentially irreversible short of real catastrophe. The maintenance of private transportation by automobile, transport of food and goods by truck, air passenger and freight traffic, and agricultural production is now entirely dependent upon these fuels. Yet sometime late in this century or early in the next the finite reserves in the earth's crust, on which this vast system of dependency is based, must inevitably shrink and finally dwindle to insignificance. This is the most predictable aspect of the world energy picture at the present time. Energy is also needed for electricity, industrial process heat, and heating buildings; but these needs do not loom with quite the urgency as does that for liquid fuels in the transportation sector.

It is of primary importance, therefore, to inquire what can be done when gasoline and other petroleum-derived liquid fuels are no longer available. One answer, already resorted to in the past in wartime, is the alcohols - methanol and ethanol. At the present time, even at current high world prices for crude oil, these are too expensive to compete with gasoline. In the long-range when these prices have doubled or tripled, as they will, to $25-35 per barrel or $4-6 per million Btu in current dollars, they will become quite competitive. At $6 per million Btu, the price of gasoline at the pump would be 70¢ per gallon exclusive of taxes (4). The corresponding price for the same energy content of methanol would be 34¢ per gallon and 46¢ per gallon for ethanol. Assured prices at this level would make the manufacture of these alcohols, by presently available methods, a very attractive commercial option.

The transition from a petroleum-based economy - with its vast network of supply, transportation, refining, and public distribution - to one based on alcohols would be difficult and complex to manage. No attempt will be made here to analyze the complexities of this transition or to describe how it might be made, except to note that with an automotive turnover of 5-10 years it should be possible to accomplish it in a decade or so. Since this discussion is concerned only with the long range, it will simply be assumed that the transition has already somehow been accomplished. Once it has, however, there is little question that the resulting situation would be entirely feasible and satisfactory. With only minor modifications in engine design, both alcohols can be used effectively as high octane fuels in internal combustion engines. In automobiles, trucks, and jet aircraft, larger fuel tanks would be required (double for methanol, 50 percent larger for ethanol) for the same fuel supply because of the lower heat values. Other than this the alcohols make entirely satisfactory motor fuels.

1. Solid Fuel

The basic system for the production of both solid fuel and methanol from biomass is pyrolysis. In pyrolysis wood, leaves, grass, or any similar material, including the organic component of municipal solid wastes, are heated in a closed container or converter by partial burning of a portion of the feedstock with air or oxygen introduced in a controlled manner at the base of the converter. The product is a low Btu gas, volatile vapors, and a solid carboniferous char. The gases are mostly hydrogen and carbon monoxide; the condensable vapors are steam and a variety of volatile organics; and the char is a solid like charcoal. In low temperature pyrolysis the air intake is reduced and its rate adjusted in proportion to the feedstock rate so as to minimize the production of gas and maximize that of char. A major research and development program for this purpose has been carried out in the Engineering Experiment Station of the Georgia Institute of Technology over the last eight years (5). Extensive tests of the system with a variety of organic feed materials have been performed in a 25-ton-per-day pilot plant. A commercial plant of 50 tons per day has been operating at a sawmill in Cordele, Georgia for two years producing charcoal briquettes from the sawmill wastes. As a result of this work the technical design and operating parameters for commercial plants are now well established.

The product of the process is a free-flowing, dry black powder similar to a finely ground coal. It has a heat value of 11,000-13,000 Btu per pound which is the same as that of Eastern bituminous coal. It has essentially zero sulfur content and much lower ash than coal. It can be used in the same way as coal to form a slurry with fuel oil for use in oil-fired boilers, or mixed with high sulfur coals to form a reduced sulfur fuel for use in coal-fired steam generators. At present coal prices, this fuel is just economic when the feedstock wastes are provided without charge. In the long range considered here, when fossil fuel prices are much higher, it would become economically attractive even with ample payments to the supplier of the biomass feedstock.

The raw feedstock, generally running 50 percent moisture content, is fed through a hammer mill and thence through a dryer heated with low Btu gas from the converter. From the dryer it is fed continuously into the converter at a rate which governs the flow rate of air to the combustion portion of the converter. The volatile organics are condensed at a temperature greater than the off-gas dew point to avoid moisture condensation, and the oil is mixed with the ground char to form the free-flowing powder or char-oil. Power to operate the system is provided by a derated gasoline engine running on the low Btu pyrolysis gas. Start-up of the engine and dryer is accomplished from an auxiliary propane supply. Typically, 450 pounds of char-oil product is obtained from each ton of undried raw waste. A mobile pyrolysis unit of a 200-ton-per-day capacity (at 50 percent moisture) is being designed for mounting on two standard 55 foot trailers which can be moved from one collection site to another.

The penetration of the solid fuel market by char-oil is likely to be hastened by increasingly stringent sulfur emission standards. The initial production will most probably be at the sites of major continuous waste production for which a means of disposing of the wastes would be an economic benefit to their producer. An example of this would be sawmills, cotton gins, sugar mills, and plants generating such wastes as peanut hulls, rice hulls, bagasse, etc. There are also perhaps as much as 200 million dry tons of wood wastes accumulated over the years from past sawmill operations in the Southeast, Maine, Michigan, and Oregon, including whole canyons filled with it in Northern California. The processing of these wastes could stimulate the growth of a sizeable industry for the manufacture of the mobile pyrolysis units as well as a growing market for their product. Once both of these have become established, demand for no-sulfur, very-low-ash, high-Btu char-oil fuel is likely to increase very rapidly as fossil fuel prices continue to rise and environmental protection measures become more stringent.

In the long range considered here, the potential for producing char-oil fuel in the United States is undoubtedly very large but also largely indeterminate. The reason for the indeterminancy is that so far there has been no motivation to use biomass as an energy resource. Agricultural wastes are simply plowed back into the ground and forestry wastes left in place after logging or pulpwood collection, or accumulated in vast sawdust piles thousands of acre-feet in volume. There are vast stretches of uncultivated forests where the ratio of culls to marketable trees is very high and logging operations not pratical. In Maine there are 5 million acres with an infestation of the spruce budworm which are entirely suitable for energy harvesting but not for lumber or pulp. Considering all these sources, U. S. forests probably produce some half-billion dry-weight tons of woody material annually which are suitable for char-oil production when unused forest material is combined with wastes and culls from logging and pulpwood. Canadian forests could add a large increment to this annual production.

Our perspective on the magnitude of the energy resource in solar fuels is distorted by the abundance of cheap fossil fuels we have enjoyed since the start of the industrial revolution two centuries ago. In this period, plant material has been grown exclusively for food, fiber, lumber, and paper. Everything grown which is not suitable for these end-products we call weeds, culls, or wastes. In a long-range future, when oil and gas are dwindling in supply and have become very expensive, the situation will be radically different: solar-derived fuels will have become quite valuable; farmers will be deriving nearly as much income from the sale of their annual product to an energy conversion industry as they do from the sale of food or fiber; forest management will yield as annual income from energy feedstocks comparable to that from logging and pulpwood production. In such a situation, agricultural production will strive for maximum production of food and energy or fiber and energy. Wetlands not suitable for food or tree crop production will be developed for growing tall grasses, reeds, or other plants with a high yield in dry tons per acre. A joint program of the University of Georgia and the Southeastern Forest Experiment Station has been devoted to growing sycamore, sweetgum, or yellow poplar trees in rows which are harvested after one to four years of growth with equipment equivalent to corn silage cutters (6). After cutting, the trees resprout from stumps and growth continues. Land in the Piedmont and Georgia Coastal Plain not suitable for other purposes produces well in this type of culture. On a four-year growth cycle, annual yields of sycamore of nearly six tons per acre were realized.

Only a small fraction of the total biomass in wheat, corn, or soybean production is harvested for food. When the cost of energy approaches $6 per million Btu, however, the rest of the biomass will represent a saleable product which can materially increase the income derived from farming. In such a situation, agricultural research will be devoted to maximizing both food and biomass yields. Hybridizing to reduce the height of corn will be reversed so as to return to the corn which "grows as high as an elephant's eye". Harvesting machinery will be developed which minimizes the cost and effort in harvesting both food and biomass simultaneously.

What is visualized here is a growing complex industry developing in response to assured markets for energy at increasingly attractive prices. It will involve new concepts of land use and management not previously contemplated. The sheer magnitude in economic value of this industry will lead to extensive agricultural and forestry research, new designs in harvesting machinery, and new institutional arrangements for handling the chain of events between the farm or forest and the end users of the solar-derived fuel produced in the system.

In the tropics, with their much higher annual production of biomass per acre, the production of char-oil fuel for local use in electric generation or industrial process heat is a very attractive possibility now. These countries can ill afford to import Middle East oil for these purposes. A U. S. or multinational aid program to supply them with the relatively simple equipment for char-oil production and specially designed machinery for harvesting and delivery could pay off handsomely in economic benefit to the recipient country for a minimal outlay of aid dollars.

2. Liquid Fuels

When a pyrolysis unit is operated at a high temperature with increased air or oxygen supply, most of the char and oil are converted into the gaseous component. This gas can be used as the synthesis gas for the production of methanol. For this purpose, two moles of hydrogen are combined with one mole of carbon monoxide at a pressure of some 100 atmospheres and a temperature around 700°F in the presence of a catalyst, to produce one mole of methanol (CH_3OH). The process is well established and has been used for many years in the United States to produce non-fuel industrial methanol. The 1972 production was 26 million barrels and the present market price for tank car lots is 40¢ per gallon.

For many years into the future, fuel methanol in the United States would most probably be produced from coal rather than organic wastes. The 34¢-per-gallon delivered cost of methanol previously stated (corresponding to 70¢ per gallon for gasoline) is based on coal delivered to the plant for $20 per ton. At this price, if dry biomass were substituted for coal in amounts sufficient to equal the same production of methanol, the annual income to those harvesting and delivering the feedstock to the plant would be $16 per ton.

In a recent book devoted to the world food problem, Erick P. Eckholm gives an excellent analysis of the status and prospects of agriculture in the humid tropics (7). Every effort to achieve sustained tropical production of food in the past has been disappointing at best and catastrophic at worst. The most promising approach is an agrisilvaculture which combines food and forestry in a closed cycle of food crops on cleared land which is followed by a planting of fast growing trees before the last food crop is harvested. It would appear that this mode, in a system in which fuel methanol was the major economic crop supplemented with food and timber production for auxiliary income, might prove to be the most desirable route for tropical peoples to follow. This joint cropping system could be supplemented with biomass grown exclusively for methanol production for which a major tropical pest such as the giant elephant grass could be a prime candidate. A similar possibility for such development would be selected species of reeds and similar plants which grow with exceptionally high yields in tropical bogs and marshes, not useable for food production.

The other alcohol which could serve as a motor fuel is ethyl alcohol or ethanol. Industrial ethanol (190 proof) is produced in the United States from ethylene, but for fuel use in the long-range future some source other than one derived from petroleum would have to be found. Such a source has been developed recently by the Army Natick Laboratory using a fungus which causes jungle rot in wood and other cellulosic material in Vietnam. An enzyme produced by selected strains of this organism converts properly prepared cellulose into glucose with very high yields. The Army estimates that 5 million barrels of ethanol could be produced by the enzymatic hydrolysis of 3 million tons of cellulose from municipal or agricultural wastes

For the production of large quantities of ethanol in the tropics, the tropical plant Manihot utilissima seems ideally suited (8). Commonly called manioc in Africa, yuca in Latin America, and cassava in English-speaking regions, it is best known in the United States and Europe by its product name, tapioca. The plant is a woody perennial which can grow to a height of 10 feet. It produces several below-ground tubers growing radially from the root stem to a length of a foot or more, weighing up to 30 pounds each. It is extensively used as a food by natives in the Amazon basin, the Congo, Madagascar, Indonesia, the Phillipines, and elsewhere in the tropics and subtropics mainly because of the ease in growing it. Plots in the forest are slashed and burned, leaving stumps and large trees; stems of cassava plants from the previous harvest are simply thrust into the ground through the coating of ashes and new plants grow from these cuttings in rather poor soil not suitable for other, more nourishing food plants.

The cassava roots are very high in starch and very low in protein and other nutrients. Other foods are desirable for raising nutritional levels in tropical native populations. This would be possible if cassava could be grown as an energy crop of high monetary value. The use of the plant for the production of fuel ethanol would constitute just such an application. For this purpose, the tubers can simply be sliced and sun-dried for two to three days to produce a durable starch product called gaplek in Indonesia. Molds which develop during drying, plus fiber and other constituents of the whole root, make gaplek flour unsuitable for human use but entirely satisfactory for fermentation to industrial alcohol.

Besides its simplicity of culture and its ability to grow in relatively poor tropical soils, cassava has the further advantage of great drought resistance. In a prolonged period of drought it sheds its leaves so that transpiration is greatly reduced; when rains come again it puts out new leaves and continues to grow. Whenever alcohol replaces gasoline as a fuel, the value of cassava as a primary feedstock for its production will be greatly enhanced. At that time the income derived from growing it should amply cover the means of replacing it with much higher quality food.

In a combined agri-silvaculture management of tropical ecosystems there would be the possibility of combining methanol and ethanol production. In clearing the forest, the good logs would be sold and the remaining branches, culls, and residual biomass delivered to a nearby methanol plant. Cassava grown in the clearings and later interplanted with fast growing trees would be delivered as dried gaplek to an adjacent ethanol plant. In order to be economic, both plants should have capacities of the order of 15,000 barrels per day. This would require that they each have an assured supply of around 2 million tons of feed material per year. At a low tropical production rate of 2 tons per acre of both biomass and gaplek, the alcohol production plants would require a service area of a million acres and a delivery radius of 20 miles. At a more likely tropical production rate of 16 tons per acre of each product, the service area is reduced to 125,000 acres and the delivery radius to eight miles. Because so much depends on the outcome of future agri-silvaculture research, it is not possible at this stage to make reliable estimates of yields from this type of management of tropical ecosystems.

The alcohol production plants themselves are an established technology and can be built whenever and wherever required. Arrangements for supplying such plants with their required feedstocks on an assured basis over long periods will, however, be complex and organizationally difficult to consumate. Such arrangements, moreover, should only be developed and put into operation after the completion of research on safe modes and rates of removal of biomass from tropical areas and on selected species and culture of cassava for maximum production in partially cleared areas. A research and development program with these objectives is agricultural rather than technological. It is urgently needed if the tropics are to become the source of liquid fuels when petroleum ceases to be available in sufficient quantities to supply the demand for motor fuel.

The extent to which alcohols would be produced domestically for motor fuel in the U. S. will depend on the price of imported fuel from the tropics. It is doubtful whether domestic ethanol production from the enzymatic hydrolysis of cellulose to glucose could ever compete with imported ethanol from cassava. On the other hand, methanol production from coal in the U. S. would very probably be markedly cheaper than imported methanol from tropical biomass. As long as coal continues to be abundant, the production of 500 million tons per year for methanol or other liquid motor fuel is not an unreasonable expectation when petroleum is no longer available for gasoline production. This would constitute a significant fraction of U. S. requirements in the long range, assuming greatly improved automotive efficiencies and somewhat lower per capita utilization of automobiles.

3. Gaseous Fuel

We consider, finally, the potential for deriving the gaseous fuel methane from agricultural wastes by anaerobic digestion (9). Equipment for achieving this has been available and in use for some time by municipalities for sewage sludge digestion. Essentially the same equipment could be used near animal feedlots for the digestion of urine and manures. The Chemical Engineering Department of the University of Missouri at Rolla has developed and demonstrated a process to utilize a slurry of ground agricultural crop wastes in similar facilities. The digestion produces a mixture of methane, carbon dioxide, and small amounts of other gases. After scrubbing the CO_2, the product is a pipeline quality gas.

Domestic production of natural gas has been declining for the last several years. Price deregulation will stimulate the opening of new fields, the eventual exploitation of new sources such as extraction of methane from coal beds before the coal is mined, and the tapping of large reserves in Devonian shales. When the price of natural gas reaches $3 per thousand cubic feet and higher, anaerobic methane from animal and agricultural wastes will become economically attractive. When this stage is reached it seems almost certain that anaerobic digestion plants with a capacity of 100-500 tons per day will be built in the vicinity of animal feedlots and poultry farms and, later, at selected sites throughout the Midwest which have contracted with farmers within a 6-15 mile radius for their feed. The methane produced could be pumped into the existing natural gas pipe-line near the plant. At present, the entire operation is technologically feasible and only awaits a favorable product price to begin commercial deployment without government assistance or intervention.

There are two major advantages in anaerobic digestion over char-oil production. Animal wastes have too high a moisture content to be suitable as feedstock for char-oil but for the same reason are ideal for anaerobic digestion. Agricultural wastes, on the other hand, can be digested without loss of the original plant nutrients, and the digested sludge is rich in humus. Thus farmers delivering feedstock to the plant could return with a corresponding amount of dried sludge for spreading on their land.

If the same wastes were used for char-oil production, some portion of them, depending on soil character, would have to be retained for plowing back to preserve the quality of the soil. For these reasons, methane rather than char-oil will probably prove to be the preferred solar-derived fuel for animal and agricultural wastes, while char-oil will predominate for forest and marginal land biomass and for sawmill and cotton gin wastes. The demonstration equipment at the University of Missouri at Rolla, when scaled up to a large plant, has shown that such a plant could produce 50 million cubic feet of methane per day from an annual delivery of 1.5 million tons of crop waste.

In addition to animal and crop wastes, there is a large potential in growing material such as water hyacinths in wetlands and marshes specifically for the purpose of anaerobic digestion to methane. A novel proposal of this sort contemplates growing forests of help in the ocean which could be harvested in large quantities for methane production.

Conclusions

The use of solar radiation for hot water and for heating buildings is already commercial and its potential in the long run is substantial. As the cost of fuels and electricity escalate and scarcities develop, solar heating systems seem certain to be increasingly deployed. The situation is quite different, however, with systems for the direct or indirect use of solar energy for the generation of central station electricity in utility systems. Large plants in the order of 1,000 MW(e) providing electricity to users on demand are unlikely to ever actually be built and operated at economic gain as long as any other alternative is available. This will be considered an overly pessimistic conclusion by many but the case for it, developed in the body of this article, is substantial.

The long-range prospect for solar-derived fuels seems, on the other hand, assured. The technology for such fuels - solid, liquid, and gaseous - is already well developed. Their extensive utilization awaits only a favorable price level and a massive effort in tropical and temperate zone agriculture and agricultural engineering. As alcohols begin to replace gasoline for transportation fuel, countries in the humid tropics can begin to develop a growing, lucrative, and assured export market. The potential of this market for alleviating critically pressing world economic and social problems is a secondary benefit of solar-derived fuels of the greatest importance.

(This paper is also being published in the American Scientist, 1976.)

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Cost Comparison Between Base-Load Coal-Fired and Nuclear Plants in the Mid-Term Future (1985-2015)*

by

Doan L. Phung

Institute for Energy Analysis
Oak Ridge Associated Universities
Oak Ridge, Tennessee 37830

Abstract

The relative costs between the coal and nuclear modes of electricity generation in the period between 1985 and 2015 has been examined with the "best" estimates" approach coupled with a scenario study that covers various sensitive factors. Baseline data for capital and operating costs at "beginning of life" are determined by careful examination of past, present, and short-term future trends. Estimated inflation of the economy and net fuel cost increases are internalized in the determination of life-cycle levelized cost of electricity in several plausible scenarios.

Best estimates for capital costs in 1985 dollars are determined to be \$1,080/kWe, \$860/kWe, and \$700/kWe, respectively, for nuclear plants, coal-fired plants with SO_2 scrubbers, and coal-fired plants without SO_2 scrubbers. Several factors such as geographical location, construction scope requirements, and construction duration contribute to an uncertainty of ±40 percent to these capital costs. Baseline nuclear fuels are estimated at \$75/lb U_3O_8 and \$150/SWU, but still result in a nuclear fuel cost at approximately half the cost of coal.

Of the five typical regions of the country considered in the study (the Midwest, the Northeast, Florida and Texas, Appalachia, and the northern mountain states), results indicate that the low-sulfur coal option is always attractive in the northern mountain states, whereas the nuclear option would be less costly elsewhere. The magnitude of cost difference between the options depend on the inflation rate of the economy and on the methods of discounting a stream of future expenditures to a fixed point in time.

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*This report was prepared as an account of work under Contract E-(40-1)-GEN-33 between the U. S. Energy Research and Development Administration and Oak Ridge Associated Universities.

Introduction

The purpose of this study is to examine the relative costs between the coal and nuclear modes of electricity generation in the period between 1985 and 2015. These two modes of power generation are likely to be the mainstay of the country's source of electrical power in that time period. A thorough understanding of their competitiveness is not only important in utility companies' decisions to go one route or the other, but is also important to the government and the public when answers must be found for difficult questions, such as economic and environmental implications of a massive societal leaning toward either option.

Intuitively, the cost advantage of one option over the other depends on locations, capital requirements, fuel supply, and environmental and safety regulations. It is also to be expected that the competitiveness of the costs of electricity as produced by a coal-fired plant and a light water reactor plant will depend strongly on the cost trends of coal and uranium over the entire 20-40 year life span of the plants. Furthermore, it is important whether or not the comparison includes the effect of inflation which, over the life span of the plants, will most likely turn out to be different from the inflation expected at the time of capitalization.

In this study the primary and secondary factors that affect the cost comparison of coal-fired and nuclear plant options for the mid-term future have been separated and arranged so that they can be examined systematically. Baseline data for capital and operating costs at "beginning-of-life" are determined by careful examinations of past- and short-term future trends. The effect of the capital structure and of mid-term economy is determined by the tax rate, the expected rate of inflation at the time of capitalization, the net rate of fuel cost increases, and future eventualities of inflation. Other factors such as plant life spans, capacity factors, changes in baseline capital, and fuel costs are considered in sensitivity studies.

Of the five typical regions of the country analyzed in this study (the Northeast, the Midwest, Appalachia, Florida and Texas, the northern mountain states), the results indicate that the low-sulfur coal option is always attractive in the northern mountain states, whereas the nuclear option would be less costly elsewhere. The magnitude of cost differences between the options depend on the inflation rate of the economy and on the methods of discounting a stream of future expenditures to a fixed point of time.

The costs of electricity considered in this study are the generation costs at the busbar of a power station. No attempt has been made to examine other cost aspects such as social costs and shadow prices. Furthermore, no effort has been made to study the generation costs of a power system which slowly builds new generation stations and phases out old ones.

Comparison Formulation

The cost of electricity at the busbar of a base-load power plant increases from year to year under present and future conditions because capital and operating costs increase from year to year. The best way to visualize a series of time-dependent costs is to use the concept of levelization. The levelized cost of electricity at the busbar is a "fictitious", constant charge in current-year dollars such that the present worth of such a stream of equal charges over the years is the same as the present worth of all future actual revenues. Actual revenues are predicated such that they are sufficient to cover all current-year costs including a normal capital recovery.

The levelized cost of electricity at the busbar consists of two components, capital and operating charges:

$$\bar{C} = \bar{C}_k + \bar{C}_{op} \ ,$$

where $\bar{C}$ represents the levelized costs, $\bar{C}_k$ is the levelized capital fixed charge component, and $\bar{C}_{op}$ is the levelized operating charge component.

The levelized capital fixed charge is a commonly used concept in the utility industry and can be expressed as follows:

$$\bar{C}_k = \alpha(I_o, E)\phi(\tau, d, \pi, x_k) = \frac{I_o}{E}\left\{\frac{\frac{1}{1-\tau}}{\sum\limits_{i=1}^{M}\frac{1}{(1+x_k)^i}} - \frac{\tau}{1-\tau}d + \pi\right\},$$

where E is the amount of electricity produced every year (assumed constant in this study by the use of a constant capacity factor); I_o is the total initial investment (in dollars per kW); and where the expression in the bracket is the book fixed charge rate which depends on the effective federal and local tax rate (τ), the book depreciation rate (d), the property tax and insurance rate (π), the effective cost of money (x_k), and the life span of the plants (M years).

If capital consists of bonds and stocks at fractions f_b and f_s, and having returns r_b and r_s, respectively, then the effective cost of money x_k is:

$$x_k = (1-\tau)\ f_b r_b + f_s r_s \ .$$

Note that r_b and r_s are functions of the expected rate of inflation at the time of capitalization ($\hat{u}$):

$$r_b = (1 + r_{bo})(1 + \hat{u}) - 1 \ ,$$

$$r_x = (1 + r_{so})(1 + \hat{u}) - 1 \ ,$$

where r_{bo} and r_{so} stand for the net bond and stock returns in the absence of inflation.

The levelized operating charge can be written as initial operating charge multiplied by a function of future inflation and net fuel cost increase:

$$\bar{C}_{op} = \beta\bar{F}\ (u,\ y,\ x_{op})\ ,$$

where

$$\beta = C(o)\ ,$$

and

$$\bar{F}(u,\ y,\ x_{op}) = \frac{\sum_{i}^{M} \frac{(1+y)^i\ (1+u)^i}{(1+x_{op})}}{\sum_{i=1}^{M} \frac{1}{(1+x_{op})^i}}\ ;$$

where u is the actual year-to-year inflation rate of the economy, y is the net fuel cost increase, x_{op} is the effective discount rate for operating costs, and $C_{op}(o)$ is the operating cost at the start of the plant's commercial operation.

The discount rate for a stream of future operating charges (x_{op}) is of prime importance to the comparative analysis of options. In this study, three methods for the selection of x_{op} have been considered. These are:

1. The discount rate for operating charges is the same as that for capital charges and is a simple function of inflation:

   $$x_{op} = x_k = (1-\tau)f_b r_b(u) + f_s r_s(u),$$

   where τ, r_b, r_s, f_b, and f_s have been previously described.

2. The operating discount rate is 6 percent in the absence of inflation and is increasing with inflation such that

   $$1 + x_{op} = (1+6\%)(1+u).$$

   This method has been used by Stauffer et al.,[1] in the assessment of economic incentives for the Liquid Metal Fast Breeder Reactor program.

3. The operating discount rate is 10 percent in the absence of inflation and is increasing with inflation such that:

   $$1 + x_{op} = (1+10\%)(1+u).$$

   This method conforms partially to the method recommended by the President's Office of Management and Budget (OMB)[2] with the exception that the OMB recommendation has been expanded to cover inflation as well.

When the capital and operating charges for the generation of electricity have been levelized as prescribed above, the comparative electricity costs between the coal-fired and nuclear options can be expressed as a ratio, namely:

$$\frac{\bar{C}_{HSC}}{\bar{C}_N} = \frac{\alpha_{HSC} + \beta_{HSC}\left[\frac{\bar{F}}{\bar{\phi}}\right]_{HSC}}{\alpha_N + \beta_N\left[\frac{\bar{F}}{\bar{\phi}}\right]_N} ,$$

$$\frac{\bar{C}_{LSC}}{\bar{C}_N} = \frac{\alpha_{LSC} + \beta_{LSC}\left[\frac{\bar{F}}{\bar{\phi}}\right]_{LSC}}{\alpha_N + \beta_N\left[\frac{\bar{F}}{\bar{\phi}}\right]_N} ,$$

where subscripts HSC, LSC, and N represent high-sulfur coal, low-sulfur coal, and nuclear, respectively.

The above ratios indicate that the relative costs of electricity by the coal-fired and nuclear options depend on base line, beginning-of-life data represented by α's and β's. It also depends on the ratio $\bar{F}(u, y, x_{op})/\phi(d, \tau, \pi, x_k)$ which can be simply expressed as the relative behavior of economic forces acting on operating costs as compared to the economic forces acting on capital costs.

Geographical Locations

Five typical regions have been selected for analysis. These are:

1. Region 1: Base Case — an industrial location not far from Eastern coal mines, at medium distance from Western coal mines, and with average construction costs. Example: midwestern states.

2. Region 2: Extreme Case — an industrial location far from coal mines and having high construction costs. Examples: New England and Southern California.

3. Region 3: Long-Distance Case — a location far from coal mines but otherwise endowed with good transportation means and average construction costs. Examples: Florida and Texas.

4. Region 4: Low Case — a location close to Eastern coal mines and with low construction costs. Examples: Appalachian states or Southern Great Plains states.

5. Region 5: Western Coal Case — a location close to Western coal mines.

Table 1 gives the capital, fuel, and operation and maintenance costs used for each of these regions. Data are for established technologies of 1,000 MW(e), coal-fired plants and Light Water Reactor plants starting commercial operation in 1985. The manner in which the data are selected and their sensitivity to changing parameters are described below.

TABLE 1: COST ASSUMPTIONS FOR FIVE REGIONS[a]

	LOW-SULFUR COAL-FIRED	HIGH-SULFUR COAL-FIRED	LIGHT WATER REACTOR PLANT
A. Capital Cost [$/kW(e), 1985]			
Region 1	700	860	1,080
Region 2	850	1,000	1,300
Region 3	700	860	1,080
Region 4	650	800	950
Region 5[b]	860	N/A	1,080
B. Fuel Cost [$/M Btu, 1985]			
Region 1	2.38 (W)	2.00	0.90[c]
Region 2	2.80 (E) 3.40 (W)	2.40	0.90
Region 3	2.60 (E) 3.00 (W)	2.20	0.90
Region 4	2.20 (E)	1.60	0.90
Region 5	1.20 (W)	N/A	0.90
C. Operation & Maintenance Costs [mills/kWhr, 1985]			
All Regions	2.0	4.0	3.0

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[a] Based on a single-unit, 1,000 MW(e) plant and on heat rates of 9,500 Btu/kWhr for coal, 10,500 Btu/kWhr for nuclear. Costs in 1985 dollars are generally based on a 5 percent per year decay rate of the dollar and a 3 percent per year net escalation over and above inflation. Exception is taken for nuclear fuel which is assumed to increase at an aggregate rate of about 10 percent per year between 1975 and 1985.

[b] Low-sulfur, coal-fired plants in Western states that have plenty of low-sulfur coal seem to need SO_2 scrubbers because local environmental standards are much stricter than Federal emission standards.

[c] Corresponds to a steady state recycle fueling program with $75/lb U_3O_8; $150/SWU; $200/kg fabrication; $250/kg conversion, reprocessing, and disposal; $30/kg shipping; and 16 percent per year carrying charge.

Capital Costs

The capital costs of both coal-fired and nuclear plants have shown dramatic increases in the early 1970's and these cost increases have been fully accounted for in this study. The capital costs have been examined from the following viewpoints:

1. Direct and indirect cost components for materials, labor, and financial charges such as incurred at a favorable site and using the AEC Code of Account.[3]

2. Actual costs of new, large, base-load power plants that went into commercial operation between 1969 and 1975 and that are reported by utilities to their stockholders and to Federal agencies.

3. Estimates of total costs for power plants that will go into commercial operation in the 1980's undertaken by utilities, architect-engineers and consulting firms.

4. Sensitivity of the capital costs to such important factors as duration of construction, escalation, safety and environmental requirements.

It is important to note that while cost increases have caused traumatic disruption in the cash flow of many utility companies in the mid-1970's, it is unlikely that the high rates of increase experienced in the recent past will continue into the future. Besides the dramatic inflation spiral of the early 1970's that affected all commodity costs, cost escalations of nuclear plants are traceable to the maturation of a new major industry with its unique problems of societal acceptance, changing scope of construction, and delays in construction. While coal-fired plants have been based on an established technology for a long time, they also encountered delays in difficulties in siting and, in addition, the costs of meeting emission standards have not been fully reflected in the capital costs of plants that went into commercial operation before 1975.

Table 2 shows the capital costs of nuclear and coal-fired plants for 1975 and 1985 as available from various sources. In this study the capital costs for a single-unit, 1,000 MW(e) plant that must satisfy all environmental and safety criteria as of 1975 have been estimated on the basis of the AEC Code of Account. Rounded-off values in 1975 dollars of $325 per kW, $400 per kW, and $500 per kW have been obtained for a low-sulfur coal-fired plant (without scrubbers), a high-sulfur coal-fired plant with SO_2 scrubbers, and a nuclear plant, respectively. At the start of commercial operation in 1985, the costs become $700 per kW, $860 per kW, and $1,080 per kW, respectively, when escalation and interest during construction are included. An aggregate escalation rate of 8 percent per year and an interest rate of 8 percent have been assumed. Furthermore, it has been assumed that nuclear plants take five years to build, and coal-fired plants take four years, although this assumption is not crucial when escalation and interest rates are both at 8 percent per year.

TABLE 2: CAPITAL COSTS OF NUCLEAR AND COAL-FIRED PLANTS

	COAL-FIRED W/O SCRUBBERS	COAL-FIRED WITH SCRUBBERS	NUCLEAR
1975 Capital Cost ($/kW, 1975)			
This Study:			
Base Case Selection	325	400	500
Range Due to Special Factors (Table 3)	225-375	275-465	345-575
AEC Code of Account Method	318	371	458
Other Estimates:			
United Engineers and Constructors, Inc.[a]	-	375	460
Bechtel[b,c]	-	-	462
General Electric[d]	360	440	465
A. D. Little, Inc., for New England (1974)[e]	-	-	454
Commonwealth Edison (1974)[f]	300	420	421
Federal Energy Administration (1974)[g]	-	-	438
Colstrip, MT (Coal, 3 x 686 MW)[h]	359	-	-
Hartsville, TN (4 x 1,250 MW)[i]	300	342	335
Skagit, WA (2 x 1,250 MW)[j]	-	-	542
Costs of Some Plants that Went Commercial in 1975:			
Browns Ferry 2, AL	-	-	246
Brunswick 2, NC	-	-	427
Hatch 1, GA	-	-	480
Indian Point 3, NY	-	-	415
Powerton 6, IL	220	-	-
Mansfield, PA (1976)	464	-	-
Trojan, OR (1976)[k]	-	-	407

TABLE 2: CAPITAL COSTS OF NUCLEAR AND COAL-FIRED PLANTS (continued)

	COAL-FIRED W/O SCRUBBERS	COAL-FIRED WITH SCRUBBERS	NUCLEAR
1985 Capital Cost ($/kW, 1985)			
This Study:			
Base Case Selection	700	860	1,080
Range Due to Special Factors	410-950	475-1,110	600-1,370
AEC Code of Account Method	690	804	994
Other Estimates:			
United Engineers and Constructors, Inc.	-	750	950
Bechtel	-	850	1,030
Sargent and Lundy[l]	-	910	1,005
General Electric (1984)	770	850	953
Skagit, WA	-	-	1,030
Tyrone Park, WI (800 MW)	-	-	916
Carroll County 2, IL[m]	-	-	686
Davis Besse 3, OH (906 MW)[n]	-	-	865
Greenwood 2 and 3, MI (2 x 1,200 MW)[o]	-	-	820
Naughton 5, WY (400 MW) (1974)[p]	763	-	-

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[b] H. F. Brush, Bechtel Corporation, "Power Plant Economics", Testimony before the Connecticut State Public Utilities Control Authority (January 21, 1976).

[c] W. Kenneth Davis, Bechtel Corporation, "Economics of Nuclear Power", Paper presented at the International Symposium on Nuclear Technology and Economics, Taiwan (January 13, 1975).

TABLE 2: CAPITAL COSTS OF NUCLEAR AND COAL-FIRED PLANTS (continued)

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[e] R. McWhorter, S. M. Stoller Corporation (a division of A. D. Little, Inc.), "Economic Comparison of Base-Load Generation Alternatives for New England", presented at the joint ANS/ASME luncheon meeting, Boston, Massachusetts (November 3, 1975).

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[g] Federal Energy Administration, "Project Independence Report", U.S. Government Printing Office, Washington, D. C. (November 1974).

[h] Northern States Power Company "1975 Annual Report", (1975).

[i] Tennessee Valley Authority, "Final Environmental Statement – Hartsville Nuclear Plants", Chattanooga, Tennessee (1975).

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[k] Portland General Electric Company, Portland, Oregon, preliminary prospectus dated August 5, 1976 for 1,500,000 shares of common stock (August 1976).

[l] W. W. Brandfon, Sargent and Lundy, "The Economics of Nuclear Power", paper presented at AIF Conference on Nuclear Power Financial Considerations, Bal Harbor, Florida (December 8, 1975).

[m] Commonwealth Edison Company, Chicago, Illinois, prospectus for 125,000 shares first mortgage 9-3/8 percent bonds, series 33 (Due May 15, 2004).

[n] Toledo Edison Company, Toledo, Ohio, preliminary prospectus dated June 11, 1976 for $50,000,000 first mortgage bonds, percent series due 2006 (June 1976).

[o] Detroit Edison Company, Detroit, Michigan, "1975 Annual Report" (1975).

[p] Utah Power and Light Company, Salt Lake City, Utah, prospectus for 700,000 shares of common stock (June 23, 1976).

Table 3 shows the sensitivity of 1975 and 1985 cost data presented above when one or more factors are changed that cause the basis for the cost estimation to be different from that of the AEC Code of Account method. It is noted that not all factors listed can change at the same time, and that in the "best estimate" of cost range, cost of a real project is more likely to be found on the high side.

TABLE 3: EFFECTS ON PLANT COSTS DUE TO DEPARTURE FROM AEC CODE OF ACCOUNT ASSUMPTIONS

FACTORS	CHANGE IN BASE CONSTRUCTION COSTS (Percent)	CHANGE IN COST AT COMMERCIAL OPERATION (Percent)
AEC Code of Account, Single-Unit, 1,000 MW(e), Middletown Site Contingencies, 7%	0	0
Sizes		
Double-Unit	-7	-7
1,200 MW(e) for Nuclear	-5	-5
800 MW(e) for Coal	+5	+5
Geography		
Northeast Site or California	+10 to +15	+10 to +15
Midwest Site	+5 to +10	+5 to +10
Southeast Site	-10 to +5	-10 to +5
Change in Scope of Construction		
Deferred Investment at $5 Million Per Year Throughout Life	0	+6 to +8
Once-Through Cooling Instead of Wet Towers	-2	-2
Dry Towers Instead of Wet Towers (coal)	+5	+5
Dry Towers Instead of Wet Towers (nuclear)	+7	+7
Capitalized Cost of Decommission (estimate)(nuclear)	0	+10
Capitalized Cost of Decommission (estimate)(coal)	0	+2
Partial Class 9 Accident Mitigation (estimate)(nuclear)	+2 to +5	+2 to +5
Underground Siting (nuclear)	+7 to +15	+10 to +20
Contingencies at 10%	+3	+3

TABLE 3: EFFECTS ON PLANT COSTS DUE TO DEPARTURE FROM AEC CODE OF ACCOUNT ASSUMPTIONS (continued)

FACTORS	CHANGE IN BASE CONSTRUCTION COSTS (Percent)	CHANGE IN COST AT COMMERCIAL OPERATION (Percent)
Financial and Construction		
Construction 6 Months Longer	0	+3.5
Construction 6 Months Shorter	0	-3.5
Escalation Rate at 7% Per Year	0	-6.5
Escalation Rate at 9% Per Year	0	+7.5
Interest Rate at 7% Per Year	0	-2
Interest Rate at 9% Per Year	0	+2
Compounding of Factors		
Best Estimate of Range	-25 to +25	-40 to +40

The capital costs, I_0, at the beginning-of-life of power plants (taken here as 1985) represent the total initial investment. They enter into the comparative framework through the coefficient $\alpha \equiv I_0/E$, where E is the yearly amount of electricity produced by a kilowatt of installed capacity. It has been tacitly assumed in this formulation that E is constant throughout the life of the plant. A capacity factor of 65 percent has been assumed for nuclear plants and high-sulfur coal-fired plants with SO_2 scrubbers. A capacity factor of 75 percent has been assumed for a low-sulfur coal-fired plant. A change in capacity factor of 5 percent is equivalent to a change of about 7 percent in initial capital cost of the plant (in the opposite direction).

Fuel and Operation & Maintenance Costs

The process of determining the coefficient β for the various options has been undertaken in a manner similar as in the case of capital costs. Past and future cost trends have been examined. The cost of operation and maintenance of large power plants has been about 1 mill per kWhr for nuclear and coal-fired plants; but when SO_2 removal is included, the cost is estimated as high as 2.5 mills per kWhr in 1975.[4] Based on various trends of nuclear power plant staffing on the one hand, and expected operational advancement in SO_2 removal on the other, it is reasonable to allow 1 mill per kWhr, 2 mills per kWhr, and 1.5 mills per kWhr (1975) for the operation and maintenance of low-sulfur coal-fired plants, high-sulfur coal-fired plants with scrubbers, and nuclear plants, respectively. Projection to 1985 is achieved by doubling the costs, which is equivalent to an overall escalation rate of approximately 8 percent per year. After 1985, and for the duration of plant life spans, operation and maintenance costs are combined with fuel costs.

Both coal and uranium that are fed into power plants operating between 1985 and 2015 are assumed to originate from new mines. The costs of opening these mines including capital, royalty, and depletion allowances have been reflected in the price of coal. In addition, the cost of transportation of coal from the mine to the power plants has been based on distance. The best estimates for the total coal fuel cost as used at the power plants in 1975 and 1985 for five regions of interest were shown in Table 1. Sensitivity studies on these base line costs are presented in Table 4.

Nuclear fuel was assumed to cost 36¢ per million Btu (M Btu) in 1975 and 90¢ per M Btu in 1985. The 1985 figure represents yellow cake prices at $75 per pound, enrichment service at $150 per SWU, fabrication at $200 per kg, reprocessing and disposal at $250 per kilogram of heavy metal. These unit costs are higher than the actual costs in the past, but seem to be in line with current trends and estimates for the short term. These base line costs (1985) and their increase pattern in subsequent years play a pivotal role in the competitiveness between the coal-fired and nuclear options.

The mechanism that underlies the price escalation of fuel is complicated by geopolitical policies of nations, scarcity of resources, legislation and regulations, and profit motives. It is assumed in this study that there will be no drastic fuel price adjustment in the mid-term future similar to the 1973-1975 fuel price spiral. It is further assumed that the cost of fuel, f.o.b. power plant, will escalate monotonically when measured in current-year dollars. The escalation rate is defined to consist of a general inflation rate of the economy (u) and a net increase rate (y) which is due to totally intrinsic causes such as limitation of resources, regulations, transportation, and disposal. Both the general inflation rate of the economy (u) and the net increase rate (y) are studied parametrically; for the base case, an inflation rate of 5 percent per year and a net increase rate of 2 percent per year are assumed.

Inflation, Discount Rate, and Fixed Charge Rate

Cost levelization, which is found very useful in comparative analyses of options, involves the process of discounting, which depends not only on the discount rate but also on the inflation rate. While there is a school of thought that inflation would not distort results of the comparison if the analysis is carried out consistently, it is this study's conclusion that the effects of future inflation on the capital and operating components of the electricity cost are different; indeed, a distortion of results can take place. When a capital venture is undertaken, the capital fixed charge rate is based on equity and debt ratio, tax, depreciation, and the expectation of inflation ($\hat{u}$) which form the basis for bond and stock rates of return. For example, the current bond rate of 9 percent per year and stock return (for utilities) of about 14 percent per year appear to be based on an expected decay

TABLE 4: BASE CASE SENSITIVITY OF PARAMETERS

	ADVANTAGE (OR DISADVANTAGE) OF NUCLEAR OVER COAL OPTIONS	
	Nuclear Over HSC	Nuclear Over LSC
Base Case (Region 1)	27%	21%
Changes in Base Line Factors		
1. LWR plants cost $200/kW more in 1985	16	10
2. LWR plants achieve only 50 percent overall capacity factor	10	4
3. Nuclear fuel costs 50 percent more in 1985 (e.g., $110/lb, U_3O_8)	9	3
4. Coal costs 20 percent less in 1985	14	5
Changes in Capital Structures		
1. Bond rate at 10 percent, stock rate at 16 percent per year from 1985	25	18
2. All capital publicly financed	40	37
Changes in Inflation and Fuel Escalation		
1. No inflation, no fuel cost increase	17	7
2. No inflation	23	15
3. Inflation at 3 percent per year	26	18
4. Inflation at 8 percent per year	31	25
5 Percent Inflation But Changes in Calculational Methods*		
1. $x_{op} = x_k(u)$	27	21
2a. $x_{op} = 1.06\,(1+u) - 1$ $\bar{\phi} = 18$ percent	24	17
2b. $x_{op} = 1.06\,(1+u) - 1$ $\bar{\phi} = \bar{\phi}(u)$	24	17
3a. $x_{op} = 1.10\,(1+u) - 1$ $\bar{\phi} = 18$ percent	21	13
3b. $x_{op} = 1.10\,(1+u) - 1$ $\bar{\phi} = \bar{\phi}(u)$	21	13

*Methods 2a and 2b happen to give the same result at u=5 percent but for different values of u's, the results are different. Same phenomenon is the case for 3a and 3b as can be seen in Figure 1.

rate of the dollar (or inflation rate of the economy) of at least 5 percent per year. A time series for utility bond and stock rates for the last few decades reveals that the time opportunity value of return when inflation has been discounted is approximately 2-4 percent for bonds and 6-9 percent for stocks.

The proper discount rate is the effective cost of money (x_k) that is used to build the plant. However, the discount rate for operating costs (x_{op}) that will incur in the future but have not been capitalized may or may not be the same as the capital discount rate (x_k). Various conventions have been selected for the value of the operating discount rate and three simple ones have been previously discussed.

Figure 1 shows the variation of the rate $\bar{F}/\bar{\phi}$ with respect to inflation, and Figure 2 shows the variation of cost advantage (or disadvantage) of the coal-fired options versus the nuclear option. Convention 1, which stipulates that $x_{op} = x_k$ and which tracks the inflation rate of the economy in the manner capital is raised, should be the convention that is theoretically most interesting. Methods 2a, 2b, 3a, and 3b have been used by various authors. Theoretically, in the absence of inflation ($u = o$), all conventions should have the same value of $\bar{F}/\bar{\phi}$. The fact that they do not, in Figure 1, indicates that these conventions not only give different effects of inflation on the comparative results but they are also mutually inconsistent.

If a "bias point" for decision-making has been selected, based on reasons external to the economic analysis (for example, due to larger uncertainties, a utility would not build a nuclear plant unless it shows at least 5 percent advantage over a comparable coal-fired plant), it is clear from Figures 1 and 2 that the method of discounting is of prime importance in the analytical exercise.

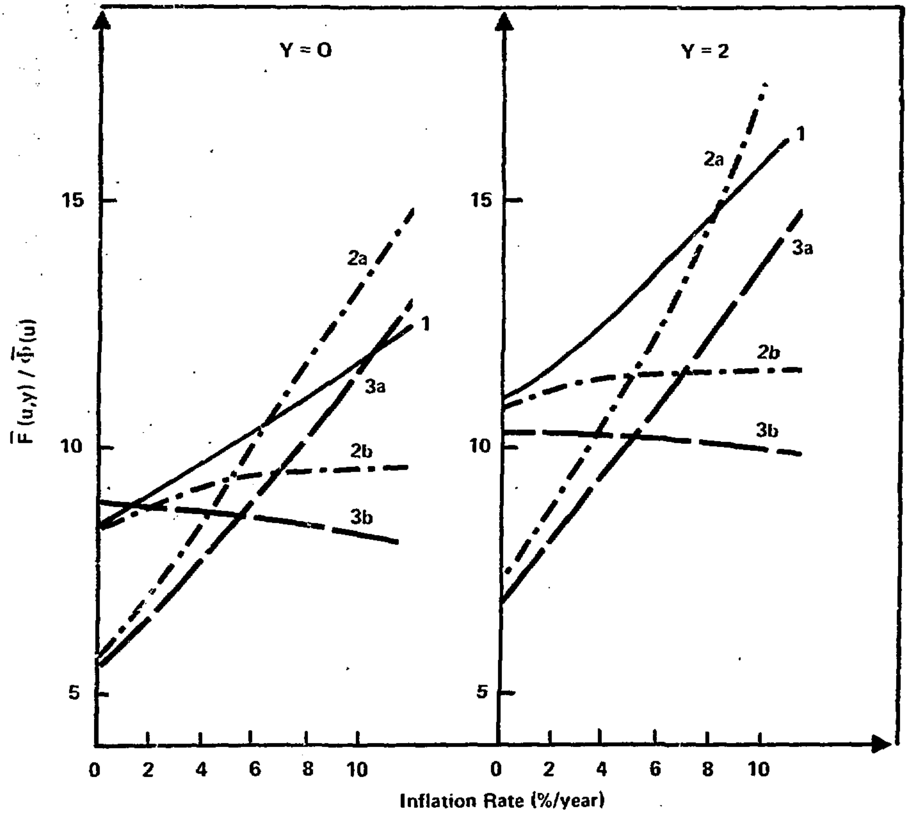
Cost of Electricity Generation

Table 5 shows the cost of electricity generation for the five regions described in Table 1. Cost figures are presented as levelized over the period 1985-2015 and measured in current-year dollars. Capital fixed charge rate is 18 percent per year which corresponds to an expectation of 5 percent inflation per year, a bond rate of 9 percent per year, a stock return of 14 percent per year, an effective tax rate of approximately 50 percent for corporation, a bond-to-stock ratio of 0.6/0.4, an insurance and property tax rate of 3 percent per year, and a straight line depreciation over the 30-year life of the plants.

It is noted that in all regions except Region 5, the cheapest coal alternative still shows a disadvantage when compared to the nuclear plant option. In Region 5, even when scrubbers have been included in low-sulfur coal-fired plants due to local environmental laws, the low-sulfur coal option is the cheaper alternative. This is primarily because Western coal does not cost much to develop, and the cost of transportation of such coal to the vicinity of the mines is also relatively low.

What would be the results if the comparison is made in settings different from that in Table 5? Table 4 shows the effects of various assumptions on the cost advantage (or disadvantage) of nuclear over

FIGURE 1: EFFECT OF INFLATION, DISCOUNT RATE, AND CAPITAL FIXED CHARGE ON CAPITAL COST COMPARISONS



Convention 1: $x_{op} = x_k = (1 + u)x_{ko} + u(1 - \tau f_b)$

Convention 2a: $x_{op} = 1.06(1 + u) - 1; x_k = x_k(\bar{\phi} = 18\%)$

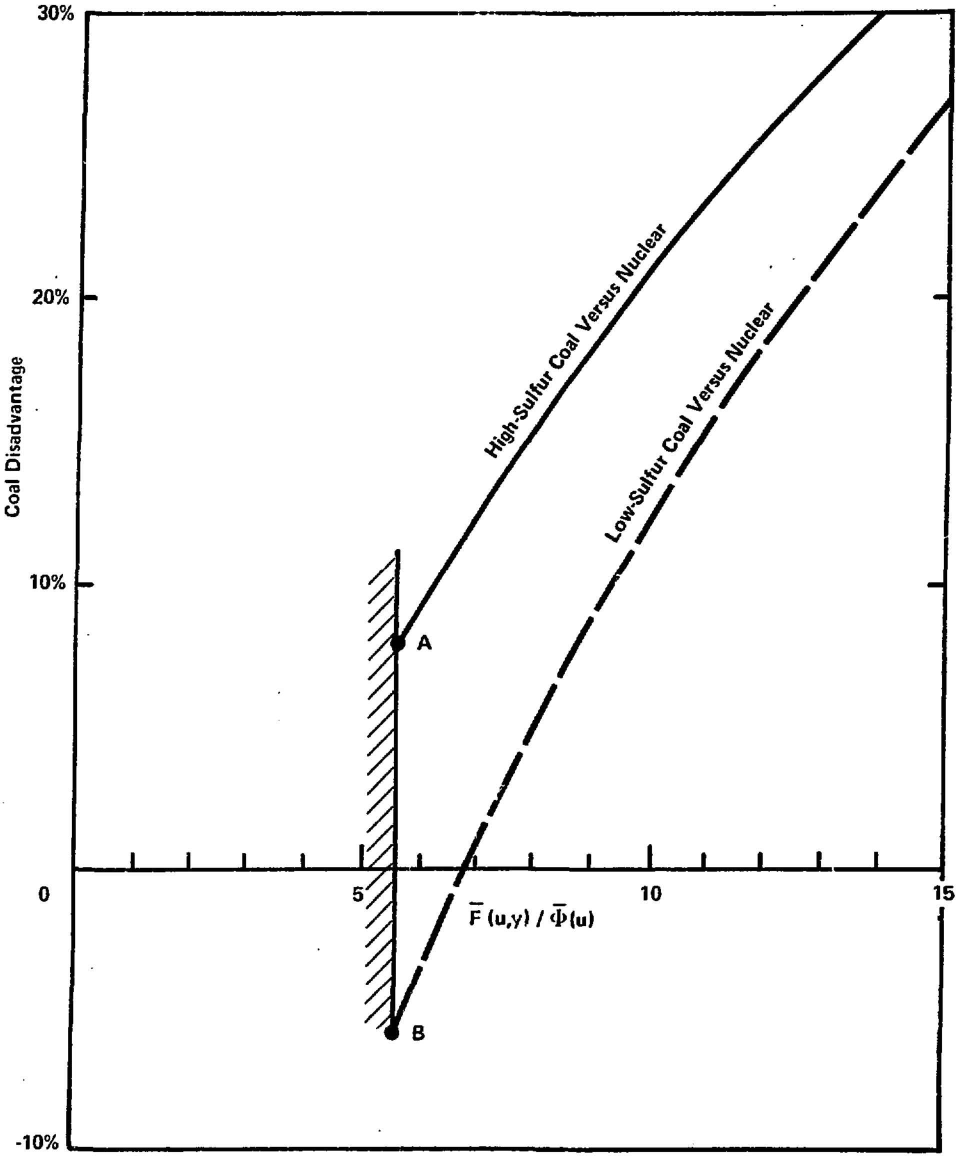
2b: $x_{op} = 1.06(1 + u) - 1; x_k = (1 + u)x_{ko} - \tau f_b u + u$

Convention 3a: $x_{op} = 1.10(1 + u) - 1; x_k = x_k(\bar{\phi} = 18\%)$

3b: $x_{op} = 1.10(1 + u) - 1; x_k = (1 + u)x_{ko} - \tau f_b u + u$

(where τ = tax rate, f_b = bond fraction, u = inflation rate, x_{op} = discount rate of operating cost, x_k = discount rate for capital, $\bar{\phi}$ = levelized fixed charge, y = net fuel escalation rate)

FIGURE 2: COST COMPARISON OF COAL-FIRED VERSUS NUCLEAR PLANT OPTION AS A FUNCTION OF $\overline{F}/\overline{\phi}$



The vertical hatched line represents the minimum $\overline{F}/\overline{\phi}$ value in Figure 1. Depending on coefficients α and β, points A and B move along this vertical line.

TABLE 5 : COST OF ELECTRICITY GENERATION

Rate Assumptions (Percent/Year)

Expected Rate of Inflation at Capitalization	5
Actual Rate of Inflation Throughout Life	5
Effective Cost of Capital	8.3
Net Fuel and O&M Cost Escalation After 1985	2
Capital Fixed Charge Rate	17.9
Heat Rate (Btu/kWhr)	9,500 (coal) 10,500 (nuclear)

Base Line Cost Assumptions: Table 1

Levelized Cost of Electricity at Busbar, 1985-2015*
(in cents/kWhr, current-year dollars)

Convention 1: $x_{op} = x_k(u)$	Low-Sulfur Coal-Fired	High-Sulfur Coal-Fired	Nuclear
Region 1 (Base Case)	7.6 (W)	8.0	6.3
Region 2 (Extreme)	8.9 (E)	9.3	7.0
Region 3 (Far from Coal)	8.1 (E)	8.5	6.3
Region 4 (Low Case)	7.1 (E)	7.0	5.9
Region 5 (Close to Western Coal)	5.9 (W)	N/A	6.3
Convention 2a: x = 11.3%			
Region 1 (Base Case)	7.0 (W)	7.4	6.0
Region 2 (Extreme)	8.2 (E)	8.7	6.7
Region 3 (Far From Coal)	7.4 (E)	7.8	6.0
Region 4 (Low Case)	6.5 (E)	6.5	5.6
Region 5 (Close to Western Coal)	5.5 (W)	N/A	6.0
Convention 3a: x_{op} = 15.5%			
Region 1 (Base Case)	6.3 (W)	6.8	5.6
Region 2 (Extreme)	7.5 (E)	8.0	6.3
Region 3 (Far From Coal)	6.7 (E)	7.2	5.6
Region 4 (Low Case)	5.9 (E)	6.0	5.2
Region 5 (Close to Western Coal)	5.1 (W)	N/A	5.6

*Note that 0.1 cents/kWhr difference represents a difference of 60 million in constant dollars when the total electricity output of 30 years is accounted for. (E) stands for Eastern low-sulfur coal, (W) stands for Western low-sulfur coal.

coal-fired options for Region 1. Four categories of factors are presented:

1. Base Line 1985 Parameters. If the base line cost assumptions for 1985, which have been carefully established in this study, change drastically, the cost advantage of the nuclear option over the coal options is reduced. Thus if Light Water Reactors can achieve only 50 percent capacity factor throughout life, or if nuclear fuel in 1985 costs as much as $75 per pound of U_3O_8, or if low-sulfur coal costs 20 percent less than expected, then the nuclear and low-sulfur coal option would be a toss-up in Region 1. Toss-up has been defined as a situation where difference in the costs of two or several options are within a few percentage points. The same effect could result for the high-sulfur coal option as compared to the nuclear option if more drastic changes take place.

2. Capitalization. If all projects are publicly financed in a similar manner as the projects of the Tennessee Valley Authority or Bonneville Power Authority, then the advantage of the nuclear option in Region 1 is even higher than in the case of investor-owned utilities. This is due to the fact that public financing lowers the capital fixed charge which tempers the adverse effects of the high initial capital investment of the nuclear option. Conversely, when the money market is tight which forces utilities to pay expensively for capital, then the cost edge of the nuclear option over the coal option is reduced.

3. Future Inflation and Fuel Escalation. If no inflation is assumed for the period 1985-2015 but the capital fixed charge is still at 18 percent per year, then the nuclear option is still more attractive. If no inflation is assumed and, in addition, no net fuel escalation is assumed, then the low-sulfur coal option would be in a toss-up situation with the nuclear option. In reality, these two cases are unlikely because the capital fixed charge rate would be lower than 18 percent per year when there is no inflation over an extended period.

   The sensitivity study with respect to inflation indicates that future actual inflation (which is almost certainly different from the expected rate of inflation at the time of capitalization) has a bearing on the relative advantage of the nuclear option. When the future actual inflation rate is lower than the expected value at capitalization, the utility may or may not have the option to recall its bonds in order to issue new ones at lower costs. However, when the future actual inflation rate is higher than the expected value at capitalization, then the utility can continue to rely on a low fixed charge rate for the committed power plant, whereas the investors' only resort is to redeem the bonds in the marketplace at a substantially lower price than their book value.

This appears to be an important institutional issue in the finance of future energy projects.

4. No Inflation but Changes in Calculational Convention. Five calculational conventions have been considered in the comparison as previously discussed. Figures 1 and 2 indicate that the effect of inflation is apparent in all cases. This effect happens to be very mild for Conventions 2b and 3b. Most of the "base case" results in this study are based on Convention 1 which is theoretically most sound. A rationale can be developed for Convention 2a in that the capital structure of a committed project is rather rigid with respect to changes in inflation, but such rationale is not any better than the rationale for the choice of Conventions 2b, 3a, and 3b.

Differential Fuel Cost Increase

Results of the above analysis have been based on net fuel increase rates of 0 and 2 percent per year due to intrinsic conditions of fuel supply. The fuel supply situations for coal and uranium are quite dissimilar, however, and there are reasons to believe that the costs of coal and uranium could increase at different rates.

Figures 3 and 4 illustrate the outcome of cost comparison between coal and nuclear electricity for scenarios in which nuclear fuel costs increase at a rate faster than coal. As previously discussed, the nuclear option shows an advantage over the coal option for all regions considered except Region 5 for any inflation rates, so long as both nuclear fuel and coal undergo a net increase larger than 2 percent per year. But, if coal costs do not increase at all after 1985, and if nuclear fuel costs increase at 2 percent per year, then a toss-up situation occurs in all regions except in Region 5 where low-sulfur coal is the winner.

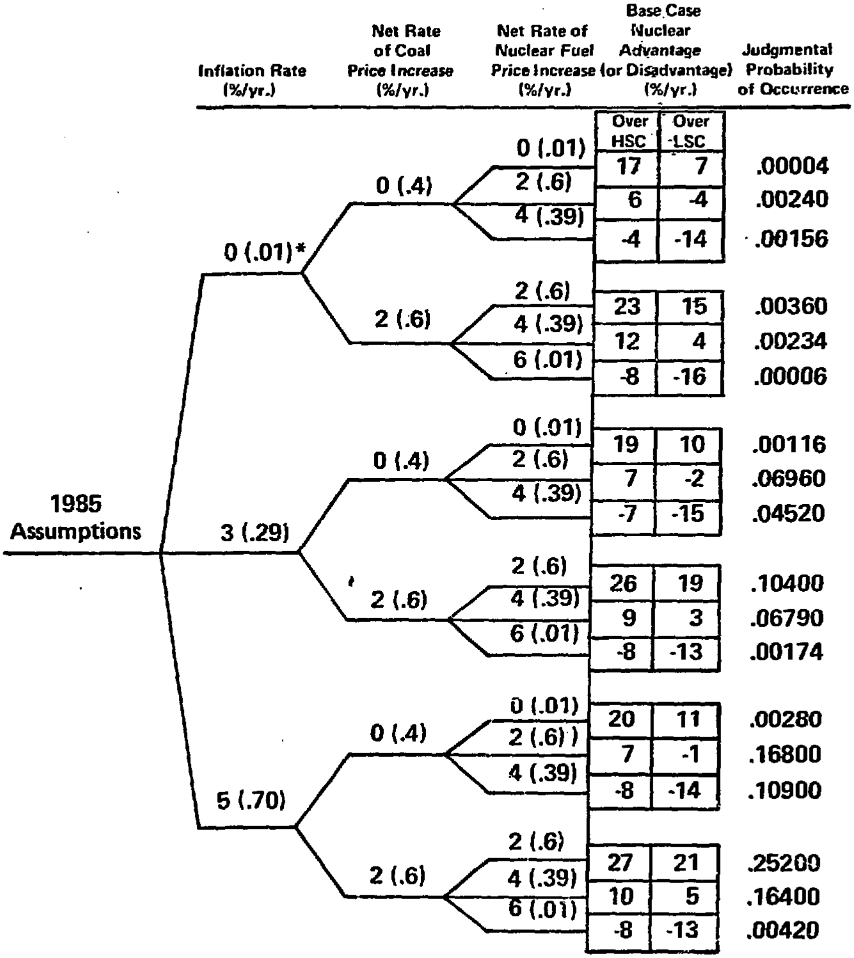
If coal costs increase at 2 percent per year whereas nuclear fuel costs increase as much as 6 percent per year, then the nuclear advantage fades away — first to low-sulfur coal, then to high-sulfur coal — and the process would occur sooner in Region 4 and later in Region 2.

Conclusions

This study has compared the costs of coal and nuclear electricity in the mid-term future (1985-2015) in various regions of the country and under various assumptions. A cost comparison framework has been formulated and parameters of importance have been classified into various levels of importance and confidence. Baseline data for 1985 have been established for the low-sulfur coal-fired, high-sulfur coal-fired, and nuclear options. Importance has been attached to the future actual inflation rate of the economy and the methods of discounting future costs. The level of confidence of various parameters and their effects on comparative results have been examined through a series of sensitivity analyses.

Figure 3

Sensitivity of Differential Fuel Cost Increase Between Coal and Nuclear



Inflation Rate (%/yr.)	Net Rate of Coal Price Increase (%/yr.)	Net Rate of Nuclear Fuel Price Increase (%/yr.)	Base Case Nuclear Advantage (or Disadvantage) (%/yr.) Over HSC	Base Case Nuclear Advantage (or Disadvantage) (%/yr.) Over LSC	Judgmental Probability of Occurrence
0 (.01)*	0 (.4)	0 (.01)	17	7	.00004
		2 (.6)	6	-4	.00240
		4 (.39)	-4	-14	.00156
	2 (.6)	2 (.6)	23	15	.00360
		4 (.39)	12	4	.00234
		6 (.01)	-8	-16	.00006
3 (.29)	0 (.4)	0 (.01)	19	10	.00116
		2 (.6)	7	-2	.06960
		4 (.39)	-7	-15	.04520
	2 (.6)	2 (.6)	26	19	.10400
		4 (.39)	9	3	.06790
		6 (.01)	-8	-13	.00174
5 (.70)	0 (.4)	0 (.01)	20	11	.00280
		2 (.6)	7	-1	.16800
		4 (.39)	-8	-14	.10900
	2 (.6)	2 (.6)	27	21	.25200
		4 (.39)	10	5	.16400
		6 (.01)	-8	-13	.00420

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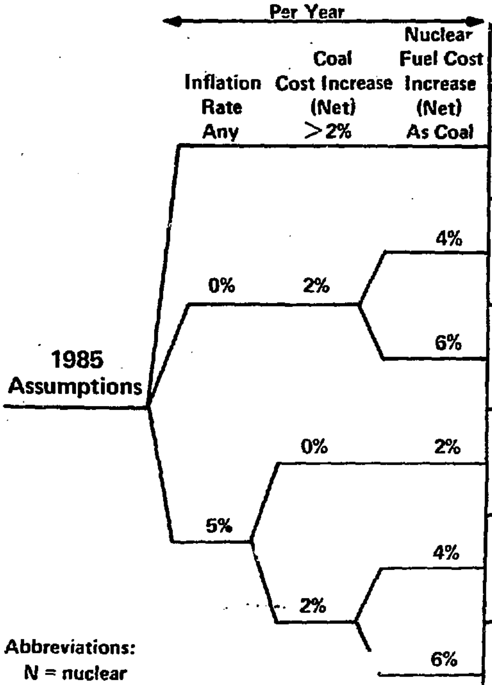
* ( ) indicates author's judgmental probability of occurrence for the event.
The Monte Carlo method considers a distribution instead of discrete numbers.

Figure 4
EFFECTIVE DIFFERENTIAL FUEL COST INCREASES ON THE MOST ECONOMICAL MODE OF GENERATION IN VARIOUS REGIONS



Inflation Rate	Coal Cost Increase (Net)	Nuclear Fuel Cost Increase (Net)	Winning Option: Region 1	Region 2	Region 3	Region 4	Region 5
Any	>2%	As Coal	N	N	N	N	LSC(W))
0%	2%	4%	N or LSC(W)	N or LSC(E)	N or LSC(E)	LSC(E)	LSC(W)
		6%	LSC(W)	Toss-up	Any coal	Eastern Coals	LSC(W)
5%	0%	2%	Toss-up	N or LSC(E)	N or LSC(E)	Toss-up	LSC(W)
	2%	4%	N	N	N	Toss-up	LSC(W)
		6%	Toss-up	N or LSC(E)	Toss-up	Toss-up	LSC(W)

Abbreviations:
N = nuclear
LSC(E) = low sulfur, Eastern
LSC(W) =low sulfur, Western
Toss-up = all options are within 5% of one another in generation costs.

Under a wide range of scenarios, it is concluded that the coal option is attractive in the Northern Rocky Mountains and Northern Great Plains areas while the nuclear option is more attractive elsewhere in the country. The advantage of the nuclear option is most clear in the Northeast area, while the stiffest competition between the options occurs in the Appalachian and Southern Great Plains areas. In addition, it is further concluded that the more highly capital-intensive nuclear plants are a better hedge against inflation than their coal counterparts.

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Determining the Ecological Effects of Power Plant Cooling

by

Charles C. Coutant

Environmental Sciences Division, Oak Ridge National Laboratory[1]
Oak Ridge, Tennessee 37830

ABSTRACT

Determining the environmental impacts of power plant cooling systems requires an intimate knowledge of the engineering design and operation of the cooling system, a clear conceptual framework for conducting the analysis, an understanding of the hydraulics and ecology of waters used for cooling, a knowledge of the literature on thermal and other power plant effects on biota, and a comprehension of the natural resources held valuable by society at the site. These various elements are briefly discussed, with examples and key references, to give guidance to those seeking to pursue the topic further.

I. INTRODUCTION

Whatever energy sources are used to supply electricity for future generations, one problem will remain, namely that of the disposal of waste heat from the conversion of heat energy to electrical energy. This discussion considers the potential "thermal pollution" problem in aquatic environments and its important corrolary issues as they relate to present-day and planned thermal electric generating stations. The basic questions concern determination of the environmental impacts of disposing of power station waste heat, with the objective of selecting criteria for siting, design, and operation of power stations which will minimize environmental damages and maximize benefits.

There are many environmental impacts potentially arising from power station operation, and cooling water use creates only a fraction of them (Fig. 1). There are impacts from the extraction, transportation, and processing of the fuel, whatever its type. These impacts are usually away from the power generating station and often are not thought of in terms of the product electricity. At the site, the fuel must be delivered and stored. Coal unloading is noisy and storage piles produce runoff of silt, acids, and dissolved materials.

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[1] Operated by Union Carbide Corporation for the Energy Research and Development Administration. Environmental Sciences Division Publication

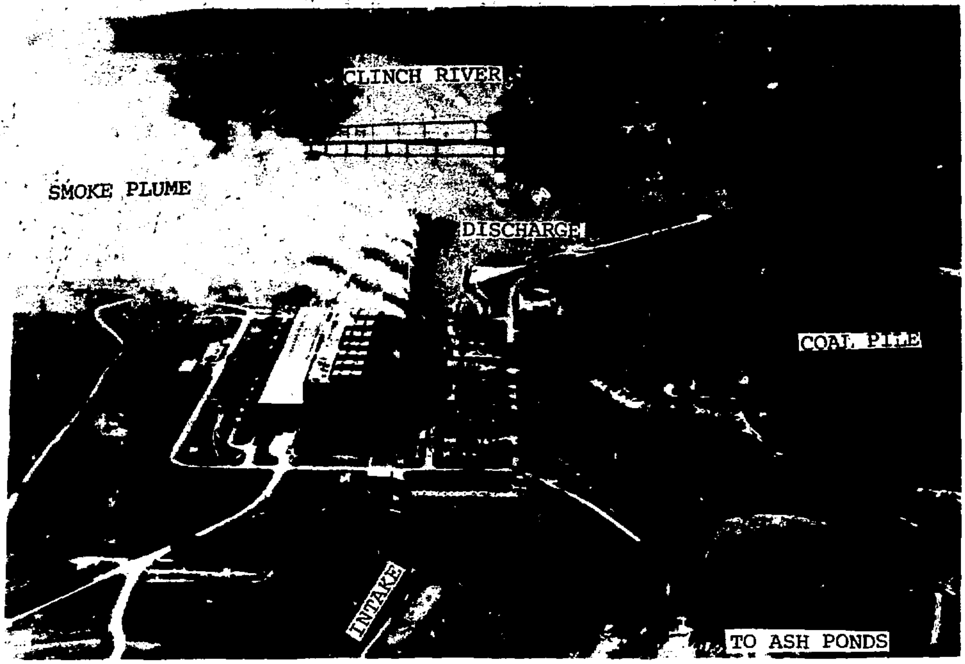


Figure 1. Aerial photo of the Kingston Steam Plant showing various environmental impacts.

Combustion of fossil fuels yields an airborne residue of ash particles, sulfur oxides, and nitrogen oxides that have aesthetic ecological and human health consequences. In coal plants, the bottom ash and most of the fly ash must be disposed of in huge ash ponds. Ponding is required for ash particles to settle out of water used to transport it in a slurry pipeline from the plant. These ponds use considerable amounts of land and contribute inorganic pollutants to surface waters through seepage, designed overflow, and occasional spills. Nuclear plants have their own problems of radioactive waste disposal. There are also impacts from the transmission lines which carry electricity to the customers. These are but a few examples.

The impacts considered in this paper arise from the condenser cooling system, which is represented in Fig. 1 by the intake canal, the intake screens and pumps, and the discharge canal. This condenser cooling system is an essential component of the energy cycle of a steam electric station, regardless of the type of fuel that is used (Fig. 2). Of the energy supplied in the fuel, only about one-third is actually converted to electrical energy; the remainder is wasted as heat. Most of this waste heat is removed at the steam condensers (where boiler steam is condensed after passage through the turbines, thus giving the turbine a partial vacuum on the exit side as well as pressure on the boiler side); some is lost through piping, and a significant amount is lost up the stacks in combustion of gas, oil, or coal. The best of the new fossil fueled power stations today deliver about 40% of the fuel energy as electricity, while nuclear plants (with special safequards) average about 33% (which is also about the average for all ages of fossil-fueld plants). For further details of the steam cycle, see Healy 1974; Eisenbud and Gleason 1969.

The coolant source for steam condensers of power stations has traditionally been a convenient body of water — river, lake, or estuary — from which water is pumped and to which the warmed water is discharged. This is the open-cycle, or "once-through" system (Fig. 2). Heat is released directly to the water body, where it disperses through mixing, evaporation and radiation to the atmosphere (for additional information see Parker and Krenkel 1969a,b; Coutant 1970).

Because of environmental concerns over thermal discharge effects (see Krenkel and Parker 1969; Parker and Krenkel 1969b), alternative cooling systems have been devised. Principal among these is use of evaporative cooling towers in which the open cycle is partially closed by substituting towers for the cooling capacity of the natural water body. In cooling towers, warm water is allowed to fall among slats which break the flow into fine droplets, while air is drawn (either by fans in mechanical-draft towers or by convection in natural-draft towers) through the artificial waterfall. Cooling takes place largely by evaporation, and the warm, moisture-laden air leaves the top of the tower. The cooled water collects in a basin at the tower base where it is recycled back to the condenser. Other types of "closed-cycle" systems are also used, including artificial ponds and canals where evaporation may be enhanced with spray modules.

Two factors act to prevent the "closed-cycle" from being truly closed. The first is water loss from the evaporative cooling mode; water lost by evaporation must be made up from an outside source. The second is the long-term concentration of mineral salts in water that is continually evaporated, thus necessitating a "blowdown" or release of a certain percentage of the circulating flow to maintain proper water chemistry. This also necessitates additional makeup water. The overall water requirement to account for evaporation and blowdown is often about 10% of the circulating water flow. The direct withdrawal of water from a natural water body is thus reduced by about 90% when compared with open-cycle cooling.

II. ENVIRONMENTAL IMPACT ASSESSMENT

The objective of obtaining criteria for siting, design, and operation of electrical generating stations with minimum ecological damage from the cooling systems can best be reached with a synthesis of field and laboratory research as this research relates specifically to the proposed power station and its ecological setting. This synthesis is now known as environmental impact assessment or analysis.

Environmental impact analysis today is a refined process that follows several essential steps (Fig. 3), which have developed from experience in preparing detailed environmental impact statements for nuclear power plants (available from the U.S. Nuclear Regulatory Commission, Washington, D.C.). First, the sources of potential biological damage must be carefully identified, using knowledge of the engineering system and the literature on power station effects (useful references include Krenkel and Parker 1969; IAEA 1974, 1975; Coutant 1970, 1972, 1976; Electric Power Research Institute 1976; Clark and Brownell 1973; Cairns 1968, 1974; Mihursky and Kennedy 1971; Raney, Menzel, and Weller 1974; and annual reviews of thermal effects literature in the Journal of the Water Pollution Control Federation, the latest being Coutant and Talmage 1976). These sources of damage should be measured or otherwise quantified in the manner in which they function to stress biological systems. The functional quantification is especially important for it may differ from the quantification used by project engineers (for example, toxicants and lethal temperatures must be quantified in terms of durations of exposure as well as in concentration or temperature change). Because we must consider sources of potential biological benefit as well as biological damage, so the most appropriate designation might be biological <u>change</u>.

Second, we must determine the likelihood that susceptible organisms will become involved with the source of potential damage. Detailed understanding of the hydraulic patterns of water flow and of the distribution and abundance of organisms is necessary to make accurate predictions.

The next step conceptually, which may have preceded the others in actual chronology, is determination of the probability of direct damage to organisms involved. If the stressing factor does act on a particular species or life stage, what will the effect be on the individuals of that species? The scientific literature contains abundant references to species-specific responses to toxicants (Becker and Thatcher 1973; Kemp et al. 1973; Mattice 1976), temperature (NAS/NAE 1974; Coutant 1975; Brown 1974) and other factors that are useful in making at least preliminary judgements. Should problems be likely, then more detailed information on local organisms and local water conditions may be necessary.

We then determine whether the local population of the affected species will "feel" the loss of some of its members. We know that mortality is a natural part of population dynamics, but we wish to know the likelihood that the size or structure of the population will be changed by any mortalities or lost reproduction induced by the power station, either directly or indirectly. We do not want induced losses to interfere with other uses of the population such as recreational or commercial fishing. Population dynamics studies of aquatic species are, for the most part, in a rudimentary state even though many of the principles are well known (e.g., Ricker 1968). At community and ecosystem levels, risks to normal structure and function are evaluated (e.g., changes in diversity and types of species, and functional aspects such as energy flow and nutrient cycling). Often computer modeling is the best approach to examining population, community and ecosystem effects.

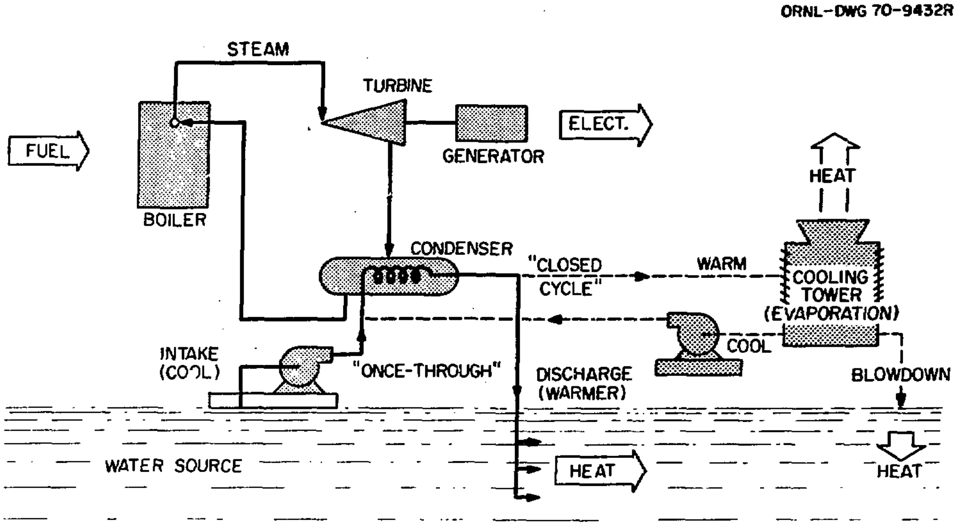


Figure 2. The energy cycle of a thermal electric generating plant using two alternative cooling systems, the open circuit ("once-through") system (solid lines) or a representative closed cycle, cooling tower system (dashed lines).

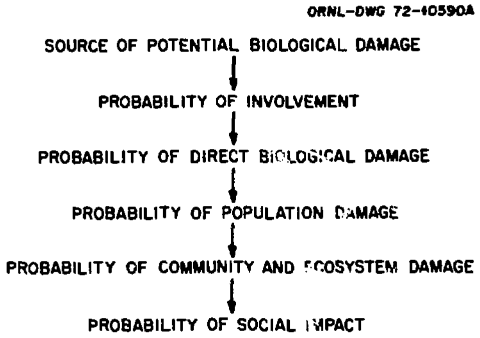


Figure 3. Simplified flow path for environmental impact analyses. An analysis begins with detailed examination of the power plant for sources of potential ecological change and leads to a judgement of significance, usually determined by human social values.

In many instances it may be sufficient to terminate the chain of Fig. 3 with ecological damage. On the other hand, human concerns and specific directives (e.g., the National Environmental Policy Act of 1969) dictate an additional step — consideration of the probability of inducing social impacts. Social decisions for the protection or exploitation of ecosystems and for benefit-cost balancing are often made with impacts on man foremost in mind. For example, ecological damage to striped bass in the mid-Atlantic states will certainly result in social impacts to sport and commercial fishermen and to a significant segment of a regional economy. Social impact includes not only measurable economic effect on man, but those amenities, such as aesthetics and future results of man's cumulative effects on the environment.

Figure 3 is oversimplified in the same sense that the traditional ecological concept of a linear, stepwise food chain is over-simplified. A population or ecosystem is stressed by a multiple array of sources of potential biological damage, and there are many natural and social feedback loops. Our inability to place quantitative value on many of these additions emphasizes the primitive state of ecological quantification. Yet for specific impact analyses, that is what must be done to the best of our ability.

Sources of Potential Ecological Change

The sources of potential ecological change from once-through (open-cycle) power station cooling systems are currently recognized to be the following (Fig. 4):

1. Change in the physical (structural) makeup of the intake and discharge areas by dredging, filling, change of substrate, or construction of inlet and outlet works;

2. Changed current patterns near the intake and discharge which may extend to areas far removed from the power station and result in changed patterns of estuarine salinity or lake thermal (and biochemical) stratification, etc.;

3. Entrapment and impingement of larger organisms, principally fish, on intake screens;

4. Entrainment of phytoplankton, zooplankton, and larvae and juveniles of fish and invertebrates by the pumped cooling water during which these organisms are exposed to:

   (a) physical stress from mechanical contacts with pumps and piping, pressure changes and shear;
   (b) temperature changes in the condenser tubes followed by a duration of exposure to elevated temperature until the discharge is reached;
   (c) chemicals principally chlorine which is added periodically to the circulating water as a biocide to prevent accumulations of fouling materials on heat exchange surfaces and other parts of the piping system, but also including such materials as laundry wastes or radionuclide activation products;

5. Plume entrainment in the discharge area where planktonic organisms in the ambient water mix with the effluent and receive thermal and chemical exposures (physical damages may also result if pumps are used to augment effluent mixing);

6. Temperature elevation for resident organisms which is greatest in the vicinity of the discharge and is less at more remote locations, and may affect to some degree the whole of small lakes, rivers and estuaries;

7. Unnatural temperature changes, often rapid, which may occur in the vicinity of the discharge due to plant operations (e.g., sudden shutdown) or to environmental changes which affect rates of mixing and dispersion of the effluent;

8. Changes in dissolved gas concentrations in the intake and effluent areas due to increased biochemical oxygen demand of warmed waters, to pumping of oxygen-poor hypolimnetic waters, or to gas supersaturation of discharge waters in winter.

9. Combinations of the above, which may cause effects greater than the sum of individual effects (synergisms).

Cooling towers have several sources of potential ecological change, some of which are unique while some are similar to, but of lesser magnitude, than those for once-through systems. They include:

1. Impingement and entrainment of aquatic organisms at the intake where makeup water is added to the cooling loop to compensate for evaporation and dilution ("blowdown") flows;

2. Chemical releases to water bodies in "blowdown" released from the "closed-cycle" loop to prevent buildup of dissolved solids, which contains materials added to the cooling loop to prevent corrosion (e.g., chromates, zinc, organophosphorous complexes) or to eliminate biological fouling (e.g., chlorine);

3. Chemical "drift" in the form of small droplets and aerosols from the towers which contains, in addition to water, chemicals used in the circulatory water system;

4. Temperature elevations or other changes due to heat in the "blowdown" releases;

5. Meteorological effects, including fogging, which affect the terrestrial environment, including man;

6. Combinations of the above (synergisms).

The relative importance of the several sources of potential ecological change from either the once-through system or cooling towers will be different depending upon the engineering design of the power station cooling system and the biota and environmental characteristics of the site.

Probability of Involvement

Local conditions of the water body and surrounding environment used by the power station are now seen to be as important to assessing risks to the biosphere as are the general data on the direct biological effects of the effluent or other human activity (USEPA, in press). This fact is at variance with the long-held philosophy that standards for pollutants can be established for regions or countries as a whole, based on representative scientific literature. To consider only the potential effect of an effluent, structure or process without looking at its realistic interactions with the affected ecosystem is to see only half of the picture. Regulatory restrictions developed using risk analyses will necessarily be localized restrictions, tailored to the particular ecosystem (waterbody, regional air mass, etc.).

To determine the likelihood that an organism will be subjected to potential damage at a power station, one must be familiar with (1) the pertinent engineering designs of the intake and discharge, (2) the fluid dynamics of the waterbody as these affect withdrawal of water and organisms by the intake and dispersion by the discharge, and (3) the life patterns of the organisms found there.

The zone of influence of the power station should be determined, both for the intake and the discharge. Elaborate mathematical models of hydraulic patterns have, in some instances, been required to estimate the likelihood that eggs and larvae of anadromous (returning to freshwater to spawn) fishes in an estuary would be entrained with power station cooling water before they successfully pass from the affected zone (see for example, Eraslan et al. 1975). The significance of entrainment for planktonic organisms depends largely upon the volume of water pumped relative to the volumes available. This seemingly simple calculation becomes complex when one takes into account the physical factors of estuary mixing of fresh and salt water and the upstream-downstream oscillation due to tides. With some simplifying assumptions, however, one is able to calculate the probability of entrainment for randomly distributed planktonic organisms passing the power plant or the probability that organisms drifting at a certain location in the water body will be withdrawn (Fig. 5). Similarly, the likelihood that organisms in the discharge area will receive thermal exposures of given magnitudes and durations can be determined from accurate understanding of thermal effluent dispersion and flow rates in the discharge area (Figs. 6 and 7) (for a summary of analytical modeling of thermal discharges, see Benedict et al. 1974; for a summary of actual field measurements in lakes, see Tokar 1971).

The ecological resource which we believe to be at risk from power plant operations should be clearly defined. Chronic effects of power stations on an estuary, for example, can hardly be evaluated against vague notions of the "proper functioning" of the estuary ecosystem. The essence of quantifying "probabilities of involvement" is to explicitly draw the relationship between the ecological resources that we deem valuable and their interaction(s) with the power station.

Accurate understanding of the ecology of potentially affected organisms is essential to estimating the probability of their involvement with the power plant system. Distribution and abundance of each species will almost certainly vary with location and time of year. The annual movements of mobile organisms can be drawn in relationship to the intake and discharge of the power station to assist in visualizing places and times of probable interaction (Fig. 8).

The reproductive strategies of the organisms may be especially crucial for predicting impacts because the life stages most often affected are larvae or juveniles.

Probability of Direct Biological Damage

The likelihood that organisms will be harmed by a power station can be evaluated from two kinds of information — experimental results obtained under controlled conditions in the laboratory, and observations of phenomena

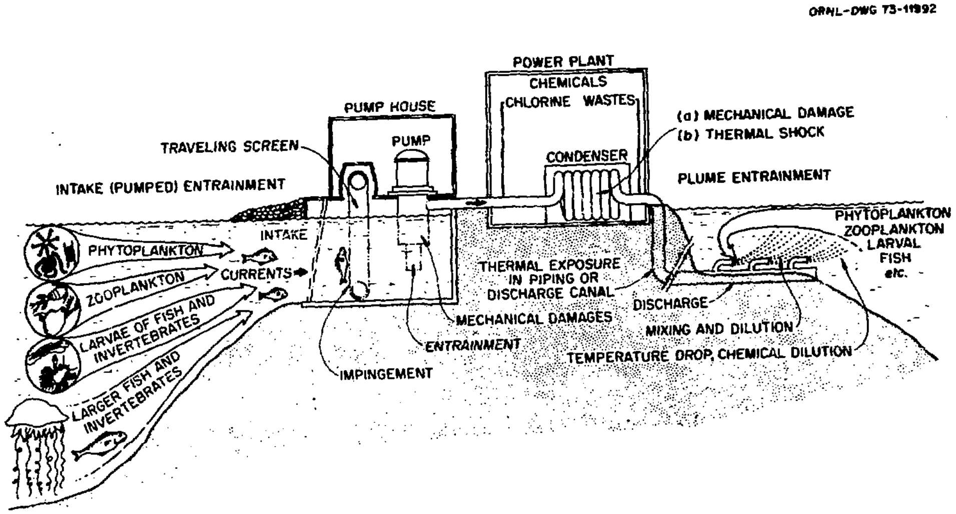


Figure 4. Sources of potential ecological damage in a power plant cooling system.

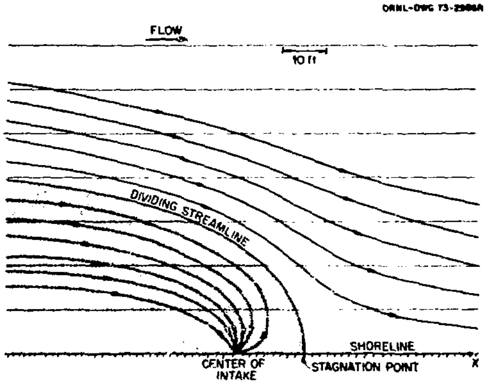


Figure 5. Idealized flow field from a river into a power station intake (Adapted from Dresner et al. 1973). In practice there is not a clear dividing line between the entrained zone and the bypass zone, rather there are isopleths of decreasing probability of entrainment as one progresses toward the center of the river.

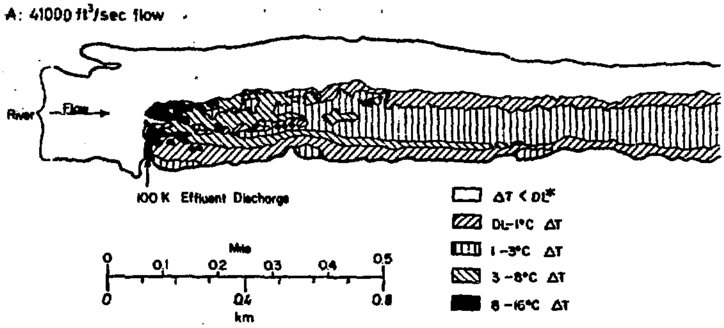


Figure 6. Thermal characteristics of an effluent discharge plume in the Columbia River (Jaske et al. 1971).

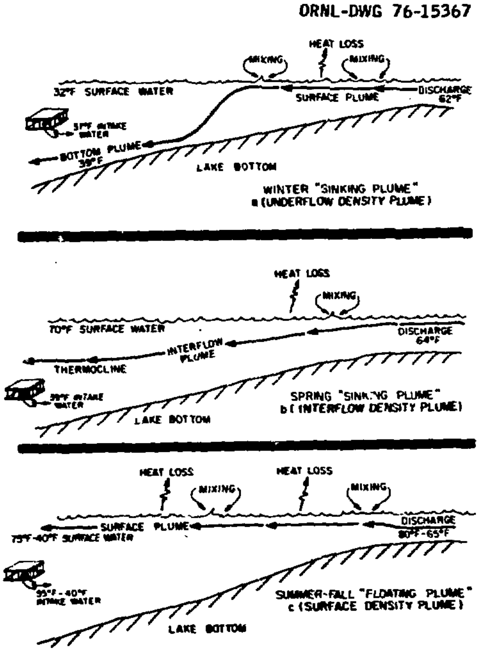


Figure 7. Plume models of the water discharge into the inshore waters of Lake Michigan at the Palisades Plant (from USAEC 1972a).

occurring in field situations, both natural and at power stations (or at similar intakes and discharges). Each type of research data has its advantages and its place in the analytical process. Neither type can be expected to yield confident predictions alone. What is desired is a combination of laboratory and field data — the laboratory data providing, in principle, quantitative predictability for the biological effect of a particular stress (or combination of stresses) while the field data provide both the initial stimulus for seeking quantitative results and the real situations in which to verify them.

Estimates of the probability of direct biological damage can be made in a general way for some impacts and calculated with some precision for others. The likelihood of fish deaths on intake screens can be seen to rise dramatically with higher intake velocities at the Indian Point Plant on the Hudson River (Fig. 9). With high intake velocities (i.e., greater than 1 fps) one would estimate a high probability of damage from impingement.

Effects of thermal stresses can be calculated with more accuracy using techniques that have been described in another paper (Coutant 1972 and NAS/NAE 1973). Such calculations employ basic temperature tolerance data (see Fig. 10 which shows the time and temperature dependence of death of young chinook salmon) and the time and temperature predictions for the power plant (Fig. 11) to estimate whether thermal exposures in the cooling system will be lethal or significantly stressing. Fig. 10 itself can be used as a nomogram to determine effects of fairly constant temperature exposures. For changing temperatures such as in Fig. 11, the calculations can be made on short-time increments and the incremental results can be summed to estimate mortality (if any) during the entire, changing time-temperature exposure.

The time dependency of other sources of potential damage, such as chlorine, can be used in a similar fashion to estimate the likelihood of biological damage (Fig. 12). Fewer data are available for chlorine, however, so Fig. 12 is a composite of data for all species. The time-dependent portion gives way to a low chronic toxicity after about 1000 min.

Data on the growth rates of fish as functions of temperature are particularly useful for determining maximum desirable temperatures (NAS/NAE 1973). Each fish species has a characteristic temperature-growth curve that indicates the temperature range for maximum growth rates and the high temperatures at which so much food energy is used for accelerated metabolic processes that none is left for additional growth (Fig. 13). It is a current concensus that temperatures high enough to reduce maximal growth by more than about 1/3 over long period are undesirable (NAS/NAE 1973).

Fish behavior is increasingly recognized as an important factor in determining the biological impacts of power stations. Fish will actively select preferred temperatures (which often correspond to growth optima) (Coutant 1975, Fig. 14). This causes them to be attracted to thermal discharges in cool months and to avoid them in warm months. The consequences can be good or bad, depending upon the specific circumstances at the site.

Probability of Population Effects

For selected species, detailed analyses of population dynamics may be desirable to quantitatively predict whether effects of power plants will cause a decline in numbers in future years. Such a decline may lead to lower, but stable, numbers of individuals in the population or to a trend of continued decline that could, in the extreme, lead to extinction of the population at that

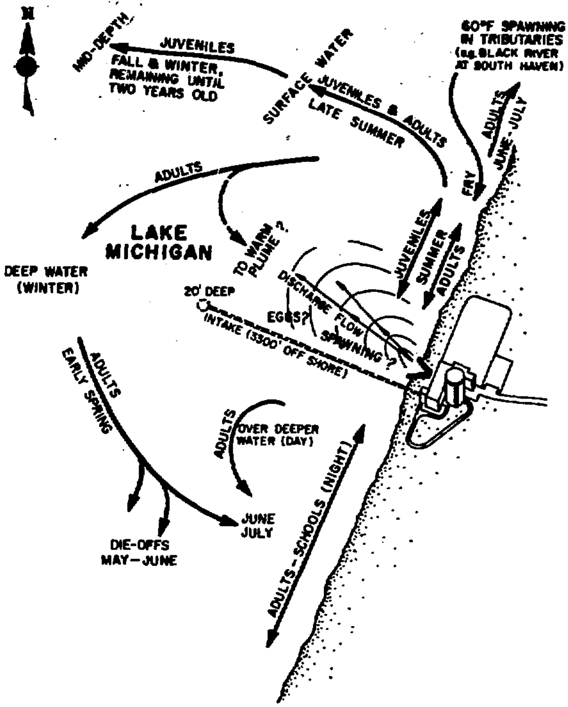


Figure 8. Schematic diagram of the life cycle of the alewife (<u>Alosa pseudoharengus</u>) in relation to the Palisades plant on Lake Michigan (USAEC 1972a).

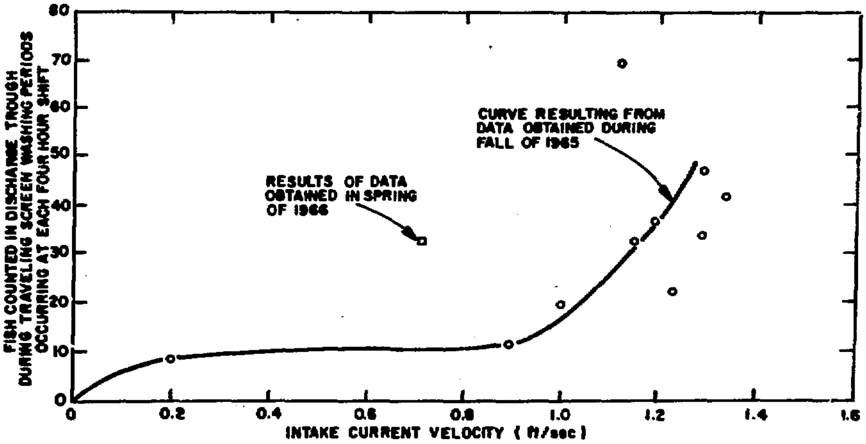


Figure 9. Numbers of fish killed on each intake screen at the Indian Point Plant Unit 1 versus average current velocity (from USAEC 1972b).

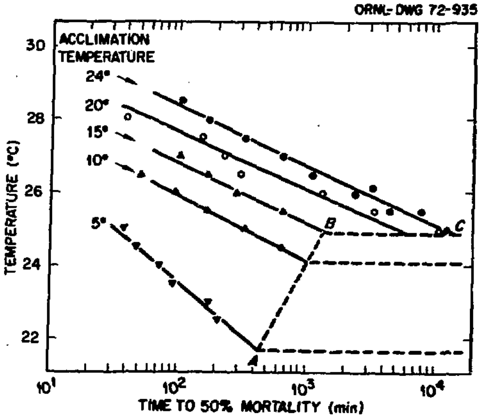


Figure 10. Median resistance times to high temperature among young chinook salmon acclimated to the temperature indicated. Line A-B denotes rising incipient lethal temperatures with increasing acclimation temperature. This rise eventually ceases at the ultimate incipient lethal temperature (line C-D). (From Coutant, 1972 adapted from Brett, 1956).

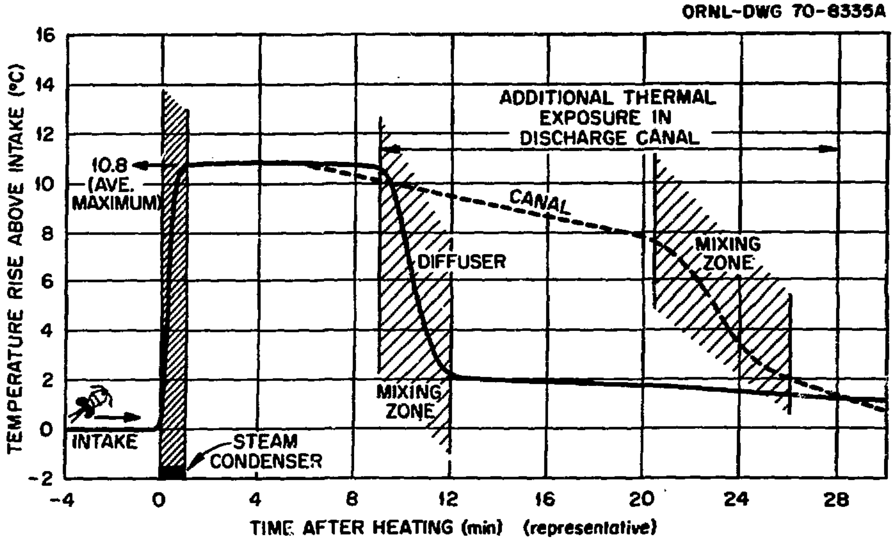


Figure 11. Hypothetical time-courses (left to right) of acute thermal shock to organisms pumped with condenser cooling water, raised to an average increase of 10.8 deg. C (19.4 deg. F), and discharged by set diffuser or via a discharge canal (adapted from Coutant 1970).

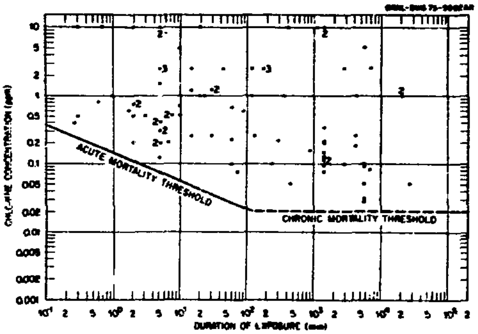


Figure 12. Composite toxicity data for freshwater organisms. Numbered points represent data in the literature for particular species, and most represent median effect levels for mortality or sublethal physiological rates. Threshold lines approximate zero-effect levels. (After Mattice and Zittel, in press).

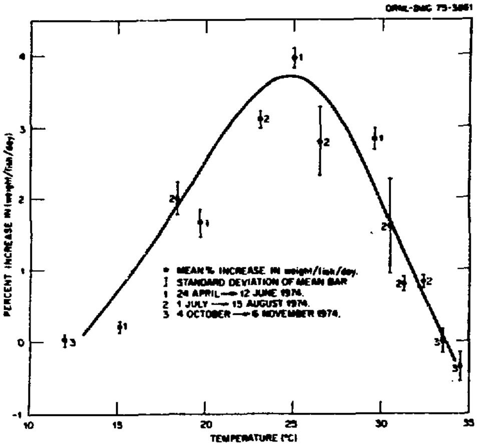


Figure 13. Growth rates of striped bass, Morone saxatilis, as a function of temperature (from Cox and Coutant, in press).

site. Two excellent examples of such analyses are (1) the Hudson River striped bass (Van Winkle et al. 1974, USNRC 1975), and (2) winter flounder spawning in Niantic Bay (Hess et al. 1975). Brief discussion of one case study, the striped bass, will indicate the type of analysis which has proven useful in assessing power plant effects.

The striped bass, Morone saxatilis, occupies the lower Hudson River where there are seven existing power plants and one proposed project, the Cornwall pumped-storage facility (Fig. 15). The concentration of power plants between mile points (MP) 38 and 65 is of particular concern, due primarily to the large cumulative water withdrawal from the Hudson River by these plants. From 1950 through 1972 there was a steady but gradual increase in water withdrawal as Indian Point Unit 1 and the various relatively small units at Lovett and Danskammer came on line. Since 1972 there has been a rapid and large increase in the cumulative water withdrawal as the relatively large units at Bowline, Roseton, and Indian Point (Units 2 and 3) have come on line. Water withdrawal in future years is in question and depends on the fate of the proposed Cornwall pumped-storage facility, the installation of closed-cycle cooling at Bowline, Roseton, and Indian Point Units 2 and 3, and the construction of additional power plants in this middle region of the lower Hudson River.

Although the cumulative effects of thermal and chemical discharges from these plants clearly require monitoring because of potential habitat alteration, the primary concern has been the direct cropping impact on fish populations due to impingement on the intake screens and entrainment in the water passing through the plants. In response to this concern, the three utilities involved have supported a steadily escalating research program that somewhat parallels the water withdrawal curve and that now involves expenditures exceeding $5 million per year.

Entrainment and impingement data indicate that the fish species having the greatest potential for being adversely effected by the operation of the power plants are striped bass, white perch, tomcod, alewife, blueback herring, and anchovy (USNRC 1975). For several reasons, however, the impact assessment has concentrated on one of these species, the striped bass. The striped bass is a "representative and important species" in that it is the object of an intensive sport and commercial fishery, it is an anadromous species, and it is one of the top carnivores in the fish community in the Hudson River estuary. Secondly, the spawning distribution of striped bass in the Hudson River is in and immediately above the region in which the plants are concentrated, while the major nursery area for young-of-the-year striped bass is in Haverstraw Bay and Tappen Zee Bay immediately below Bowline, which is below most of the other plants. Data (USNRC 1975) indicate that the majority of young-of-the-year striped bass which survive to reach this major nursery area move past these power plants at an entrainable size (i.e., less than 50 mm long). Finally, considerably more information is available for striped bass than for any of the other five fish species of concern, thus permitting a more detailed and accurate assessment. The assessment has been at the population level, as opposed to either the individual organism level or the fish community or ecosystem level.

Although the assessment was carried out in the course of the licensing procedure for a single power plant (Indian Point Unit 3), young-of-the-year striped bass are subjected to entrainment and impingement impacts from the entire complex of power plants on the Hudson River. Consequently, a multiplant or regional assessment of the impact was necessary.

As an aid in determining the significance of the entrainment and impingement impact on the Hudson River striped bass population, two simulation

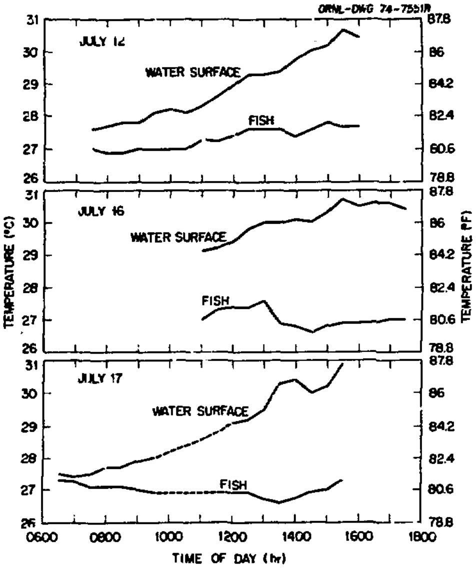


Figure 14. Temperatures selected by an adult largemouth bass and water surface temperatures at half-hour intervals for three days in July 1974, K-25 pond, Oak Ridge, Tenn., USA (from Coutant 1975).

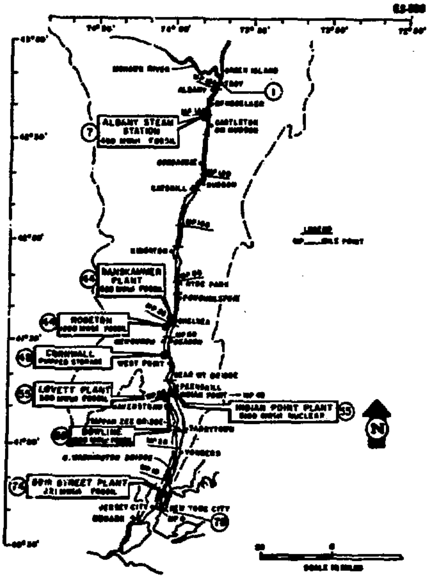


Figure 15. The Hudson River showing major existing and planned power generating plants (USNRC 1975).

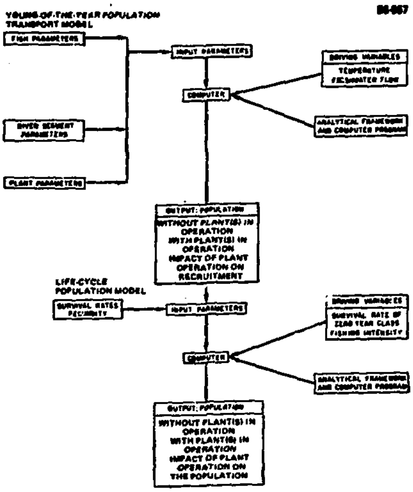
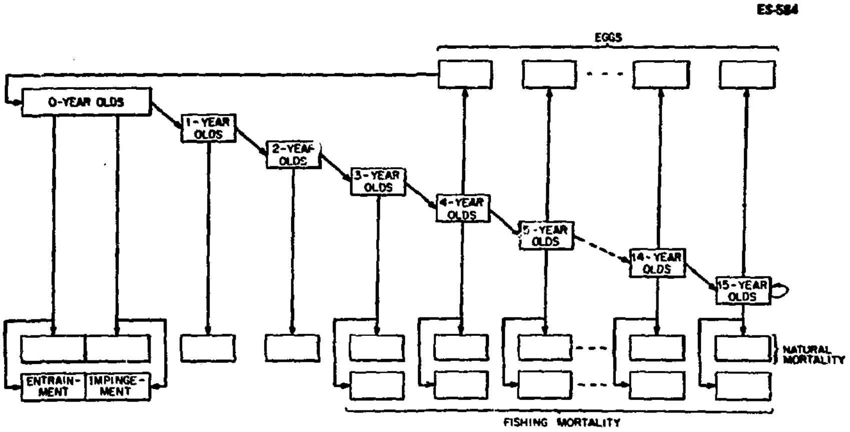


Figure 16. Overview of the striped bass young-of-the-year population transport model and life-cycle population model (Van Winkle et al. 1974).



Population Model.

Figure 17. Box-and-arrow diagram for the striped bass life-cycle population model illustrating aging transfers, production of eggs by sexually mature females, and losses due to natural mortality, fishing mortality, and entrainment and impingement at power plants (Van Winkle et al. 1974).

models were developed (Fig. 16): a young-of-the-year population transport model (Eraslan et al., in press), and a life-cycle population model (Van Winkle et al. 1974). Other simulation models for the Hudson River striped bass population have been developed by Clark (1972), Lawler (1972), and Texas Instruments (1974).

The young-of-the-year model (Eraslan et al., in press) considers six life stages (egg, yolk-sac larva, post yolk-sac larva, and three juvenile stages), and it includes dependence of spawning rate, mortality rates, growth rates, apparent survival probabilities, and maximum swimming speeds on temperature, salinity, and population densities. The transport of these life stages in the Hudson River is formulated in terms of a daily transient (tidal-averaged), longitudinally one-dimensional (cross-section-averaged) hydrological transport scheme. The validation procedure for this model involves a comparison of simulated and observed weekly standing crop values in the Hudson River for each of the young-of-the-year life stages.

From the striped bass young-of-the-year population model, one obtains forecasts of the percent reduction in the number of striped bass surviving their first year, due to mortality at the power plants. This percent reduction value provides input to the striped bass life-cycle population model (Fig. 17) (Van Winkle et al. 1974). The life-cycle model is designed to evaluate the long-term impact on the striped bass population of changes in mortality in the youngest age class. The general question concerns what happens to a fishery when new density-independent sources of mortality which act on the young-of-the-year are added to already existing sources of mortality. This model considers all age classes of striped bass from young-of-the-year to fifteen-year-olds and older. The model is strictly time-dependent and, unlike the young-of-the-year model, does not include spatial considerations. In the model the striped bass population is currently assumed to be regulated in the long-term time frame by fishing in a compensatory (density-dependent) manner.

Typical (but hypothetical) results from the life-cycle model are illustrated in Fig. 18 for two designs. Design 2 involved an annual reduction of 50% for each of the first 35 years in the number of striped bass surviving their first year, due to mortality at the power plants, and then no power-plant impact for the next 65 years. Design 1 involved an annual reduction of 50% for the first five years, followed by an annual reduction of 10% for the next 30 years following installation of cooling towers, and then no power plant impact for the next 65 years. Relative yield is defined as the ratio of the yield to the fishery with a power plant impact to the yield with no power plant impact. The hatched area in Fig. 14 represents an index of the difference in the expected impact on the striped bass fishery from the two power plant designs, and it can serve as a basis for calculating an index of risk of irreversible damage to the striped bass population (Christensen et al., in press). This index takes into account both the number of years and the extent to which the relative size of the population is depressed below 0.5 of its original steady-state size.

Public policy decisions regarding use of cooling towers or other off-stream cooling devices for future power plant developments on the Hudson River can presumably be made from a clearer understanding of the impacts on this one important species. Alternative models and assumptions provide critical guidance for needed field research, as can be seen in the licensing proceedings for one new power station (USNRC 1975).

Probability of Community and Ecosystem Changes

Except for the zones very close to power station discharges, effects at the community and ecosystem levels have received little attention (see, for example, Gibbons and Sharitz 1974, Johnson and Schneider 1976). This is regrettable, for the high costs of many alternative cooling systems and mitigating devices are raising questions about the broad ecological significance of power station impacts as opposed to "the killing of a few fish." An important indication that society as a whole places values at the higher levels of ecological organization is the United States' Water Pollution Control Act Ammendments of 1972 (PL 92-500) which state that closed-cycle cooling shall be used at power stations unless it can be shown that the power station has no effect on the balanced, indigenous populations of the water body. The phrase "balanced, indigenous populations" actually referred to multiple-species assemblages in communities and ecosystems. As a result of this law, electric utilities in the U.S.A. are currently gathering data at many power stations in an effort to demonstrate lack of community and ecosystem damage.

There are basically two approaches to estimating community and ecosystem effects: (1) make measurements or predictions based on the expected consequences of altered species responses (metabolism, growth, reproduction, etc.) (disease, parasitism, predation, competition, etc.), or (2) seek changes in the emergent attributes of ecosystems, i.e., the structural characteristics and dynamic properties which govern the flow of energy and cycling of elements in the biosphere. Reichle (1975) tabulated important attributes of ecosystems which do not derived directly from lower levels of organization (Table 1).

Table 1. Attributes of Ecosystems (from Reichle 1975)

Structural	Dynamic	Strategic
Components	Homeostasis	Optimization
Organization	Circulation	Efficiency
Diversity	Stability	Adaptation
Connectivity	Sensitivity	Perpetuation

Perhaps the best examples of the influences of small temperature changes on aquatic ecosystems are to be seen in latitudinal differences and in changes in the distribution and abundance of species when there are slight climatic changes. Certain zones (e.g., Cape Cod, USA) are known to be natural limits to geographic ranges of many species. Species living at the extreme southern limits of their ranges might be in danger of being eliminated following a slight temperature rise (Kennedy and Mihursky 1971, Dickie 1958). Others with northern affinities might be greatly reduced in abundance while species with southern affinities could increase. The abundance of many species, especially commercially important species, has been shown to vary over a wide geographic range within a relatively short period of time (1 decade) in response to climatic changes of $4C^{o}$ in seawater temperature (Dow 1964, 1969, Southward and Crisp 1954; Taylor, Bigelow, and Graham 1957, Welch 1968, Hubbs and Shultz 1929).

One striking example of community change occurred at a shallow water discharge from a power station on the middle Delaware River (Coutant 1962). Here, the heated portion of a riffle area was nearly devoid of macroinvertebrates while algal populations (bluegreens and certain diatoms) flourished (Fig. 19). A bottom community quite similar to the unheated portion of the riffle was able to maintain itself about a mile downstream, with the exception that this downstream community had an especially high abundance of filter-feeding insects and mussels. These filter-feeders were apparently utilizing the unharvested organic production from the warmed upstream riffle.

Unfortunately for the impact analyst, most changes at the community and ecosystem level require several years to become evident. By that time, however, power plant impacts may have progressed to the point where mitigation is either not possible or would itself require a long time. Gradual eutrophication is an example. Extreme cases of eutrophication have been reported for cooling ponds in the USSR (IAEA 1974). They have been caused by gradual accumulation of nutrients in closed water bodies, and gradual changes in the biotic communities which have been supported. The annual changes were probably small, however, and the ecosystem change was not evident until the long-term damage had been done.

Because of the inherent time lag, ecosystem modeling has been developed as a predictive tool. Its use corresponds with population dynamics modeling discussed earlier, but it focuses on different interactions (i.e. those which pertain directly to ecosystem structure and function). Patten (1975) described a reservoir cove ecosystem model and the changes in its steady state when the cove was, through mathematical experiment, given a perturbation of a 3C° constant rise in the annual temperature cycle. This rise increased the rates of virtually all biological processes in the model since most coefficients were temperature dependent. The results (Table 2) showed highly variable changes from the normal third year mean values among the different ecosystem components. Cross production declined 3.5% while respiration increased 5.5%. The P/R ratio, often used as an index of ecosystem "health", declined in the model prediction by 8.6%. As with population models, however, validation remains a difficult problem.

Probability of Social Impacts

Analysis of the social impacts of changes in the composition of aquatic environments due to "pollution" is a complex task that is much beyond the expertise of aquatic ecologists alone. Some social impacts are quantifiable (e.g., economic effects of loss of a fishery) but others (such as changes in benthic fauna) are not. Many "impacts" relate more to social values for various aspects of the human environment than they do to quantitative economic criteria. As the social costs of damaging technologies increase and the economic burdens of mitigating measures also increase (often at rates faster than the reduction in social costs), we can expect increasing social debate over costs vs benefits of our actions.

Knowledge of local social values is crucial to developing an acceptable assessment of environmental impacts. There are definite regional differences in preference for sport and commercial fishes, for example. Impacts that could be acceptable in one location will be intolerable in another, due to differing social values, not to the ecosystems *per se*. In actual practice, assessments of environmental impact generally begin with consideration of the "important" species to be protected or enhanced. The character of the subsequent assessment is often determined by this initial

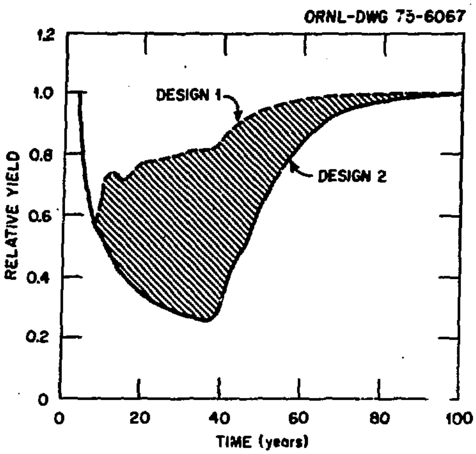


Figure 18. Two hypothetical curves of relative yield to the fishery versus years to illustrate the type of biological information needed in addressing the two questions: Is the socioeconomic benefit of the project greater than the socioeconomic cost of the impact of the project on the biological system? Is the present design (including mode of operation) of the project optimally cost-effective with respect to minimizing the damage to (or enhancing the value of) the biological system? (after Christensen et al., in press).

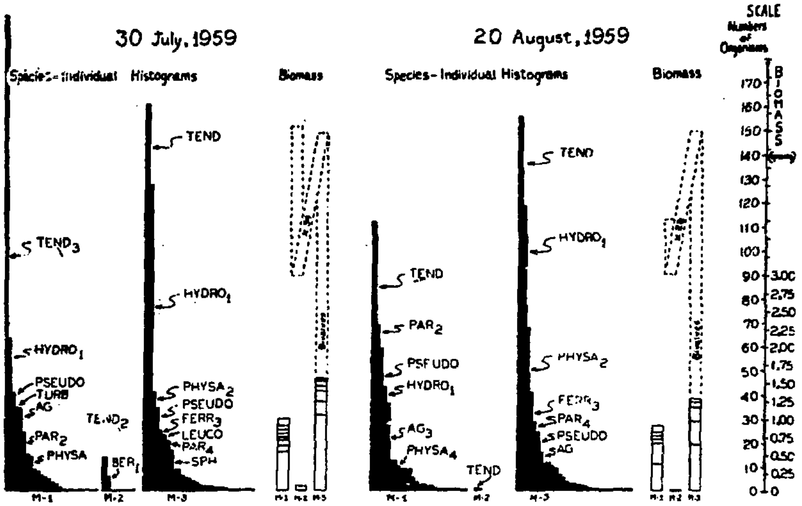


Figure 19. Species-individual and biomass histograms for two 1959 collections of macroinvertebrate bottom fauna near the Martin's Creek Power Plant. Station M-1 was upstream of the discharge, station M-2 in the maximally heated riffle area, and station M-3 was in a riffle area about 1 mile downstream. All data are per one square foot. The numerically important taxa are labeled (see paper for key to abbreviations). Subscripts indicate the organism's rank in the biomass of the sample. Dotted line extensions of biomass histograms are for bivalve mollusks. (after Coutant 1963).

Table 2. Results of perturbation experiments, as percentage deviations [increase (+) or decrease (-)] from nominal third year means (second column) (Patten 1975)

Variable	Third year nominal mean (g m^{-2})^{a}	Thermal pollution Δ mean (%)
State variables		
Small phytoplankton	1.53×10^{-2}	-1.1
Medium phytoplankton	1.32×10^{0}	-2.3
Large phytoplankton	1.47×10^{-2}	-3.5
Blue-green crusts	1.77×10^{-2}	+2.0
Floating mats	2.44×10^{-1}	+8.8
Attached algae	5.52×10^{0}	-4.2
Aufwuchs	4.90×10^{-1}	-2.2
Submergent plants	2.63×10^{0}	-1.0
Emergent plants	1.86×10^{0}	-11.9
Small zooplankton	2.95×10^{-3}	0.0
Large zooplankton	3.76×10^{-2}	+0.6
Larval fishes	4.52×10^{-2}	-27.5
Fingerlings	6.44×10^{-2}	+1.5
Filter feeding fishes	4.23×10^{-1}	+7.7
Bottom feeding fishes	9.85×10^{-2}	+13.5
Minnow-like fishes	7.78×10^{-1}	+58.1
Carnivorous fishes	1.14×10^{-1}	+29.5
Turtles	5.95×10^{-2}	+17.2
Plant harvesters	2.02×10^{-2}	+5.7
Animal harvesters	2.59×10^{-2}	+43.2
Suspension feeders	5.78×10^{-2}	-4.3
Deposit feeders	1.74×10^{0}	+1.2
Predators	1.53×10^{-1}	+15.6
Dissolved organic	2.42×10^{1}	+3.7
Particulate organic	2.49×10^{0}	-5.7
Plant carcasses	1.51×10^{0}	-4.9
Animal carcasses	5.20×10^{-4}	+78.3
Nitrogen	9.09×10^{-2}	+42.8
Phosphorus	2.90×10^{-2}	+8.6
Carbon dioxide	1.44×10^{2}	+0.5
Dissolved oxygen	1.72×10^{1}	-7.2
Output variables		
Gross production	2.87×10^{0}	-3.5
Respiration	2.66×10^{0}	+5.5
P/R ratio	1.08×10^{0}	-8.6

[a] g m^{-2} wk^{-1} for X19, X20, gross production and respiration; unitless for P/R ratio.

selective procedure. Criteria for selecting such species are currently under debate (see Coutant, in press). Some attempts are being made to determine the economic and social importance of certain types of ecosystems (Sweet 1971).

Long neglected, but now receiving deserved attention in the midst of the current energy shortages, is the productive use of energy otherwise wasted in the power plant cooling system. There are potential physical applications, such as process heating and district (building) heating, and biological applications such as fish culture and greenhouse heating. Both have been discussed at several conferences in the USA (Mathur and Stewart 1971, Yarosh 1972), in state-of-the-art reports (e.g. Yarosh et al. 1972). A summary of beneficial uses of waste heat is given by IAEA (1974). Beall (1970) tabulated a number of beneficial uses of waste heat.

III. SUMMARY

This review is intended to be an educational article for those who are considering the impacts of power plant cooling for the first time. It is the written version of an oral presentation given to the ORAU Summer Institute on "Energy Sources for the Future" to illustrate major problem areas and to serve as a guide to the extensive literature.

The major environmental impacts from power plant cooling now seem to be recognized. The task now is to quantify the effects, to place theorized effects in the context of local populations and ecosystems at power plant sites, to make reasoned judgements about significance of impacts for both local ecology and man, and to develop mitigating plans for siting, design, and operation of new or modified systems that make a reasonable balance between environmental benefit and cost to the consumer of electricity.

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TECHNOLOGY OF THE LIGHT WATER REACTOR FUEL CYCLE*

R. G. Wymer

Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830

I. INTRODUCTION

The nuclear fuel cycle generally is taken to consist of all of the steps required to produce the fuel for nuclear power reactors, and to recycle valuable fuel materials and dispose of the resultant wastes. The reactors themselves are not considered to be a part of the fuel cycle. Because power reactors rely on the fissioning of either ^{235}U, ^{239}Pu, or ^{233}U, these materials are the fuels of interest. Of these, only ^{235}U is present in nature in any significant amount, and it is highly diluted with other uranium isotopes, mostly notably ^{238}U. Because of this dilution, it must either be concentrated by an isotope separation process before use, or it must be used at the naturally occurring concentration under very special conditions in certain kinds of nuclear reactors. ^{239}Pu is formed from ^{238}U in nuclear reactors, so requires no natural source other than urnaium ore for its production. ^{233}U is produced in nuclear reactors from naturally occurring ^{232}Th, which requires extraction from thorium ore.

Each step in the nuclear fuel cycle, from the mining of ore to the final storage of the wastes, requires careful attention to ensure that no one receives an unacceptable radiation dose, and that no significant release of radioactivity occurs, either through process inadequacy, or operational or functional failure. In addition, certain fuel cycle steps require special precautions, or safeguards, to ensure that deliberate attempts to divert or steal fuel will either fail or be of such short-lived or limited success as to pose no hazard to the public or to the industry. These steps are generally those involving separated and purified ^{239}Pu, or highly enriched ^{235}U.

The constraints and requirements on release of radioactivity are still evolving, and impose continually changing technological requirements. In fact, the general requirement is that radioactivity released is to be "as low as reasonably achievable," (ALARA) which by its nature is a moving target. Beyond being as low as reasonably achievable, the releases must also meet

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*Research sponsored by the Energy Research and Development Administration under contract with the Union Carbide Corporation.

specified limits, which are themselves in the process of being re-examined.

The word "reasonably" as used in the above paragraph requires further definition. It is usually defined in terms of a cost-to-benefit ratio. That is, for the expenditure of a certain number of dollars, a certain decrease in radioactivity release may be attained. The number of dollars which must be spent to attain a specified limit to radioactivity release is clearly subject to change, depending on the process chosen to retain the radioactivity, the ingenuity of the equipment designer, the buying power of the dollar, and the development of new technology--among other things. In practice, the radioactivity release is translated into the radiation dose to people which it causes, and it is the radiation dose reduction which most often is used in the cost-to-benefit ratio. Making the translation from "curies released" to "dose received" entails use of a variety of calculational models. Some of the models are meteorological in nature; some are demographical; some are geographical; some are biological; some are chemical; and some are radiological. Most of them are related to each other. Further, there is a variety of radioisotopes and of body organs to consider, each of which must be treated separately when calculating does. Thus, it is not easy to specify a cost-to-benefit ratio which is above criticism. Nonetheless, such ratios are calculated based on assumed technologies and radiation dose models, and for the most part they are accepted by knowledgeable people.

The fuel reprocessing step is the one involving the greatest chance for significant radioactivity release because it is the one in which the full assembly (which by its nature is a high-integrity container for fuel and fission products) is destroyed, and in which the fission products are put through a variety of chemical and physical forms, and a variety of pieces of engineering equipment. Thus, in fuel reprocessing great care is taken to treat all plant effluent streams to ensure that acceptably low releases of radioactivity are obtained. Beyond this, extraordinary precautions are taken to ensure that major natural disasters, such as might result from tornadoes or earthquakes, will not affect the reprocessing plants. This essay will present elements of the processes used in the fuel cycle steps, and will give an indication of the types of equipment used. The amounts of radioactivity released in normal operation of the processes will be indicated, and where feasible these will be related to radiation doses. Finally, types and costs of equipment or processes required to reduce these radioactivity releases to lower values will, in some cases, be suggested. The discussion will of necessity be sketchy and often incomplete to limit this essay to a tractable size.

II. MINING AND MILLING

Uranium ore is the ultimate source of nuclear power today. Although the U.S. has significant amounts of uranium, it is variously estimated that sometime in the decade 1990-2000 there will develop a shortage. It should be remarked in this connection that the consumption of uranium must be reckoned as that required by a reactor through its entire lifetime, not merely that needed for its first core.

A. Mining

U.S. mining is mainly (~94%) in small to medium-sized pockets or "rolls" of uranium in sandstone. Of this, about 45% is at the surface and 55% is underground. There are about 29 open pit mines and 193 underground mines in the U.S. with a total capability of producing 8.2 million tonnes of recovered ore per year. Although the present source of U.S. uranium is from "richer" (~0.2% U) ores, the future trend could be to low-grade (<300 ppm) ores that are uniform and extensive, requiring much larger mills to obtain economies of scale. An extensive program of exploration (the NURE program) is underway in the U.S. to find additional commercially useful uranium deposits. It should be noted that what today is not commercially useful, may tomorrow be the best there is, and so become useful, though more costly.

Factors affecting the selection of mining methods are: (1) size, shape, depth and slope of the ore body, (2) physical and mechanical properties of the deposit and the rock around it, (3) the hydrology of the area, (4) ore grade, production rate and comparative mining costs, (5) environmental factors.

As implied above, mining methods fall into two broad categories: (1) open pit, and (2) underground. Within these broad categories, the following sub-categories, or techniques, may be identified.

Open pit

single bench-single level of operation (shallow deposits)
multiple bench-several levels of operations, with the sides notched, or stepped for stability against slides (deep deposits)

Underground

room and pillar-excavation of a grid of rooms
Open stoping-excavation with supported or unsupported walls
shrinkage stoping-excavation method for steep beds and veins
longwall-complete ore body removal wherein roof caves in behind the face
vein-of little importance in the U.S.
sandfill-sand injection used to support mined out stope area
solution-leaching of massive, laminar or fractured bed or pocket

B. Milling

Uranium milling is carried out largely by solvent extraction or ion exchange methods, using sulfuric acid or alkaline carbonate to leach the ores, the choice depending on the nature of the ore. If the ore contains minerals that consume an excessive amount of acid, then alkaline carbonate is used. Acid leaching is more common. The product of milling is a semirefined yellow-colored uranium concentrate called yellow cake which is packaged in 55-gallon drums for shipment. Liquid and solid wastes, called tailings, are impounded near the mill. It is the tailings which present the most significant long-term radiatio problem in this part of the fuel cycle. This problem and its solutions are discussed later. Uranium milling companies and plants in the U.S. are listed in Table 1.

As was mentioned above, uranium is most commonly extracted from the ore by leaching it with sulfuric acid or with sodium carbonate solution. Prior to leaching, the ore is ground to a nominal 20- to 200-mesh (0.84 mm to 0.074 mm). Finer grinding is required with carbonate than with acid leaching to get acceptable uranium leaching rates and recoveries. If the uranium is present in the ore in a chemically reduced form, a solid or liquid oxidant may be added during leaching. Leaching in a pressurized system may be used to enhance the rate of carbonate leaching. The product of milling is either a clarified uranium solution, or a dilute slurry of fine solids in a uranium solution. The solid waste from milling is called tailings and consists of all the insoluble residues, including part of the radium and its decay chain daughters. More radium is in the tailings from acid than from alkaline leaching because radium is more soluble in carbonate than in sulfate media.

Uranium minerals containing carbonates, e.g. $CaCO_3$ and $MgCO_3$, consume acid in a direct ratio to their amounts. Above about 15 percent by weight $CaCO_3$ in the ore it is likely that the acid cost would be prohibitive, and carbonate leaching would be used.

Sulfuric acid is used in acid leaching because it is cheaper than other acids. There might be advantages to the use of nitric acid or hydrochloric acid leaching from the point of view of enhancing the removal of contributors to radiation from the tailings piles, i.e., radium and its daughters, especially radon, but major changes in some milling steps would be required, and the additional cost would be substantial.

Carbonate solutions are used in alkaline leaching because of the happy circumstance that uranyl carbonate complexes form which are of sufficient stability that the uranium is kept in solution even at high pHs, which would normally cause uranium to precipitate. Thus, the uranium can be successfully extracted from many contaminants which either remain as solids or precipitate as basic compounds. (As a matter of fact, most elements precipitate in basic solution; the fact that uranium forms highly soluble carbonate complexes is fortuitous indeed.)

1. Extraction

acid leach

Figure 1 is a schematic flowsheet for a model acid-leach solvent extraction uranium mill. Sandstone-type uranium ores contain hexavalent uranium which is soluble in acid solutions, and oxidants are added only to prevent reduction of the uranium by other ore constitutents or by uranium-reducing metals, e.g., iron, introduced during the ore grinding. Other uranium ores may contain reduced uranium as mined, and oxidation is required to obtain high uranium yields. The oxidant, which may be manganese dioxide or sodium chlorate (others such as air, oxygen,

Table 1

URANIUM MILLING COMPANIES AND PLANTS

Company	Plant Location	Nominal capacity (metric tons ore per day)
The Anaconda Company	Grants, New Mexico	2,700
Atlas Corporation	Moab, Utah	1,400
Continental Oil Company - Pioneer Nuclear, Inc.	Falls City, Texas	1,600
Cotter Corporation	Canon City, Colorado	400
Dawn Mining Company	Ford, Washington	450
Federal-American Partners	Gas Hills, Wyoming	850
Exxon-Nuclear Company, Inc.	Powder River Basin, Wyoming	1,800
Kerr-McGee Nuclear Corporation	Grants, New Mexico	6,400
Petrotomics Company	Shirley Basin, Wyoming	1,400[a]
Rio Algom Corporation	LaSal, Utah	450
Union Carbide Corporation	Uravan, Colorado	1,200
Union Carbide Corporation	Natrona County, Wyoming	900
United Nuclear-Homestake Partners	Grants, New Mexico	3,200
Utah International, Inc.	Gas Hills, Wyoming	1,100
Utah International, Inc.	Shirley Basin, Wyoming	1,100
Western Nuclear, Inc.	Jeffrey City, Wyoming	1,100[b]
TOTAL		26,050

Sohio and Reserve Oil-Under construction to start up 900-metric-ton-per-day mill in 1976.

The mills have the capability of producing about 16,000 metric tons U_3O_8 per year, considering availability of ore supplies.

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[a] Currently closed.

[b] Currently closed for modifications.

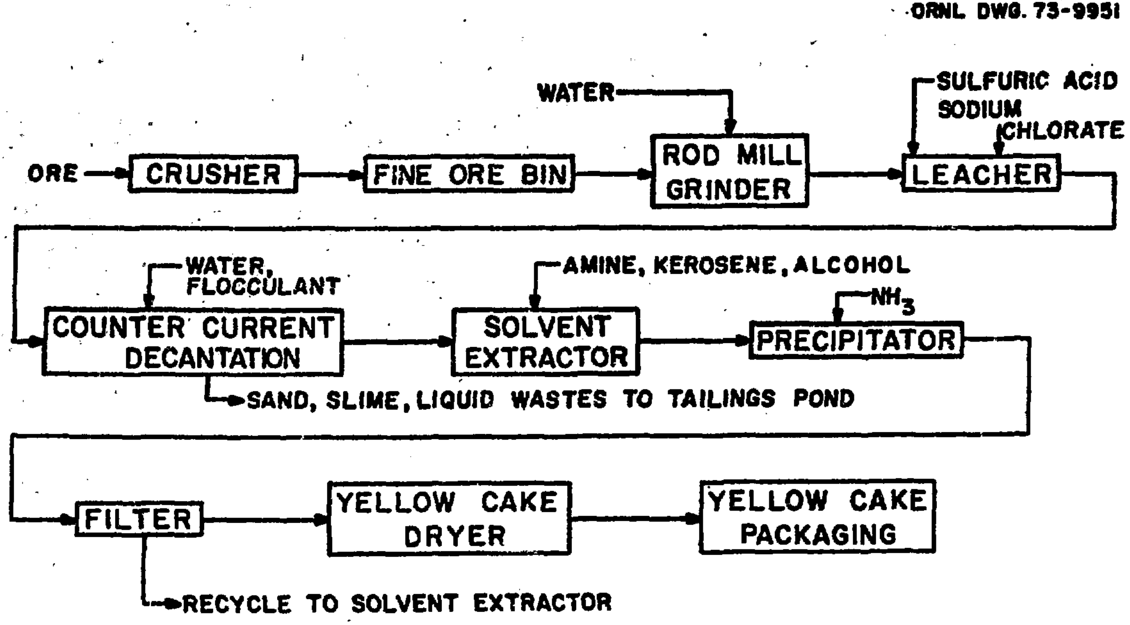

Figure 1. **Flowsheet for Model Acid Leach--Solvent Extraction Uranium Mill.**

(Taken from ORNL-TM-4903, Vol. 1,
May 1975)

chlorine, sodium nitrate and potassium permanganate work, but have high cost and other disadvantages), is added to the acidified "pulp" after the reactions between the acid leach solution and the materials which produce reducing gases, e.g., iron or sulfides have taken place. Otherwise, the oxidant would oxidize the reducing gases before their escape from the solution, resulting in parasitic consumption of the oxidant.

Acid leaching is carried out in different ways at different mills, depending on the nature of the ores. Usually, leaching tanks are arranged for series flow. Feed solution enters at the top of each tank and leaves at the bottom through risers, whose function is to reduce transfer of pulp from one tank to the next. Removal from the bottom of the tanks prevents high-specific gravity solutions, which gravitate to the bottom of the tanks, from building up and decreasing leaching efficiency. Propeller or turbine-type agitators are used to mix the slurry of ore in acid so that the reaction rate at the mineral surface is rate controlling, rather than the movement of reactants to or products from the ore particle surface. Rubber is commonly used to cover both propellers and shafts, and 18 months is about their expected service life.

alkaline leach

Figure 2 is a schematic flowsheet for a model alkaline-leach solvent extraction uranium mill. Oxidized uranium minerals are readily dissolved in alkaline carbonate solutions; however, minerals containing U^{4+} usually require extensive oxidation, often under pressure. It is important in carbonate leaching that the ore be ground fine enough to free the uranium minerals from the "gangue." Carbonate leaching differs from acid leaching in that the carbonate leach solutions are treated and recycled to reduce reagent costs. Carbonate leach solution is consumed by reaction with acidic sulfate or sulfide ore constituents to a degree which may be prohibitively expensive with some ores. Over one third of the U.S. uranium mills have used carbonate leaching at one time or another.

Carbonate leaching is carried out in open, agitated tanks, in autoclaves, or in open or pressurized "Pachuca tanks". Pachuca tanks are large tanks with conical bottoms (60° included angle) and cylindrical upper bodies, with an overall height-to-diameter ratio of about 2.5 to 1. Steam may be added through nozzles, and air may be added through a central air lift or a bottom jet. Air compressors are required for pressurized operation. Pachuca tanks are well suited for carbonate leaching because the air used for oxidation also is used for agitation. Most such tanks are between 40 and 60 feet deep. Exhaust gases are vented through cyclone separators or other vessels designed to remove excess froth or condensate. Pachuca tanks are used in series and the hot exhaust vapors may be used to preheat feed slurry. Discharged slurry from high temperature autoclave circuits is passed through a heat exchanger to recover the waste heat and to reduce the slurry temperature to below its flash point.

Recarbonization, which is necessary to convert excess

ORNL DWG. 73-9943

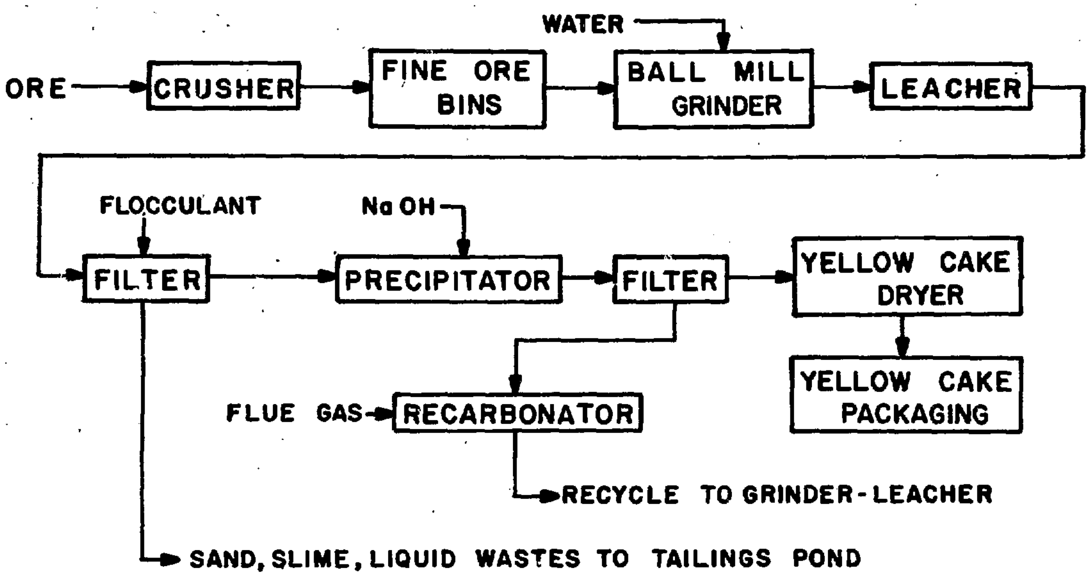

Fig. 2 Flowsheet for Model Alkaline-Leach uranium mill. Taken from ORNL-TM-4903, Vol. 1, May 1975).

caustic to carbonate (and bicarbonate) and permit its reuse, is carried out in vertical towers wherein the caustic solution passes countercurrent to boiler flue gas containing CO_2. The towers may be either packed or conventional bubble cap tray towers.

in-situ and heap leaching

Leaching ores in place (sometimes called "solution mining" or in-situ leaching) may be suitable for some ore bodies. This method eliminates the need for handling large amounts of material and for disposing of final wastes. Stated simply, in-situ leaching involves introducing leaching solutions through wells into an ore body and then recovering the leach liquor from other wells for further processing. It goes without saying that rather special ore body conditions must exist for in-situ leaching to be used. Porosity and fracturing of surrounding rock must not be excessive or the leaching solution will be lost. Since high-lime ore bodies may form insoluble $CaSO_4$, which could plug up pores necessary for movement of the leaching solution, other acids than sulfuric have been considered, e.g., nitric and hydrochloric. However, their high cost generally prohibits their use, and in addition, nitrate contamination of ground waters is objectionable.

Heap leaching is literally the leaching of a heap, or pile, of ore, either confined or in an open pile. It is accomplished by passing leaching solution down through the heap, often on a slope, with troughs under the heap leading toward the downhill side where the leach solution is collected. In general, a pile is 300 to 400 feet on a side, and is 20 to 30 feet high. Piles are generally abandoned after leaching is completed, and new piles are constructed alongside. All heap leaching operations in the U.S. employ sulfuric acid, and are carried out with typical sandstone ores.

2. Concentration and purification

Both ion exchange and solvent extraction purification techniques are in standard use in acid leaching mills. Alkaline leaching combined with ion exchange shows promise of providing a high grade pregnant liquor, and is expected to enjoy increased use.

Solvent extraction involves only liquid-liquid contacts and so processes employing it are readily designed and operated continuously (as will be seen later, these and other advantages make solvent extraction the preferred separation and purification techniques for use in nuclear fuel reprocessing plants.) It is also somewhat more selective and versatile than ion exchange. However, it is not economically feasible to use solvent extraction (often abbreviated "SX") with carbonate leach solutions, or with slurries containing large amounts of solids, whereas ion exchange (often abbreviated "IX") may be used in both applications.

solvent extractions

The SX operation involves contacting the sulfuric acid leach solution, or feed solution, with an organic solvent to effect selective transfer of the uranium to the solvent. The solvent is typically a liquid cation or anion exchanger dissolved in an inert diluent, such as kerosene. This solution of liquid ion exchanger in kerosene is immiscible with the acid feed solution, so a two-phase liquid system is formed when the two solutions are mixed and allowed to settle. In some instances emulsions form, or the phases separate only slowly, and modifiers may be added to ameliorate these problems. Cationic exchangers are typically alkyl phosphoric acid compounds such as di(2-ethylhexl) phosphoric acid (diEHPA) and dialkyl pyrophosphoric acid (DDPA). Anionic exchangers are typically either secondary amines such as Amberlite LA-2 or tertiary amines such as Alamine 336 (tricapryl). Figure 3 is a flow diagram showing the essential SX steps.

After the uranium is extracted into the organic extractant and the two phases are separated, the uranium must be removed (stripped) from the extractant so it may be reused. Stripping is accomplished by contacting the extractant with an aqueous solution which has a stronger affinity for the uranium than the extractant. Thus, extractant and stripping are, in a sense, opposite sides of the same coin, and the uranium is involved in a short of chemical tug of war, being pulled first one way (into the organic extractant) and then the other (into the aqueous strip solution). Aqueous solutions which are effective stripping solutions include sodium carbonate, sodium chloride and strong acids, with the carbonate in most common use.

Mixers and settlers are used to carry out the SX operation. Most systems are designed to provide for recycle of part of the organic phase from the settler (where phase separation occurs) back to the mixer of the same stage to maintain an organic-continuous water-in-oil dispersion, in which phase separation is much more likely to proceed successfully than in an oil-in-water dispersion.

The extractant is valuable, and losses of it must be minimized. Loss pathways include entrainment or solubility in the acid solution from which the uranium has been extracted, as well as evaporation, and chemical decomposition. Large final settling tanks are provided to permit complete phase separation and thus to minimize losses from entrainment.

ion exchange

The IX operation involves contacting the sulfuric acid or carbonate leach solution with coarse particles of an organic, solid ion exchange resin to effect selective transfer of the uranium to the resin. The resin is typically a strong base (quaternary amine) anionic type, i.e., it retains anionic (negatively charged) complexes of uranium. The complexes are either sulfate or carbonate complexes. (In the uranium industry the retention process is usually termed "absorption", which, while it is a misnomer, does no more violence to the technical language than does the universally misused term "diffusion" when it is applied to isotope separation by a method which really entails "effusion".) During use the resins may deteriorate and become less effective than when they were new. This takes place because part of the quaternary amine groups hydrolyze to form tertiary, secondary or even primary amines, which have a reduced

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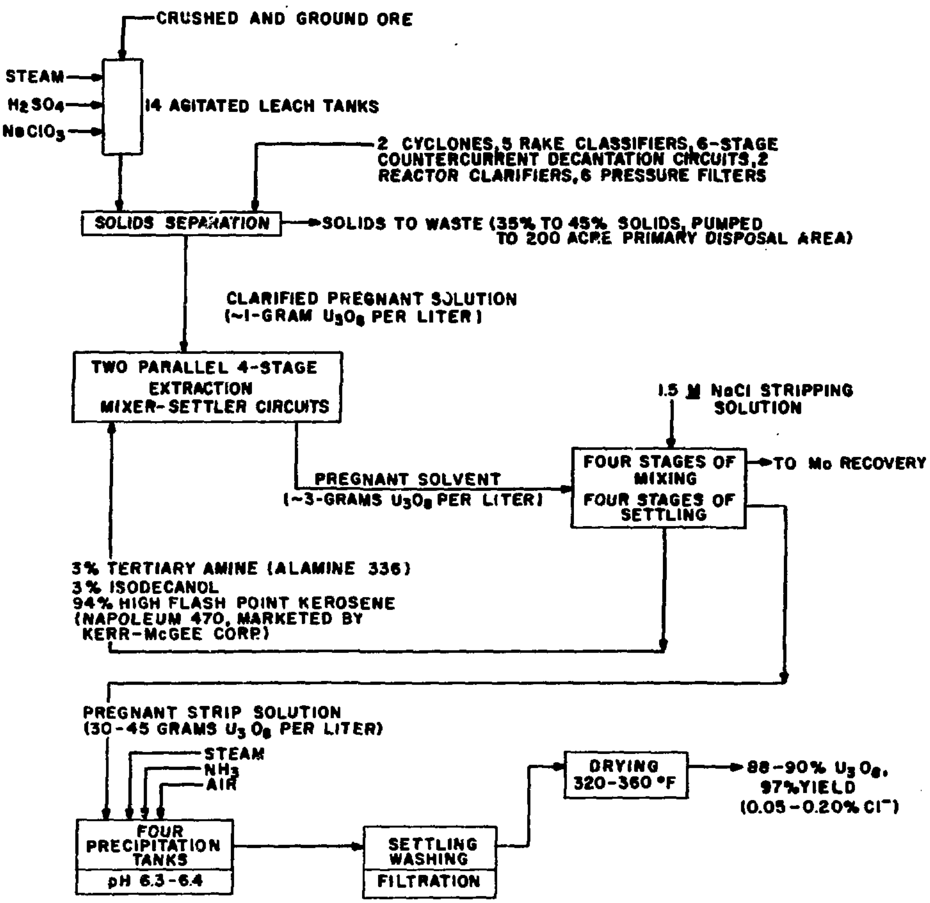


Fig. 3. SIMPLIFIED FLOWSHEET OF KERR-McGEE CORPORATION GRANTS MILL

affinity for uranium, and a slower exchange rate.

After uranium adsorption, the resin is physically separated from the spent leach solution and then the uranium is removed from the resin by a process known as elution. In elution, the resin is contacted with a solution which displaces the uranium by a process analogous to stripping in SX. This is best done with a solution containing a chemical species that both competes with the uranium for adsorption on the resin, and also changes the uranium species to one which either is not anionic, or is a less tightly bound anion than the one originally adsorbed. Chloride ion is especially effective for elution. It is provided as a fairly concentrated NH_4Cl or NaCl solution in dilute acid (either HCl or H_2SO_4). In order to prepare the resin for reuse in the next adsorption cycle it must be regenerated. That is, it must be put back in the same chemical form it had before the adsorption cycle. This entails removal of various ions present in the leach solution which have adsorbed on the resin, and were not removed by elution. The most common adsorbed ions are removed by treating the resin with caustic soda (sodium hydroxide). Concentrated sulfuric acid solutions have also been used.

In most plants ion exchange is carried out in a series of semicontinuous operations. The IX vessels are cylindrical steel pressure vessels, dished at the ends and lined with rubber. The resin itself rests on sized crushed rock, or sometimes on a perforated plate designed to resist clogging. The bed of resin occupies only about half of the tank volume to allow room for bed expansion during backwashing, an operation in which solutions are passed up through the resin bed to expand it and flush out entrained solids. Commercial IX columns are 6 to 9 feet in diameter and 12 to 15 feet high. In fixed bed IX plants either 3 or 4 columns are used. At least two columns are used in series to achieve uranium saturation in the first column before excessive uranium "leakage" occurs in the second. The first column, upon saturation, is put into the elution cycle; the second column becomes the first, while a third column, which has been regenerating, becomes the second column, and so on.

3. Product preparation

Regardless of the concentration and purification process used, there results a product solution, acidic or alkaline, which must be converted to a solid product prior to shipment to the next fuel cycle step. The solid product is a uranium concentrate called yellowcake whose specifications vary depending on the purchaser, but typically the uranium content is in the range of 60 to 65%, calculated as U.

The yellow cake is produced by precipitation of uranium from the SX or IX product solution. When the solution is alkaline carbonate, precipitation is carried out by one of several methods: adding a strong base; adding acid to displace the CO_2, thus destroying the carbonate, and then adding strong base; and passing hydrogen gas through the solution in the presence of a catalyst. Each method has its strengths and weaknesses, and the one chosen depends on the particular circumstances. An additional word of explanation is in order in the case of the third method, i.e., hydrogen reduction. It works because the uranium is reduced to U^{4+}, thereby destroying the soluble uranyl carbonate complex and permitting precipitation of uranium as UO_2.

When the product solution is an acidic solution, which is the more usual case, yellow cake is formed either by neutralization with lime, magnesia, caustic soda or ammonia, or by direct precipitation with hydrogen peroxide. The advantage of using the more costly reagent hydrogen peroxide is that it produces a very high-purity product whose cost of preparation is more than offset by low penalty charges imposed at the refinery for impurities present in the yellow cake.

Water is removed from the product by batch filers, by continuous vacuum-type drum filters or by centrifuges. A variety of devices are used to dry the final yellow cake slurry. Multiple hearth roasters are used to achieve a calcined product. The product is packaged in 55-gallon drums for shipment.

C. Radioactivity Released

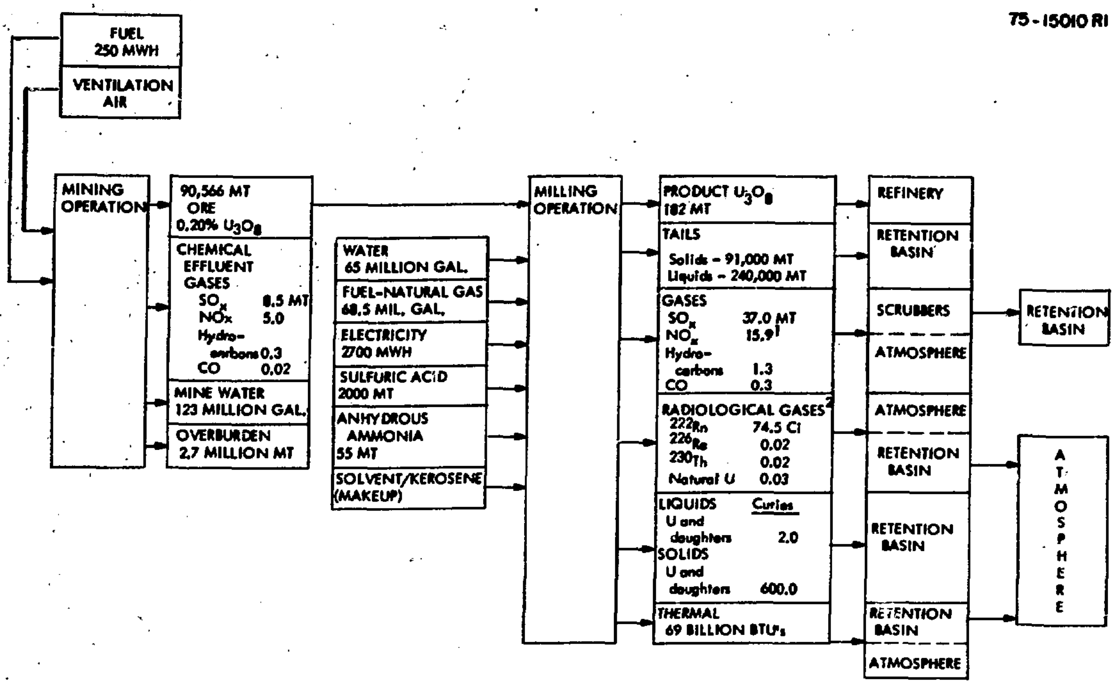
Figure 4 is a material balance flowsheet in which the amounts of material given have been calculated from uranium milling flowsheets in such a way as to show how much material must flow to provide the uranium necessary to fuel a 1000 MWe LWR for one year. These numbers are average numbers, and are for an assumed SX process. They are not expected to be very different for an IX process.

The concentrations of radionuclides in the tailings from a model acid-leach solvent extraction mill and a model alkaline-leach solvent extraction mill are given in Table 2 and 3, respectively. Since there must be greatly increased uranium mining and milling activity if the projected growth of nuclear power is to be achieved, it is important to know how these tailings will be dealt with in the long term. Obviously considerably more careful attention must be paid to this problem than was paid it in the earlier days of the industry. Various steps which might be taken, and their cost-to-benefit ratios, are given in the section D.

As far as releases of radioactivity to the public from the operations of the mines and mills themselves are concerned, there appears to be little cause for concern. Losses of dust and toxic vapor emissions are localized, and are controlled by collection and recovery systems.

D. Low-grade Ores

The supply of low-cost uranium may not meet the demand for uranium by the year 2000, or even earlier. Uranium recovery from low-grade ores has been considered. Chattanooga shale, found in southeastern U.S., and having a typical uranium concentration of about 60 ppm may be typical of such ores. A very approximate and cursory estimate of urnaium recovery from such ores suggests that the magnitude of the operation required to recover, for example, 150,000 tons U_3O_8/yr is so



Uranium Mining Capacity on January 1, 1974 was 8.2 Million MT Ore/Yr.
At 0.2% U_3O_8, this is equivalent to 16,400 MTU_3O_8/Yr.
This is equivalent to 90,000 MWe.

[1] Forty percent from natural gas use.

[2] Including airborne particulates.

Fig. 4. URANIUM MILLING MATERIAL BALANCE FLOWSHEET NORMALIZED TO ONE MODEL 1000 MWe LWR ANNUAL FUEL REQUIREMENT (182 MT U_3O_8) Assumes U Recycle only, no Pu recycle: 0.25% GDP Tails, 75% Plant Factor

Table 2

Concentrations of Radionuclides in Solid Wastes (Tailings) from Model Acid Leach - Solvent Extraction Mill

Radionuclide	Sand, > 200 mesh (p Ci/g) *	Slime, < 200 mesh (p Ci/g)
U natural	10	150
^{226}Ra	120	1610
^{230}Th	60	1750
^{234}Th	10	150
^{210}Pb	120	1610
^{210}Po	120	1610
^{210}Bi	120	1610

*pCi/g means picocuries per gram.

Table 3

Concentrations of Radionuclides in Solid Wastes (Tailings) from Model Alkaline Leach Mill

Radionuclide	Sand, > 200 mesh (p Ci/g)*	Slime, < 200 mesh (p Ci/g)
U natural	10	70
^{236}U	170	950
^{230}Th	170	960
^{234}Th	10	70
^{210}Pb	170	960
^{210}Po	170	960
^{210}Bi	170	960

*pCi/g means picocuries per gram.

huge the use of such shales can be seriously questioned. The production of 150,000 tons U_3O_8/yr would require 460 mills of 20,000 tons/day capacity, processing $9x10^6$ tons of shale/day. A total capital investment (in 1974 dollars) of $51 billion dollars would be required for plants based on leaching with sulfuric acid, and $84 billion dollars for plants based on using pressurized oxygen to convert the ore to a soluble form. Solvent extraction was assumed for uranium recovery from both types of ore treatment. Water requirements would be 700 million gallons/day if evaporator condensate were recycled, and 1.8 to 3 billion gallons/day if it were not recycled. The annual sulfuric acid requirement would be 180 million tons, about six times the current U.S. production rate.

Extraction of uranium (present at 0.15 parts per billion) from seawater has also been considered. In this case, certain highly selective inorganic sorbents might be placed in an area of the ocean where strong currents flow. Periodically these sorbents would be removed from the ocean, and the uranium leached from them. This approach to uranium recovery appears fraught with problems, and the uranium recovered thus promises to be expensive indeed.

E. Costs of Reducing Radiation Doses

"Base case" model mills representative of those which will process a major fraction of U.S. ore for the next 20 years have been studied. Each mill was assumed to process 2000 tons per day of ore containing 0.2% U_3O_8. Costs of added waste treatment operations to decrease radiological dose commitment in the surrounding area were calculated. Much of the technology assumed in the advanced treatment cases requires development and demonstration.

A total of 14.4 curies enters the mill daily. Of this, 2.1 curies is uranium, and is recovered as product. The remainder is discharged in the liquid and solid wastes (tailings) which are impounded near the mill.

Off-site releases during mill operation consist of airborne ore dust, concentrate (yellow cake) dust, tailings dust, and radon gas. After the mill is shut down the tailings are covered with earth which is overlain with rocks, or in some instances vegetation, to reduce wind and water erosion. However, radon gas will seep from the tailings pile for thousands of years, and may cause a radiation problem unless the pile is covered in such a way as to ratain the radon gas until it decays to its solid daughters. (The half-life of ^{222}Rn is about 3.8 days.)

Total costs for the case studies include capital costs, annual fixed charges and annual operating costs. Annual fixed charges are 24% of total capital investment.

Table 4 is a summary of the radwaste treatment variables. Figure 5 shows how much these treatment methods might add to the cost in relation to dose reduction achieved.

III. CONVERSION CF URNAIUM CONCENTRATE TO UF_6

Table 4. SUMMARY OF VARIABLES OF RADWASTE TREATMENT SYSTEMS FOR MODEL URANIUM MILLS*

Radwaste Case No.	1 (Current, Base Case)	2 (Limited Current Use)	3 (Near Future)	4 (Future)		5 (Advanced)	6 (Advanced)			7 (Advanced)
				a	b		a	b	c (Not applicable to alkaline leach mill)	
Airborne (mill processes only)										
Objective	Control process dust	Reduce ore dust release by 3 and yellow cake dust release by 4	Reduce ore dust release by 13 and yellow cake dust release by 10	Reduce ore dust release by 65 and yellow cake dust release by 20	Same as Case 4a	Reduce ore dust release by 65 and yellow cake dust release by 10^4	Reduce ore dust release by 10^5 and yellow cake dust release by 10^4	Same as Case 6a	Same as Case 6a	Reduce radon release from the mill by 10^2; ore dust release by 10^5, and yellow cake release by 10^4
Treatment										
Ore dusts	Orifice	Wet impingement	Low energy venturi	Reverse jet bag filter; windbreak around ore yard	Same as Case 4a	Same as Case 4a	Reverse jet bag filter; HEPA filter; windbreak around ore yard	Same as Case 6a	Same as Case 6a	Bag filter; HEPA filter; charcoal delay trap; windbreak around ore yard
Yellow cake dust	Wet impingement	Low energy venturi	Medium energy venturi	High energy venturi	Same as Case 4a	High energy venturi; HEPA filter	Same as Case 5	Same as Case 5	Same as Case 5	Same as Case 5
Liquid										
Objective	Zero liquid release to surface waters; 10% seepage from the tailings pond of radioisotopes dissolved in liquid effluents	Same as Case 1	Reduce seepage of radioisotopes by 5	Reduce seepage of radioisotopes by 100	Same as Case 4a	Same as Case 4a	Zero liquid release	Same as Case 6a	Reduce seepage of radioisotopes by 10^3; recycle acid and water	Same as Case 4a
Treatment	Natural evaporation from tailings pond; seepage to ground; 10-ft-high starter dam of native material; dam raised with tailings	Same as Case 1	Natural evaporation from pond; site selected for low seepage through bottom; earth dam with clay core	Acidic effluents; lime neutralize; alkaline effluents; copperas precipitation; natural evaporation from pond sealed on bottom and sides with 5/16-in. asphalt membrane	Same as Case 4a	Same as Case 4a	Metal evaporator	Same as Case 6a	Metal evaporator and rectifier column	Same as Case 4a
Solid										
Objective	Eliminate wind-blown tailings dust after mill closes and reduce surface water leaching of tailings	Eliminate wind-blown tailings dust while mill is active and increase probability that the long-term tailings cover will remain intact	Reduce radon emanation from tailings by 4; eliminate penetration of tailings by vegetation or surface runoff	On-site waste disposal which permits some surface use of land; reduce radon emanation by 40	Alternate method of reducing radon emanation by 40 without deep burial; decrease leach rate of solid by 10^{10}	Fix solids in a form less leachable by underground waters; reduce radon emanation by 1000	Fix solids in a form less leachable by underground waters, reduce radon emanation by 160	Same as Case 6a	Same as Case 6a	Reduce radon emanation by 50,000; lower leach rate of solids by 10^{10}
Treatment										
Basic	Tailings pile; 10-ft-high starter dam of native materials; dam raised with tailings	Same as Case 1	Tailings impoundment; dam of native materials and compacted clay core; diversion ditches and dikes to bypass surface runoff; site selected for low seepage through bottom	Tailings impoundment same as Case 3 except the bottom and sides are lined with a 5/16-in.thick asphalt membrane	Same as Case 4a	Slurry with cement and pump to landfill or mine lined with 5/6-in. asphalt for disposal as cemented product (1 part cement to 20 parts tailings)	Sand/slime separation; incorporate slimes and evaporator concentrates in cement (1 part cement to 20 parts tailings); cemented product to landfill or mine; washed sand to landfill or mine	Sand/slime separation; incorporate slimes and evaporator concentrates in asphalt; asphalt product to landfill or mine; washed sand to landfill or mine	Substitute nitric acid leach for conventional sulfuric acid leach; incorporate evaporator concentrates in asphalt; tailings to a Case 2 type impoundment	Same as Case 4a
Cover, mill active	None	All tailings either under pond water or covered temporarily with a chemical spray or mine waste	Same as Case 2	Same as Case 2	Same as Case 2	None	Cover with final cover as milling proceeds	Same as Case 6a	Cover with final cover as milling proceeds	Same as Case 2
Cover, final	Six-inch earth cover topped with rock or vegetation	Two-foot earth cover topped with rock or vegetation	Eight-foot earth cover topped with rock or vegetation	Twenty-foot earth cover topped with rock or vegetation	5/16-in. asphalt membrane and 2-ft earth cover topped with rock or vegetation	Same as Case 4a	Same as Case 4a	Same as Case 4a	Twenty-ft earth cover over evaporator concentrates incorporated in asphalt; 2-ft earth cover over tailings; both topped by rock or vegetation	1-in. asphalt membrane and 2-ft earth cover topped by rock or vegetation

*All cases apply to both sulfuric acid and alkaline leach mills except where indicated.

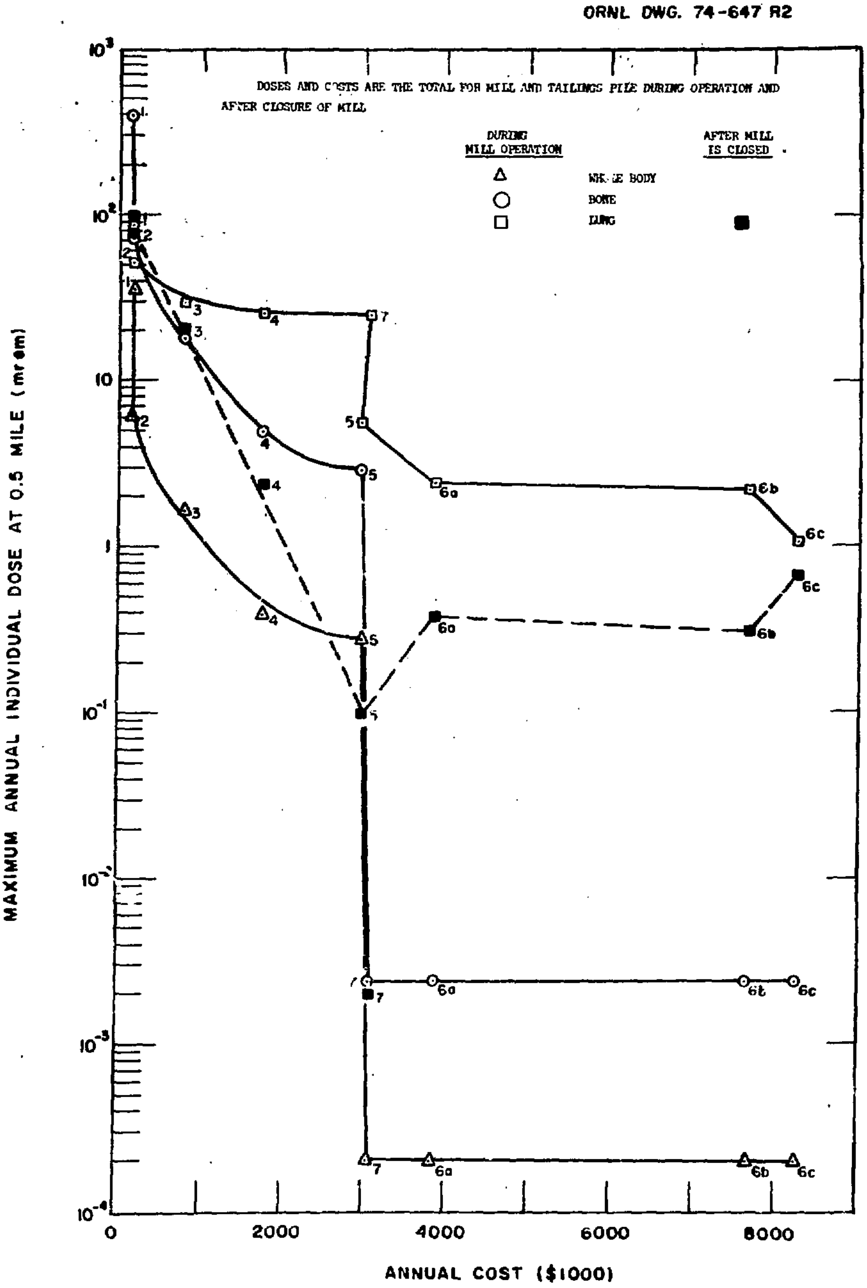


Fig. 5. Annual Cost for Dose Reduction from Acid-Leach SX Mill and Tailings Pile Airborne Effluents (Taken from Fig. 8.1 of ORNL TM-4903, Vol. 1

Uranium conversion is a highly developed part of the nuclear fuel cycle, although improvements are still being made, especially in conversion processes for use with the uranium product of the fuel reprocessing plant. The requirement for enriched uranium for most reactor fuels necessitates production of UF_6 for use in uranium enrichment plants. Enriched uranium may be prepared from U_3O_8 concentrate from the mills or from the uranyl nitrate product from fuel reprocessing plants. Since no commercial reprocessing plants are operating in the U.S., the present conversion operations use natural uranium U_3O_8 as their feed. Recycled uranium from the reprocessing plant would contain up to 0.9% ^{235}U as uranyl nitrate. About 270 tonnes of UF_6 are required to produce one GWe-yr* of electrical energy generated by LWRs. Table 5 shows what the composition of typical feed to a conversion plant might be. Table 6 gives the UF_6 product specifications.

A. Processes

The U_3O_8 concentrate from the mill is 75 to 85% U_3O_8. Conversion of U_3O_8 to UF_6 is carried out by two different processes, a dry process and a wet process, at approximately equal annual production rates. The "dry hydrofluor" process treats the concentrates directly in a series of fluidized bed reactors followed by fractional distillation which eliminates impurities either as volatile compounds or as ash. The "wet solvent extraction" process purifies the U_3O_8 feed by preferentially extracting the uranium into organic solvent before conversion to UF_6. These process differences result in substantially different radioactive effluents from the conversion plants. In the hydrofluor process the bulk of the impurities entering with the yellow cake leaves as solids from the fluorination tower. In the wet solvent extraction process the bulk of the impurities leaves as dissolved solids in the raffinate.

Table 7 is a summary of uranium refining and hexafluoride production facilities, along with references to pertinent reports.

When the feed to the conversion plant is taken to be uranyl nitrate from a fuel reprocessing plant there are several important differences from the case where it is U_3O_8 from a mill. First, the uranium is already relatively pure, and second, there are traces of transuranium and fission product elements present which were produced during irradiation in the reactor, and were incompletely removed during fuel reprocessing. It is also worth noting that there is a different ratio of uranium isotopes from those found in nature. Not only is the percent of ^{235}U variable, but so is the percent of other isotopes, e.g. ^{236}U.

1. Dry process

The dry hydrofluor process is shown schematically in Fig. 6. Schematic equipment diagrams of typical units are shown for the reduction, hydrofluorination, and fluorination steps in Figs. 7, 8, and 9, respectively.

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*GWe-yr means gagawatt-years of electrical energy.

Table 5

Typical Yellow Cake Feed to a UF_6 Conversion Plant

Constituent of feed	Concentration (wt %)	Quantity fed (metric tons/year)
Uranium (U)	73.53	10,000
	(wt %, U basis)	
Impurities		
Ammonium (NH_4^+)	3.09	420
Sodium (Na)	2.41	329
Silica (SiO_2)	1.2	163
Sulfate (SO_4^{2-})	2.94	400
Arsenic (As)	0.06	8
Boron (B)	0.003	0.4
Calcium (Ca)	0.19	26
Carbonate (CO_3^{2-})	0.31	42
Chloride, bromide, iodide (Cl^-, Br^-, I^-) calc. as Cl^-	0.07	10
Fluoride (F^-)	0.01	1
Iron (Fe)	0.38	52
Molybdenum (Mo)	0.10	14
Phosphate (PO_4^{3-})	0.26	35
Potassium (K)	0.13	18
Vanadium (V)	0.12	16
Water (H_2O)	1.91	260
Extractable organics	0.05	7
Nitric acid-insoluble uranium	0.01	1
Principal radionuclides		(Ci/year)
U_{nat}[a]		3333
^{234}Th		3333
^{234m}Pa[b]		3333
^{230}Th		141.7
^{226}Ra		15.67
^{222}Rn		15.67

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[a] One curie of natural uranium (U_{nat}) is defined in 10 CFR 20 as the sum of 3.7×10^{10} dis/sec from ^{238}U, 3.7×10^{10} dis/sec from ^{234}U, and 9×10^{8} dis/sec from ^{235}U; i.e., 1 Ci of U_{nat} consists of 1 Ci of ^{238}U, 1 Ci of ^{234}U, and 2.43×10^{-2} Ci of ^{235}U; it is also equivalent to 3000 kg of natural uranium.

[b] Metastable ^{234}Pa, $t_{1/2} = 1.18$ min.

Table 6

SPECIFICATIONS FOR UF_6 DELIVERED TO DIFFUSION PLANTS

Value[1]	Numerical Value
Maximum vapor pressure of filled container at 200°F in pounds per square inch, absolute	75
Minimum weight percent of UF_6 in material	99.5
Maximum mol percent of hydrocarbons, chlorocarbons, and partially substituted halohydrocarbons	0.01
Maximum number of parts of elements indicated per million parts of	
Total uranium: Antimony	1
Bromine	5
Chlorine	100
Niobium	1
Phosphorus	50
Ruthenium	1
Silicon	100
Tantalum	1
Titanium	1
Total number of parts of elements forming nonvolatile fluorides (having a vapor pressure of one atmosphere or less at 300°C) per million parts of total uranium, e.g., aluminum, barium, bismuth, cadmium, calcium, chromium, copper, iron, lead, lithium, magnesium, manganese, nickel, potassium, silver, sodium, strontium, thorium, tin, zinc, and zirconium	300
Maximum number of parts of elements or isotopes indicated per million	
parts of Uranium: Chromium	1,500
Molybdenum	200
Tungsten	200
Vanadium	200
Uranium-233	500
Uranium-232	0.110
Maximum thermal neutron absorption of total impurity elements as equivalent parts of boron per million parts of total uranium	8
Maximum total of gamma activity due to fission products and U-237 as percent of gamma activity of aged natural U and as measured in a high-pressure ionization chamber (Drawing D-AWM-8798 of Nuclear Division, Union Carbide Corporation	20
Maximum beta activity due to fission products as percent of beta activity of aged natural Uranium	10
Maximum alpha activity from all transuranic elements in disintegrations per minute per gram of total uranium	1,500

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[1] All specification analyses on UF_6 shall be performed on samples removed in the liquid state from each cylinder while its contents are liquid and homogeneous.

Table 7. Uranium Refining and Hexafluoride Production

Plant	Location	Sampling	"Dry" purification – fractional distillation	"Wet" purification									UO_3 reduction to UO_2		UO_2 hydrofluorination to UF_4			Fluorination to UF_6		Enriched UF_6 from enriched scrap or recycle	UF_4 reduction to U metal		Hydrolysis of enriched UF_6 to UO_2	Conversion of enriched UO_2 to U metal
				Digestion	Solvent Extraction			Denitration				ADU (ammonium diuranate ppt and calcination)												
					TBP-hexane	TBP-kerosene	TBP-dodecane	Stirred pot (batch)	Stirred trough (continuous)	Fluidized bed	Rotary tube calciner		Fluidized bed	Moving bed	Fluidized bed	Moving bed	Stirred bed (ribbon screw)	Flame tower	Fluidized bed		Magnesium	Calcium		
Allied Chemical	Metropolis, Ill.	a	a										a		a				a					
Kerr McGee	Sequoyah County, Okla.	b		b	b				b				b		b			b						
ERDA-Fernald	Cincinnati, Ohio	c		c		c		d					d				d				d			
ERDA-Paducah	Kentucky	e											f		g			f						
ERDA-Portsmouth (20 metric ton/year)	Ohio	h									h							h		h				
AEC-Weldon Springs (closed)	Missouri	e		i	i			i					i				i				i			
Eldorado	Canada	e		j		j		k				j		j		j		j			j		j	j
Malvesi	France	l		l				l				l		m		m						l		
Springfields	Great Britain	n		n		n				o		p	o		o				k		p		p	p

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[p] R. C. Alexander, L. P. Shortis, and C. J. Turner, Trans. Inst. Chem. Engrs. 38(4), 177–83 (1960).

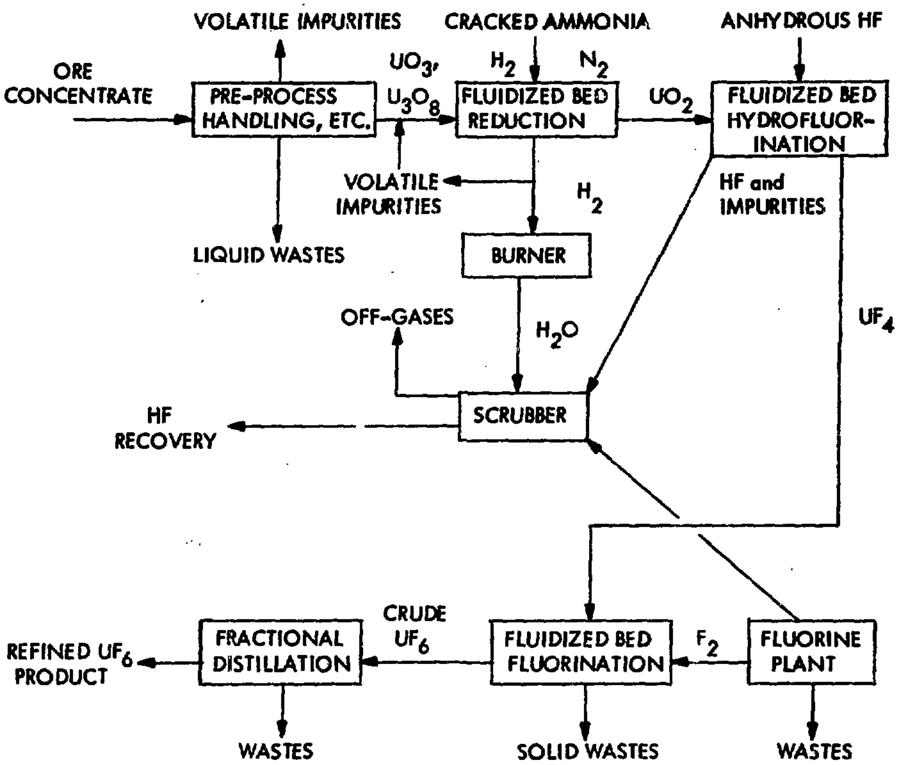

Figure 6. UF_6 Production from U_3O_8 by the "Dry Hydrofluor" Process.

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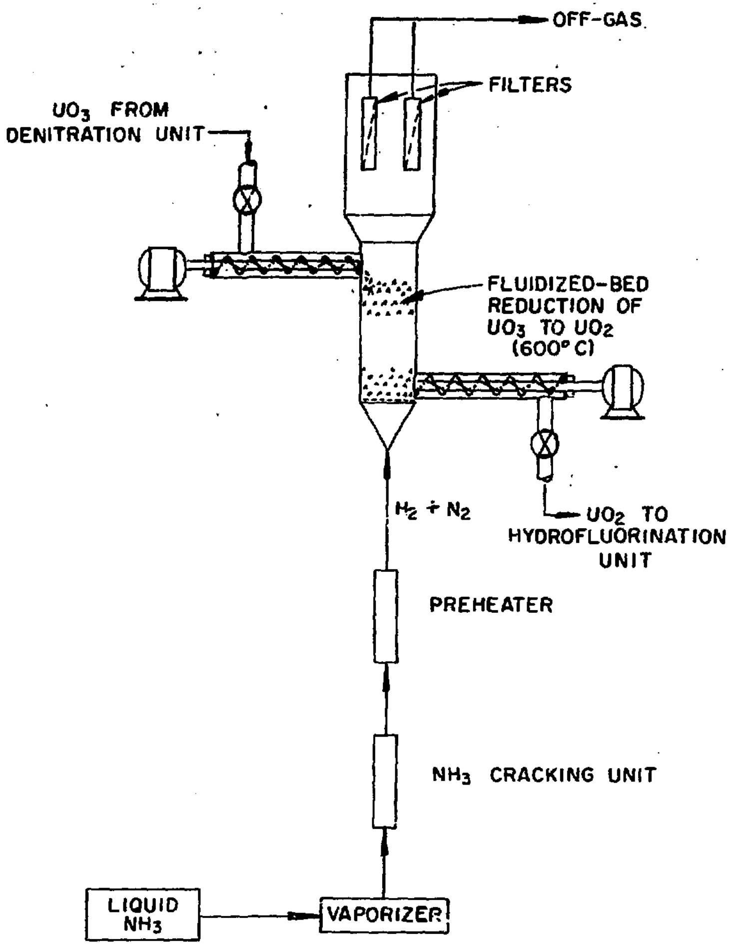

Fig. 7 Schematic of a Typical Fluidized-Bed Reduction Unit.

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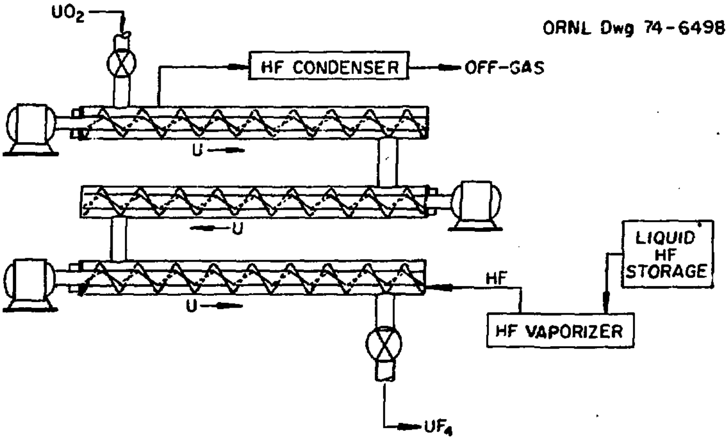
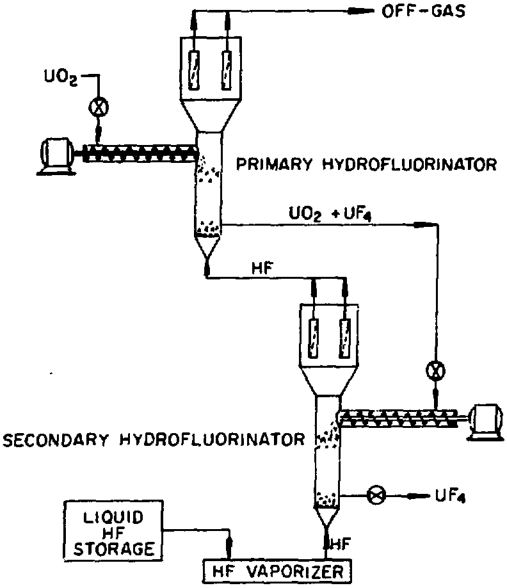


Stirred-Bed Hydrofluorination System.



Fluidized-Bed Hydrofluorination System.

Fig. 8 Schematic Diagrams of a Stirred-Bed Hydrofluorination System and a Fluidized-Bed Hydrofluorination System.

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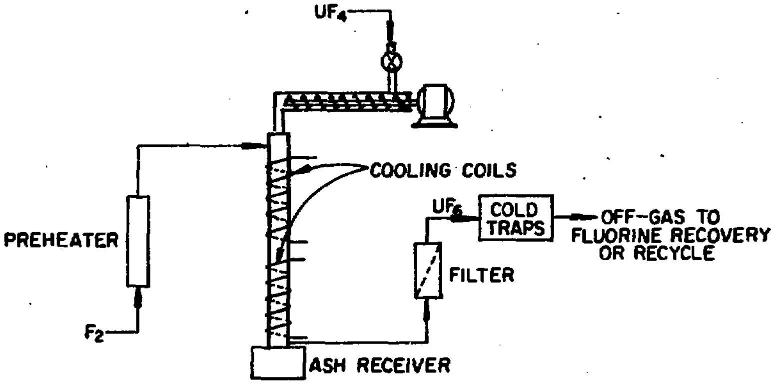
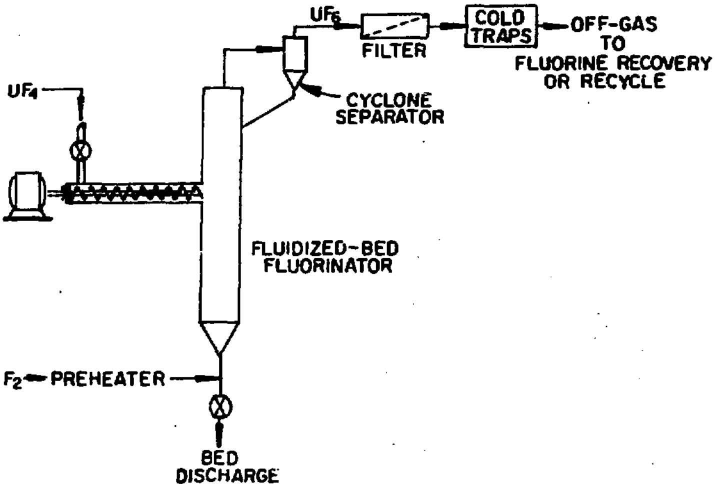


Fluorine Tower Reactor



Fluidized-Bed Fluorinator

Fig. 9 Schematic Diagram of a Fluorination Tower and a Fluidized-Bed for Production of UF_6 from UF_4.

Uranium trioxide is reduced to UO_2 by H_2 at a temperature of 538° to 621° according to the reaction

$$UO_{3(s)} + H_{2(g)} \rightarrow UO_{2(s)} + H_2O_{(g)} .$$

Hydrogen is supplied at 100% excess by cracking ammonia at 870°, viz.,

$$2NH_3 \rightarrow N_2 + 3H_2 .$$

Although the reduction reaction is exothermic, a net heat input is required to heat the feed from ambient temperature to operating temperature and to compensate for heat losses. Careful temperature control is essential to prevent sintering of the particle surfaces. Unreduced oxide hydrofluorinates to UO_2F_2, which in turn consumes more elemental F_2 in conversion to UF_6 than does UF_4, evolves more heat during fluorination, and does not fluorinate as well resulting in more ash recycle.

All U.S. plants use fluidized-bed reduction units. Nitrogen is sometimes added to the cracked ammonia to maintain the fluidizing velocity of the bed. Both single-stage and two-stage reduction are used. The product is a highly reactive uranium dioxide which can be fluorinated with only a 5 to 10% excess of hydrogen fluoride. Sulfate serves as a chemical promoter which increases the productivity of both the reduction and subsequent hydrofluorination steps.

Uranium dioxide is hydrofluorinated to UF_4 by reaction with HF at 348 to 539° according to the reaction

$$UO_{2(s)} + 4\ HF_{(g)} \rightleftarrows UF_{4(s)} + 2H_2O_{(g)} .$$

The fluid bed reactor has about 2-1/2 times the processing capacity of the screw reactor at the same conversion efficiency, and is the preferred technique in the United States. Conversion efficiency in the fluid beds may range from 98.0 to 98.5%. Overall uranium yield for the hydrofluorination step is 99.99%.

Sodium forms a relatively low-melting compound with uranium tetrafluoride (7 $NaF \cdot 6\ UF_4$, melting point approximately 675°C vs 960°C for UF_4) which restricts the diffusion of HF to unconverted UO_2, and if present in high enough concentrations forms a plastic mass which plugs the bed. For this reason, high sodium feeds must first be washed with ammonium sulfate to remove the sodium.

The fluorination reaction is highly exothermic:

$$UF_{4(s)} + F_{2(g)} \rightarrow UF_{6(g)} .$$

The fluorine utilization is 80 to 90%. The operating temperature is 800 to 1000°F. Heat removal is the limiting factor in the design. Heat generation can exceed the rate of heat transfer across the bed. Therefore, CaF_2 is used as the bed material with only a small amount of UF_4. Uranium hexafluoride, VF_5, VOF_3, and MoF_6 are volatilized. The fluorides of radioactive and other chemical impurities in the UF_4 feed are nonvolatile and remain with the bed material.

After fluorination, the UF_6 contains some impurities which are separated by fractional distillation. Crude UF_6 is melted and transferred from the cold traps to the distillation feed tanks where it is maintained in a molten state. Uranium hexafluoride is vaporized into a monel bubble cap column which separates UF_6 (sublimation point 56°C, triple point 64°C) from the more volatile UF_5 (boiling point 48°C), MoF_6(boiling point 35°C), and traces of SiF_4, CF_4, SF_6, etc. Vanadium oxyfluoride (VOF_3, sublimation point 110°C) has only limited solubility in UF_6(0.7 wt % at operating conditions). When present at high concentrations, VOF_3 is the limiting material in the separation of low-boiling impurities. Liquid uranium hexafluoride containing high-boiling impurities passes to a column where high-purity UF_6 is volatilized and collected in a second set of UF_6 cold traps similar to the first. The pure UF_6 product is finally melted and drained into a 10-ton shipping cylinder. Still bottoms consist principally of an unidentified molybdenum compound, probably an oxyfluoride, with a little UF_6, VOF_3, and traces of particulates which pass the filters. Still tops and bottoms are stored, as the values contained do not presently justify recovery. Vapor phase transfers are made by pressure difference because there is no dependable UF_6 pump.

A portion of the fluid-bed material, called ash, is withdrawn to avoid the buildup of nonvolatile impurities such as sodium which form low melting complexes with UF_6 and may cause caking in the bed, and to avoid the buildup of nonvolatile radioactive daughter products of uranium in the bed. The fluorination ash, including filter fines, is drummed, stored a minimum of six months to permit decay of ^{234}Th and ^{234} Pa, and leached with sodium carbonate to recover uranium. Essentially all the radioactive impurities in the crude uranium feed to the plant are converted to dry, solid waste.

Filters are used to remove uranium particulates from the various off-gas streams. All UF_6 plants use bag filters to recover uranium dusts from materials handling operations. Efficiencies are close to 100% for particles down to 1 micron in size. Sintered stainless steel filters are used on the reduction off-gas, and either monel or nickel sintered metal filters on the fluorination off-gas to cover uranium. A nominal 10 micron pore size filter will remove 98% of the 0.7 micron particles. Porous carbon filters are used on the hydrofluorination step off-gas. Such filters are very efficient, recovering >99.999% of the uranium dust. High Efficiency Particulate Air (HEPA) filters are used as backup filters in the UF_6 conversion processes, just as they are used in similar applications throughout the nuclear fuel cycle.

2. Wet Process

The wet process (sometimes called the solvent extraction process) is shown schematically in Fig. 10. It may operate either on the mill concentrate, or on the uranium recycled from a reprocessing plant. There is essentially no difference, and because there is at present no commercial reprocessing plant, there is no recycled uranium to convert to UF_6. When there is, it will have an abnormal mixture of uranium isotopes, and may contain traces of lanthanide and actinides not present in mill concentrate.

The wet process steps after denitration are the same as those used in the dry process, so the basic difference between the wet and dry processes is that solvent extraction is used in the wet process to remove the impurities from the mill concentrate, rather than the fractional distillation of UF_6 and selective sorption of impurities on traps used in the dry process.

In the solvent extraction step, a solution of uranyl nitrate is passed countercurrent to a solution of tributyl phosphate (TBP) in an organic diluent such as hexane. The uranium extracts highly selectively into the TBP-hexane solution, leaving virtually all of the impurities behind in an aqueous waste stream called the raffinate. A wide variety of contactors may be used to contact the uranium and TBP solutions. Both columns and mixer-settler arrangements are used.

B. Radioactivity Released

The amount of radioactivity released in gaseous, liquid, and solids wastes is relatively small from conversion plants, and except for the wastes expected from conversion of recycled (reprocessed) uranium, consists solely of uranium and its natural radioactive impurities.

1. Dry process

Table 8 gives the discharges from a model dry hydrofluor process plant. The basis for the values in the table is given at the bottom of the table.

2. Wet process

Information similar to that given above for the dry process is given in Table 9 for a model wet process using mill concentrate as feed. Table 10 gives the same type information for a wet process plant using feed from a fuel reprocessing plant. Note especially the presence of small amounts of plutonium and of certain fission products in the radioactivity released by the model plant.

C. Costs of Reducing Radiation Doses

Costs of reducing radiation doses are not presently available, although it is expected that they will be available in the near future.

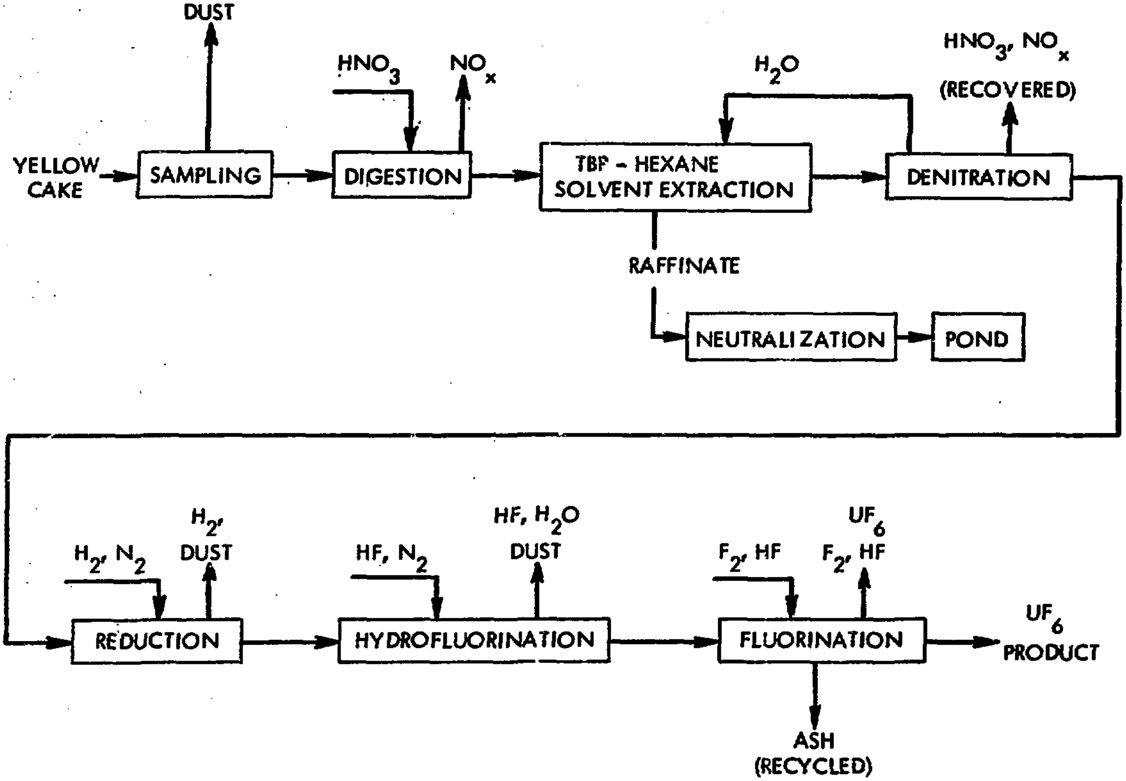


Fig. 10. Wet Process for Conversion of Yellow Cake to UF_6

Table 8

DISCHARGES FROM A MODEL DRY HYDROFLUOR PROCESS CONVERSION PLANT

[Each facility supports fourteen 1 GW_e power plants (2500 MT of Y/yr).]

Radionuclide	Pathway	Possible Chemical States	Source Term (Ci/yr)
Gaseous and Liquid Wastes			
Uranium	Air	U_3O_8, UO_2	0.04 (insoluble)
		UF_6, UO_2F_2	0.02 (soluble)
Uranium	Water	UO_2^{2+}	0.8 (soluble)
^{226}Radium	Water	Ra^{2+}	
^{230}Thorium	Water	Th^{4+}	
Solid Wastes			
Uranium-234, -235, and -238			1.7
Short-lived daughter products in equilibrium with natural uranium			1.7
Decayed separated daughter products			.25
Thorium-230			18.0
Radium-226			1.8

Basis: 0.1% Uranium loss
0.2% of radium in ore enters process with yellowcake
2.0% of Th-230 in ore enters process with yellowcake
Solids cooled one year before burial.

Table 9

DISCHARGES FROM A MODEL WET SOLVENT EXTRACTION PROCESS CONVERSION PLANT

Radionuclide	Pathway	Possible Chemical States	Source Term (Ci/yr)
Uranium	Air	U_3O_8,UO_2	0.02 (insoluble)
		UF_6, UO_2F_2	0.008 (soluble)
Uranium	Water	UO_2	2.0 (soluble)
^{226}Radium	Water	Ra^{2+}	0.006 (soluble)
^{230}Thorium	Water	Th^{4+}	0.006 (soluble)
Uranium	Ground (solid wastes)	U_3O_8, UO_2	

Table 10

ESTIMATED RADIOACTIVE EFFLUENTS FROM A REPROCESSED URANIUM UF_6 CONVERSION PLANT (1500 MT U/YR)

	Average Annual Releases (Total Ci/Yr)	
	Main Building Stack	Wall & Roof Vents
Uranium-232	2.3×10^{-4}	2.6×10^{-3}
-233	6.8×10^{-7}	7.6×10^{-6}
-234	6.1×10^{-4}	6.8×10^{-3}
-235	6.8×10^{-5}	7.6×10^{-4}
-236	1.0×10^{-2}	1.1×10^{-1}
-237	3.6×10^{-3}	4.0×10^{-2}
-238	1.2×10^{-2}	1.4×10^{-1}
U-Total	2.7×10^{-2}	3.0×10^{-1}
Plutonium -238	2.9×10^{-4}	1.8×10^{-3}
-239	2.0×10^{-5}	1.3×10^{-4}
-240	3.8×10^{-5}	2.4×10^{-4}
-241	1.1×10^{-2}	7.2×10^{-2}
-242	2.0×10^{-7}	1.3×10^{-6}
Pu-Total	1.1×10^{-2}	7.4×10^{-2}
Ruthenium-106	8.7×10^{-3}	4.2×10^{-2}
Zirconium-95	8.7×10^{-3}	4.2×10^{-2}
Niobium-95	1.7×10^{-2}	8.4×10^{-2}
Uranium	3.8×10^{4}(a)	4.2×10^{5} (a)

(a) Values in grams total uranium; all other values expressed in curies (time period - operating year).

IV. URANIUM ISOTOPE SEPARATION

Uranium isotope separation is a key step in the light water reactor fuel cycle, and is also a dominant cost in that cycle. Uranium as it occurs naturally is a mixture of the isotopes ^{235}U, ^{238}U and ^{234}U. Of these, only ^{235}U is of practical use as a direct source of fission energy. Unfortunately, ^{235}U exists only to the extent of 0.711 percent in the natural isotopic mixture. In order for natural uranium to be used in fission it must either be used in reactors which are so economical in their use of neutrons that criticality can be maintained at that low ^{235}U concentration, or it must be concentrated to greater than its natural percentage. It is entirely possible to build and operate reactors which can use natural uranium: the first nuclear reactors were of that type. However, to be successful, they must not contain materials which parasitically absorb the neutrons formed by fission of the sparse ^{235}U atoms. These neutrons must be available to produce additional fission reactions. Highly purified graphite is one material which may be used in such reactors; heavy water is another. These materials slow down the neutrons from the fission reaction to speeds where they can sustain fission in natural uranium, while at the same time do not themselves absorb an excessive fraction of the neutrons. Light water is not suitable because of excessive absorption of neutrons in the light isotope of hydrogen. Power reactors in the U.S. do use light (ordinary) water, so cannot use natural uranium. Typically, the uranium is enriched to 3 to 4% ^{235}U for use in these light water reactors (LWRs). Thus, it was necessary to provide economical methods for concentrating ^{235}U to provide uranium fuel suitable for use in light water reactors. These concentration methods were first developed for use in atomic weapons production, and are called isotope separation methods.

A wide variety of methods for isotope separation were studied during the period of the second world war. Of these, electromagnetic separation (in Calutrons) and gaseous diffusion were chosen for large scale use. Today the only uranium isotope separation method in wide use is gaseous diffusion. There is, however, a widespread interest in the use of the gas centrifuge, and it promises to assume a prominent role world wide. Both gaseous diffusion and gas centrifuge processes use uranium in the form of UF_6, a gaseous compound at temperatures above about 57°C and pressures below one atmosphere. Both capitalize on the small mass difference between the $^{235}UF_6$ and $^{238}UF_6$ molecules. Gaseous diffusion separation relies on the greater rate of effusion of the $^{235}UF_6$ molecules through a porous barrier; gas centrifuge separation relies on the greater centrifugal force exerted on the $^{238}UF_6$ molecules in a rotating system.

The renewed interest in the U.S. in the gas centrifuge process is due to the development of a new gas centrifuge, the Zippe centrifuge, and to the development of materials capable of operating at much higher peripheral speeds. Also, the increasing cost of electrical power favors the gas centrifuge process over gaseous diffusion because the centrifuge process uses only about one-tenth the power the gaseous diffusion process uses to effect a comparable separation. Finally, because the gas centrifuge process employs many parallel process streams, each operating independently to attain the desired enrichment, it achieves economic plant size at a much lower capacity than does the gaseous diffusion process. Concomitant with the smaller economic plant size is a smaller uranium inventory.

With all the above advantages for the gas centrifuge process it might well be asked what the reasons are for continuing interest in gaseous diffusion. Basically, the gaseous diffusion plant has a significantly smaller operating staff, and an anticipated much smaller maintenance problem. Beyond these factors, there is a press of time. New enrichment capacity will likely be needed in the early 1980's. There must exist sufficient component manufacturing capability to meet such a need, and this dictates use of gaseous diffusion. Also, there must exist demonstrated plant reliability, because the plant must run once it is built. Again, this favors gaseous diffusion. While gas centrifugation clearly has a place in the future of the nuclear fuel cycle, so does gaseous diffusion.

A. Separation Processes

1. Gaseous diffusion

The gaseous diffusion process itself is basically a physical separation process. (Preparation of the UF_6 gas used in the process may be done at the gaseous diffusion plant or elsewhere, and is not a part of the actual isotope separation process.) The process is carried out by allowing about half of the UF_6 to effuse through a porous barrier, at which point it is collected separately from that part of the UF_6 which did not pass through. Because the $^{235}UF_6$ effuses slightly more rapidly than the $^{238}UF_6$, a small increase in concentration of the effused UF_6 gas in the isotope ^{235}U occurs. If this "enriched" UF_6 gas is then partially effused sequentially through additional barriers, further ^{235}U enrichment occurs in the effused portion. Thus, be setting up a series of chambers containing barriers through which an ever decreasing part of the UF_6 is successively passed, greater and greater enrichment in the isotope ^{235}U may be achieved. The part of the UF_6 which has not effused through the barrier is enriched in the ^{238}U isotope. It is passed through the series of chambers, or stages, in a direction opposite to the flow of the ^{235}U-enriched stream, i.e., countercurrent to it. A collection of such stages is called a cascade. The process just discussed is a little difficult to describe clearly in words. Figure 11 may help to make it clearer. The UF_6 is introduced as "cascade feed;" UF_6 enriched in ^{235}U is the "product" and that enriched in ^{238}U is the "tails". (The tails is a potential source of "depleted" uranium for use in making the blankets for LMFBRs).

Sixteen process stages may be grouped into a "cell" for convenience of maintenance and repair. A cell is the smallest process unit that can be isolated from the operating cascade. Generally, 1200 to 1300 stages are needed to enrich natural uranium cascade feed to about 3% ^{235}U in the product with a tails assay of about 0.3% ^{235}U. The quantities which determine the separative capacity of a stage are the stage separation

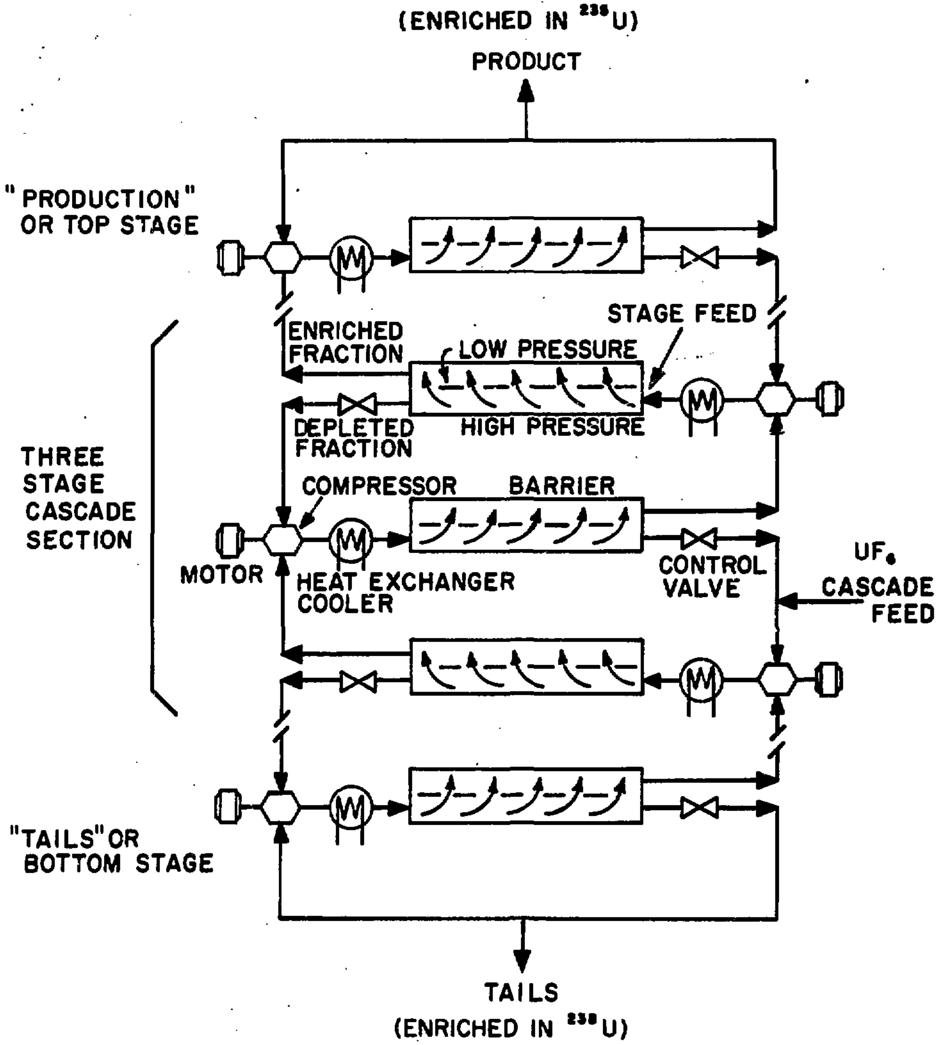


Fig. 11 Cascade of gaseous diffusion stages

factor and the rate of flow of UF_6 through the barrier. The stage separation factor is defined as the ratio of the mole ratios of the ^{235}U to ^{238}U concentrations in the enriched stream of the stage to that in the depleted stream of the stage. The formula for separative capacity is

$$U = k\ L\ (\alpha-1)^2 ,$$

where L is the flow rate through the barrier, α is the stage separation factor, and k is a constant for the system. The fact that capacity is directly related to flow rate through the barrier is the basis for a major upgrading of the existing U.S. gaseous diffusion plants. New compressors and motors to allow higher pumping pressures, and so higher pressures across and flow rates through the barriers, are being supplied to the plants. The fact that separative capacity is proportional to the square of $(\alpha-1)$ explains why so many stages are needed. The value of α is 1.0043, so $(\alpha-1)^2$ is about 0.000018, a very small number indeed.

The most important pieces of equipment in the cascade are the diffusion barrier and the UF_6 gas compressors. The barrier must have uniformly-sized porosity of a size commensurate with the mean free path of the UF_6 gas molecules to be most efficient. Since there are many thousands of square feet of barrier surface in a plant, manufacture of the barrier is a most important operation. Manufacturing details are also among the most closely guarded secrets in the nuclear industry. Both barriers and gas compressors has been subjected to continuing, intensive efforts to improve their performance. The motor-driven compressors are the only pieces of equipment with moving parts in the cascade. They consume over 90% of the power used in the plant. All process equipment pieces except the compressor motors are inside insulated metal panel enclosures to keep the UF_6 gas warm enough to prevent its desublimation. Each stage compressor adds heat to the UF_6 during compression, so a cooling system is required to keep the gas at the required temperature. The heat is removed by evaporating a halogenated hydrocarbon ($CCIF_2$-$CCIF_2$), which in turn is cooled and condensed at the cell by water-cooled condensers. It is the water from these condensers which is cooled by partial evaporation in cooling towers that creates the plumes of water vapor so characteristic of gaseous diffusion plants.

Impurities in the product UF_6, e.g., nitrogen, oxygen and $CCIF_2CCIF_2$, are removed in a "purge cascade" at the product end of the plant.

The diffusion cascade is basically a very stable and easily controlled process. The equipment has demonstrated a very low failure rate, but the high value of the enriched UF_6 product necessitates a maximum on-stream time for compressors, motors and electrical transformers and distribution systems. The electrical power requirements for a full-scale plant (~9 million separative work units* per year) is about 2400 megawatts. The cost of power is about 33% of the average separative work unit (SWU) cost.

2. Gas centrifugation

Gas centrifugation, like gaseous diffusion, is a physical separation process. The process is carried out by spinning (centrifuging) a cylinder of UF_6 gas about its axis, thereby, causing $^{238}UF_6$ molecules to preferentially concentrate near the periphery of the cylinder, and $^{235}UF_6$ molecules to preferentially concentrate near the axis. As with the gaseous diffusion process, the ^{235}U- and ^{238}U-containing streams are passed countercurrent to each other through centrifuges arranged in series. Figure 12 shows a single centrifuge diagrammatically.

The major component of a gas centrifuge is its rotor, which must be spun at very high speeds to achieve isotopic separation. The tendency for the different isotopes in the UF_6 molecules to separate based on their different masses under the influence of the centrifugal force field is opposed by their thermal agitation and the concentration gradient, which tend to homogenize the gas. The resultant dynamic equilibrium determines the degree of separation possible in a given centrifuge. The theoretical separative capacity of a gas centrifuge is given by

$$U = KZ \quad \frac{\Delta M \; V^2}{RT}^{\;2} \quad ,$$

where Z is the rotor length, ΔM is the mass difference of the gaseous molecules, V is the peripheral speed of the centrifuge, R is the universal gas constant, T is absolute temperature, and K is a constant for the system.

An ideal, or simple process separation factor may be derived for a gas centrifuge to be

$$\alpha = \exp \quad \frac{\Delta M \; V^2}{2RT}$$

It is the ideal separation factor obtained at steady state between UF_6 gas at the axis of the rotor and at the periphery when a batch of gas at absolute temperature T is rotated at peripheral velocity $V[=(a\omega)$, where a is the rotor radius and ω is the uniform angular velocity in radians per second]. This simple expression gives the maximum separation factor obtainable.

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*The amount of work required to concentrate, or separate, the ^{235}U is called separative work. It is measured in "separative work units", and the number required to produce enriched uranium of a specified enrichment is related to the enrichment sought, the ^{235}U concentration of the feed, and the tails assay.

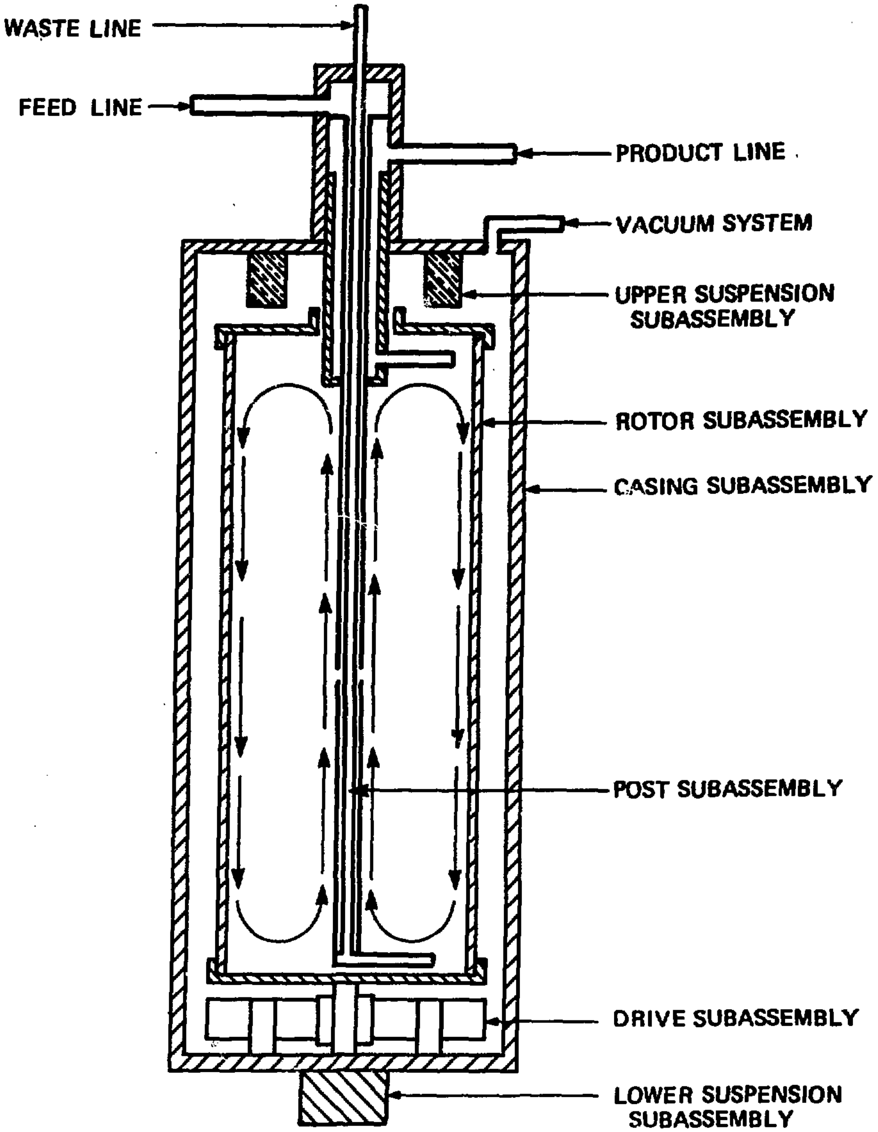

Fig. 12. SCHEMATIC OF GAS CENTRIFUGE

The expression does not take into account the axial flows which occur, or the effects of gas turbulence, both of which reduce the separation. Axial flow, as shown by the arrows in Fig. 12, results in a stream concentrated in $^{235}UF_6$ flowing up the rotor core and a stream concentrated in $^{238}UF_6$ flowing down the periphery of the rotor. Thus, an axial isotope concentration gradient as well as a radial concentration gradient is established. It too is limited by opposing diffusion effects.

These two equations express the important facts that the separative capacity and the separation factor are functions of the difference of the masses of the molecules being separated, and that the separation factor varies exponentially with the square of the velocity of the periphery of the rotor. Thus, high speeds of rotation are extremely important. The number of centrifuges in a stage (with the centrifuges operating in parallel) determines the capacity of the cascade, whereas the number of stages in the cascade determines the degree of enrichment obtained. Figure 13 shows the relationship of centrifuge, to group of centrifuges, to stage, to cascade.

Each gas centrifuge will require a small amount of cooling water to remove heat from the drive motor and the lower suspension, though nothing approaching the heat removal required by gaseous diffusion is required. (As mentioned earlier, the power input to the gaseous diffusion plant is nearly ten times that to the gas centrifuge plant of the same separative work capacity.)

3. Other methods

Because the isotope separation step is a major cost factor in the LWR fuel cycle, much attention has been paid to finding new, less expensive processes for isotope separation. Two of these are mentioned here.

laser

The separation of isotopes on a practical, commercial scale by the use of lasers is far from being demonstrated. In principle, the ^{235}U is selectively excited by a carefully controlled monochromatic laser beam. The ^{235}U may be either as highly-cooled atomic vapor or as gaseous molecules (UF_6). In the case of cooled atomic vapor, after the ^{235}U atoms are excited, they must be ionized selectively; in the case of gas molecules, the excited molecule, presumably $^{235}UF_6$, must undergo chemical reaction, e.g., disproportionation. The potential advantage to the use of a laser method for isotope separation is that, in principle, complete separation of ^{235}U from ^{238}U is possible in a single "stage", or step. Thus, even though laser separation is certain to be difficult and each unit or step will be expensive, a great deal of money can be spent before the cost approaches that of, for example, a gaseous diffusion plant, where the separation factor per stage is only about 1.004, and thousands of stages are required to achieve only 3% enrichment.

nozzle

Uranium isotope separation has been demonstrated using

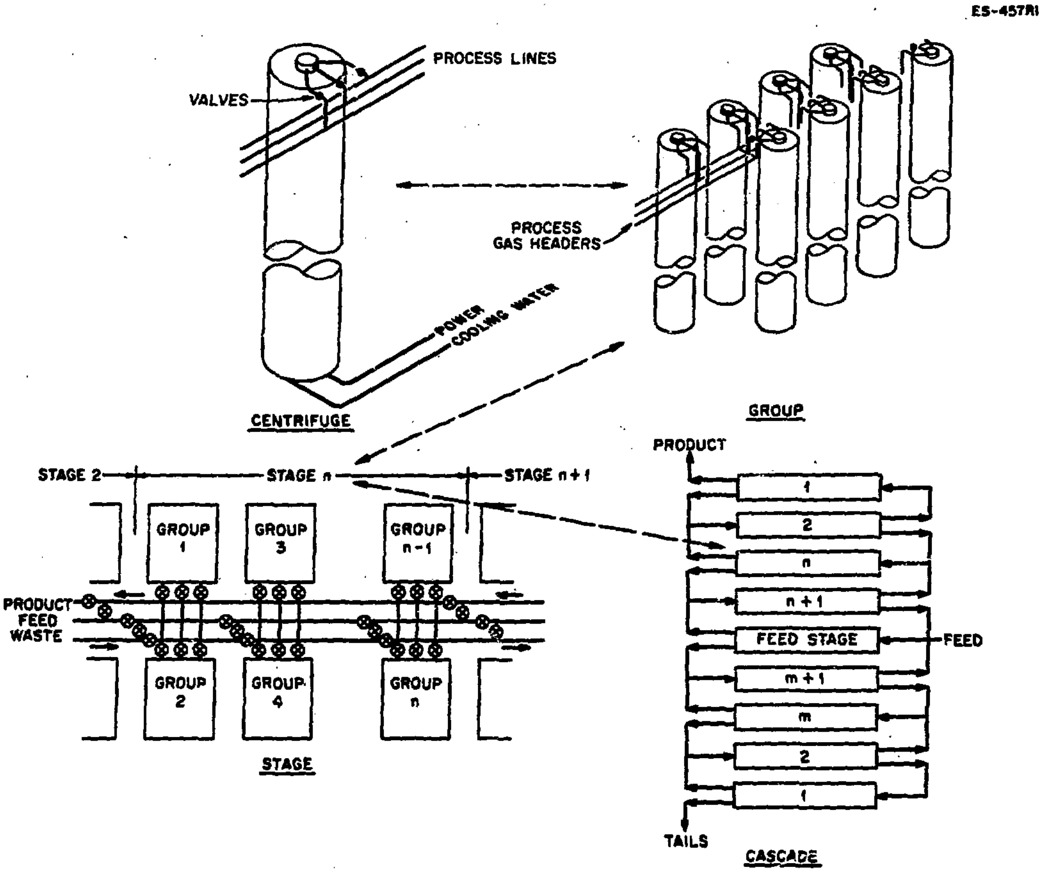

Fig. 13. CONCEPT OF A GAS CENTRIFUGE PLANT CASCADE

nozzles, or jets. Uranium hexafluoride is forced at high speed across a curved surface such that the heavier $^{238}UF_6$ molecules follow a different trajectory from that followed by $^{235}UF_6$ molecules. By interposing a sharp edge in the emerging stream of gas, the lighter molecules can be preferentially directed to one collector, while the heavier molecules go to another. This process has been operated on thousands of kilograms of uranium, and is a sort of "dark horse" in the uranium isotope separation sweepstakes. At present it appears to be more costly than gaseous diffusion. Its advantages are similar to those of the gas centrifuge, i.e., it takes less investment to build a plant.

B. Radioactivity Released

The radioactivity releases from enrichment plants are expected to be very small. Part of the reason for this is that the UF_6 feed and the enriched uranium product are both very valuable, the latter much more than the former. By the time uranium has been mined, milled, converted to UF_6 and transported, a relatively great deal of money has been invested in it, so any significant loss represents money lost. The cost of enrichment is so high that the enriched product is very valuable indeed.

The principal radioactive releases from the enrichment plants are to aqueous streams. The conversion operations carried out at the present gaseous diffusion plants, which would contribute to the emissions, have already been covered in the section on conversion, and are not included in this discussion. Table 11 shows calculated values for radioactivity releases to liquids from both gaseous diffusion and gas centrifuge enrichment plants.

C. Doses to the Public

Total body radiation doses to people living within 50 miles of a ~9 million SWU plant are estimated to be 0.64 man-rem per year per million people for each year of operation. To put this in context a little better, it is expected that in the year 2000, all of the enrichment facilities in the U.S. will contribute about 0.05% as much radiation dose as that received from natural background sources.

V. LWR FUEL FABRICATION

Nuclear fuel fabrication is a mature industry for LWR fuels using enriched uranium (2-4% ^{235}U). The same cannot be said for recycle fuel, i.e., LWR fuel containing plutonium in place of part of the enriched uranium. Development of commercial processes for recycle fuel must await a favorable decision by the Nuclear Regulatory Commission (NRC) on the use of plutonium in power reactors. Fuel made from uranium and plutonium dioxides is called mixed oxide fuel, or MOX. Small scale pilot plants for the preparation of MOX have been operated in the U.S. and abroad, but the problems of remote or semi-remote handling of the plutonium have not been adequately developed for commercialization. Table 12 is a list of commercial U.S. fabrication plants.

Table 11

CALCULATED RELEASES OF RADIOACTIVE MATERIALS IN LIQUID EFFLUENTS FROM 8.75 MILLION SWU ENRICHMENT PLANTS

(Taken from Table 3.2-6, ERDA-1543, June 1975)

Radionuclide	Gaseous Diffusion Avg. Annual Release (µCi/yr)	Gas Centrifuge Avg. Annual Release (µCi/yr)
^{90}Sr	1.5×10^3	1.5×10^3
^{95}Zr	1.0×10^4	1.0×10^4
^{95}Nb	1.0×10^4	1.0×10^4
^{99}Tc	7.0×10^6	7.0×10^6
^{106}Ru	9.3×10^4	9.3×10^4
^{137}Cs	1.5×10^3	1.5×10^3
Uranium-232	4.1	7.8
-233	2.2×10^{-2}	4.1×10^{-2}
-234	1.4×10^3	2.7×10^3
-235	5.4×10	1.0×10^2
-236	1.3×10^2	2.5×10^2
-238	1.2×10^3	2.2×10^3
^{237}Np	4.0	4.0
^{239}Pu	8.0×10^{-3}	8.0×10^{-3}

µCi = microcuries

Table 12

LICENSED, COMMERCIAL LWR FUEL FABRICATION PLANTS

Plant Location	Site Size, Acres	Population Density, People/Sq. Mi.	Plant Feed Material	Plant Product
Babcock & Wilcox Lynchburg, Va.	506	40	UO_2 Pellets	Fuel assemblies
Combustion Eng. Windsor, Conn.	532	620	UO_2 Powder	Fuel assemblies
General Electric Wilmington, N.C.	1650	50	UF_6	Fuel Assemblies
Gulf United Nuclear Hematitle, Mo.	150	300	UF_6	UO_2 powder or pellets
Gulf United Nuclear New Haven, Conn.	76*	620	UO_2 Pellets	Fuel assemblies
Jersey Nuclear Richland, Wash.	160	20	UF_6	Fuel assemblies
Kerr-McGee Crescent, Okla.	1000	110	UF_6	UO_2 Powder or Pellets
Nuclear Fuel Services Erwin, Tenn.	58	110	UF_6	UO_2 Powder or Pellets
NUMEC Apollo, Pa.	5	420	UF_6	UO_2 Powder or Pellets
Westinghouse Columbia, SC	1140	140	UF_6	Fuel Assemblies

*Shared by manufacturing and research divisions of Olin Corporation and naval reactor fuel operations of United Nuclear Corp.

Nuclear fuel is enclosed or "clad" in a container for use in power reactors. This cladding may be a metal can or long tube, or it may be graphite. Metals include a variety of alloys, but they are mostly stainless steels or Zircaloys. The cladding prevents interaction of the fuel with coolants, and inhibits the release of fission products from irradiated fuel. Graphite is in a form obtained by thermally decomposing hydrocarbons, i.e., it is pyrocarbon. LWR fuel cladding is Zircaloy, an alloy made predominantly of zirconium.

The feed material for the fabrication of LWR fuel is UF_6 enriched to 2 to 4% in ^{235}U. The UF_6 is converted to UO_2 pellets which are loaded into the Zircaloy cladding tubes. The tubes are assembled into fixed arrays to produce finished fuel assemblies ready for use in reactors. For several other reactor types, e.g., heavy-water and fast reactors, similar fabrication techniques are used, but differences in uranium enrichment, pellet size, and plutonium content are present. The present discussion will concern itself mainly with LWR fuel fabrication.

A. Processes

Plants licensed or being considered for licensing are based primarily on either the ammonium diurante (ADU) or the dry conversion (DC) process for converting UF_6 to UO_2. Current practice favors the ADU process. There is some U.S. commercial interest (by B&W) in the ammonium uranyl carbonate (AUC) process.

1. Processes for enriched uranium

ADU process

Figure 14 is a simplified flow diagram of the ammonium diuranate (ADU) process and subsequent LWR fuel fabrication steps. The process starts with UF_6 which is reacted with water to produce uranyl fluoride. Precipitation with ammonia produces ammonium diuranate, from which the process takes its name. The calcination and reduction steps, while sequential, may take place in the same piece of equipment, e.g., a rotary kiln. The UO_2 product may be pyrophoric, and can be stabilized by surface oxidation. Because a precipitation from solution is used to produce ammonium diuranate, this process may also be used with uranyl nitrate solution as feed. The significance of this is that recycled fuel from reprocessing plants leaves the process as uranyl nitrate solution. Also, uranium refineries using the wet process produce uranyl nitrate as an intermediate pure material before producing UF_6. In some cases it may be desirable to make pellets from this uranium, e.g., for use in LMFBRs.

DC process

In the dry conversion process UF_6 is reacted with steam to produce UO_2F_2, which is reacted with hydrogen to produce UO_2 according to the following net reaction:

$$UF_6 + 2H_2O + H_2 \rightarrow UO_2 + 6HF \; .$$

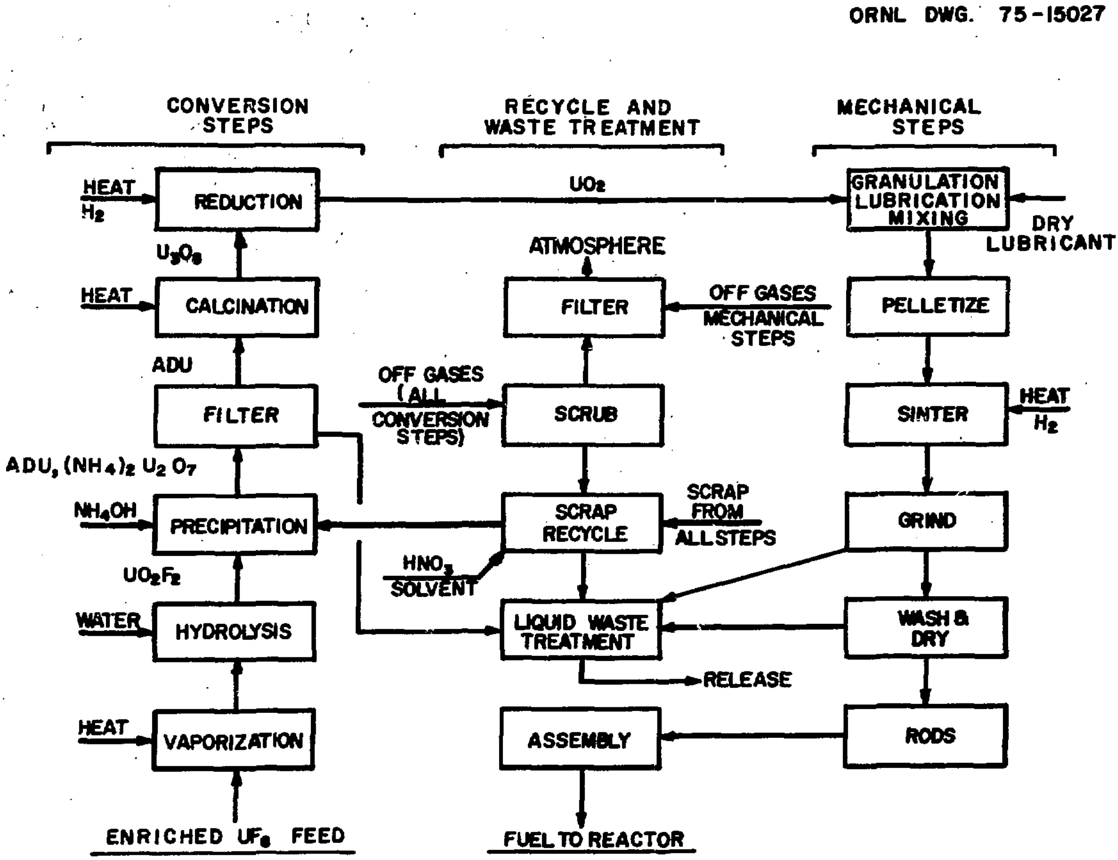

Fig. 14. SIMPLIFIED ADU PROCESS FLOW DIAGRAM FOR LWR FUEL FABRICATION

The process may be carried out stepwise, or in a single step in a rotary kiln wherein UF_6 vapor and steam are passed countercurrently to hydrogen. After preparation of UO_2, the steps are the same as those used in the ADU process. Since the DC process involves direct reaction of UF_6 with steam, it cannot be used with uranyl nitrate as a starting material.

AUC process

In the ammonium uranyl carbonate process a crystalline AUC material is formed by injection of UF_6, CO_2, and NH_3 into demineralized water. The overall reaction is

$$UF_6 + 10\ NH_3 + 3CO_2 + 5H_2O \rightarrow (NH_4)_4\ UO_2(CO_3)_3 + 6NH_4F\ .$$

The AUC crystals are about 60 microns in size and form a suspension which is filtered and washed, first with ammonium carbonate and then with methanol. The AUC is decomposed and reduced to UO_2 in a fluidized bed furnace using steam and hydrogen. Because a precipitation from solution is used in this process, it, like the ADU process, can use uranyl nitrate feed.

2. Recycle fuel

As was mentioned above, "recycle fuel" is the name given to fuel in which plutonium is used in place of enriched uranium. Fabrication of recycle fuel follows essentially the same process steps as enriched uranium fuel. The principal difference is that PuO_2 powder is prepared and blended with UO_2 powder prior to pelletizing. In this case the UO_2 is natural uranium, and may be produced by either the ADU or the AUC processes. Preparation of PuO_2 powder is shown schematically in Fig. 15. The subsequent steps involved in producing mixed oxide pellets are shown in Fig. 16.

A recycle fuel assembly for a pressurized water reactor contains only mixed-oxide fuel rods; a boiling water reactor assembly contains both enriched uranium oxide and mixed-oxide fuel rods. Radioactive materials entering the fabrication plant consist primarily of isotopes of uranium and plutonium, with americium formed by plutonium decay. The distribution of plutonium alpha and beta activity in a mixed oxide fuel fabrication plant feed is given in Table 13.

Fabrication of fuels containing recycle plutonium requires special consideration. Not only is it necessary to work in equipment which will contain the plutonium with a very high degree of integrity (e.g., gloveboxes), but also some degree of shielding to protect the workers from the penetrating radiation from the plutonium isotopes is necessary. Both x-rays and neutrons (from α,n reactions) must be taken into consideration. Fabrication experience with plutonium of the isotopic composition expected for recycle fuels is limited, and the full extent of the problem will not be known until more experience has been gained. However, it seems likely that inadequate attention has been paid so far to the need for semi-remote or remote equipment operation.

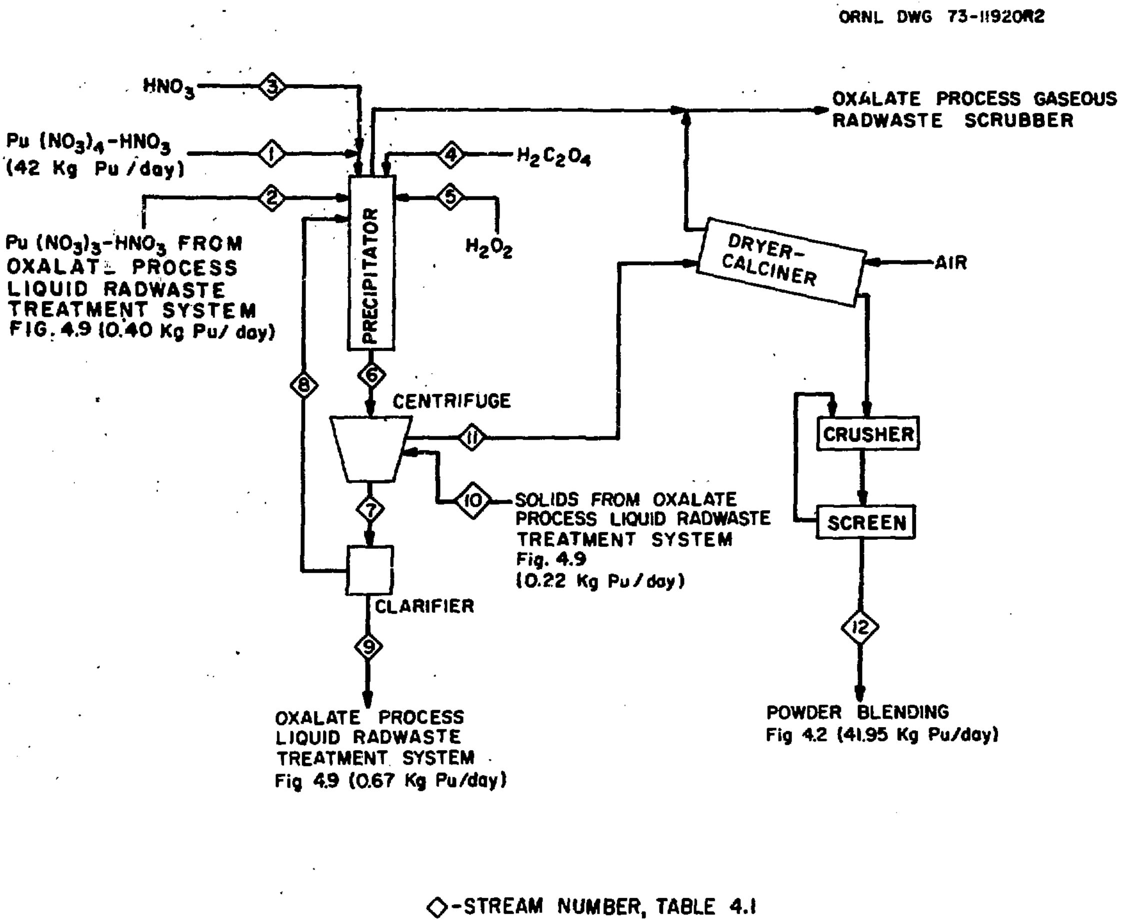

Fig. 15. **OXALATE PROCESS FOR PRODUCTION OF PLUTONIUM OXIDE** (0.042 Metric Ton Pu/Day). (Taken from ORNL-TM-4094, May, 1975)

ORNL DWG. 73-11921R1

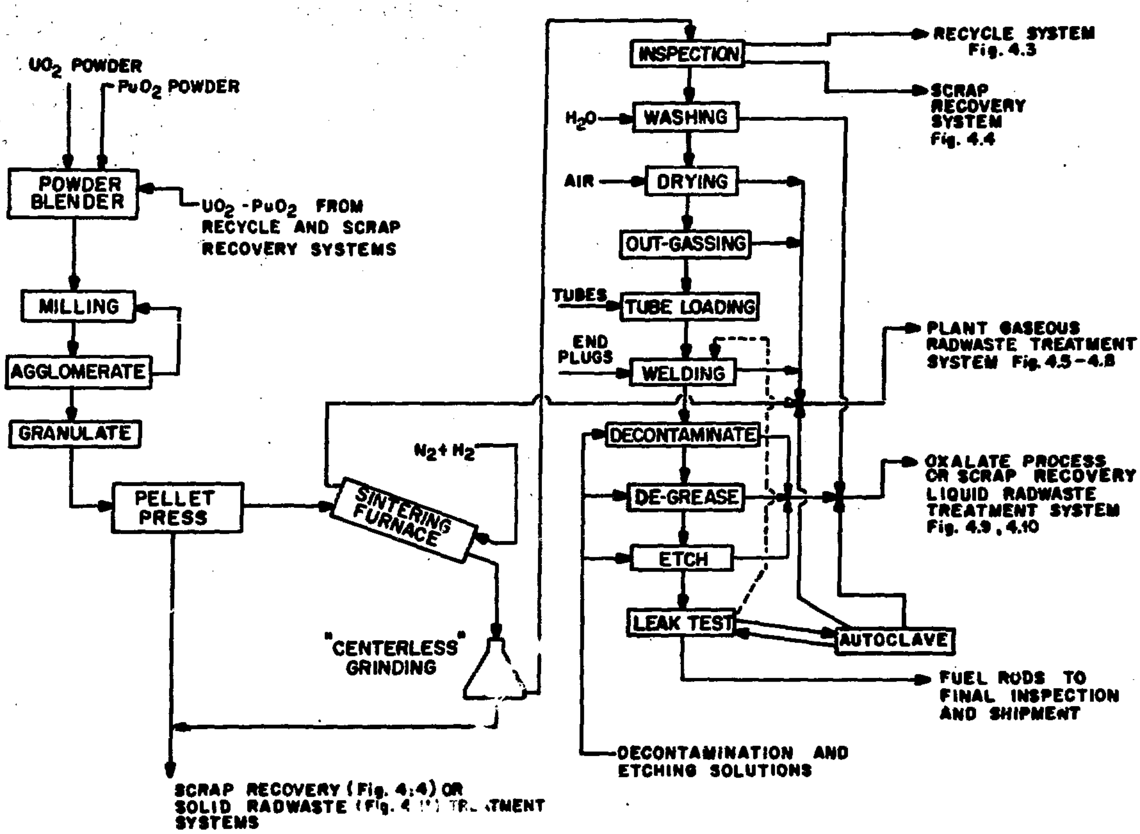

Fig. 16. FABRICATION OF FUEL FOR PLUTONIUM RECYCLE REACTORS (1.0 MT U+Pu/day)

Table 13

Distribution of Alpha and Beta Activity in 4.2 wt. % Plutonium in Mixed-Oxide Feed to the Fabrication Plant

Nuclide*	Specific Activity, Ci/g Fuel	Percent of Activity from each Isotope
^{238}Pu	2.2×10^{-2}	3.66
^{239}Pu	1.17×10^{-3}	0.20
^{240}Pu	2.56×10^{-3}	0.43
^{242}Pu	1.62×10^{-5}	0.0027
^{241}Am	1.90×10^{-3}	0.32
Total α	2.76×10^{-3}	4.60
^{241}Pu	5.73×10^{-1}	95.4
Total β	5.73×10^{-1}	95.4
Total $\alpha + \beta$	6.00×10^{-1}	100.0

*Only those contributing > 0.02% of the total inhalation hazard are included.

3. Cladding

Zircaloy is the cladding material of choice for LWR fuels because of its chemical and physical properties, but most importantly because of its low cross section for neutron absorption. The prime ingredient of Zircaloy, zirconium, and found in nature with hafnium, which by a perversity of nature has a large neutron absorption cross section. Therefore, an important part of the preparation of Zircaloy is purification of zirconium with respect to hafnium.

Zirconium is prepared most commonly by the Kroll process, which involves reduction of zircon ($Zr\ SiO_4$) to Zr metal using carbon and chlorine to produce $ZrCl_4$, followed by reduction with magnesium. The steps involved in producing pure Zr sponge are shown in Fig. 17. The step labeled liquid-liquid extraction may be carried out using aqueous solutions of the thiocyanates of hafnium and zirconium from which the hafnium is preferentially extracted using Hexone, an organic ketone.

The Zircaloy tubes themselves are produced by arc-melting the Zr sponge in a high vacuum arc furnace. At the same time, the alloying components (Sn, Ni, Cr and Fe) are added. The resultant ingot is forged and an extrusion billet clad with copper to protect and lubricate it during extrusion is produced. After extrusion the copper is removed by dissolving it in nitric acid, which does not attack the Zircaloy. Fabrication of Zircaloy tubing is different from fabrication of ferrous metal tubing in that the zirconium must be carefully protected from oxidation during most fabrication steps.

B. Radioactivity Released

1. Enriched uranium processes

ADU process

The radioactivity released from the various process streams of the ADU process are shown in Fig. 18. As can be seen, the amounts are modest, and arise primarily from the aqueous waste streams. This figure is for a "model" plant, and gives representative values from the U.S. industry, rather than actual amounts released from a specific plant.

DC process

The radioactivity released from the process streams of a model DC plant is given in Fig. 19.

AUC process

No analysis like those above has been made for an AUC plant, but it is to be expected that the results will be similar to those for the ADU and DC processes, which are, in fact, quite similar to each other. As a matter of fact, from the point of view of radioactivity released, there is no basis for choosing one process over another.

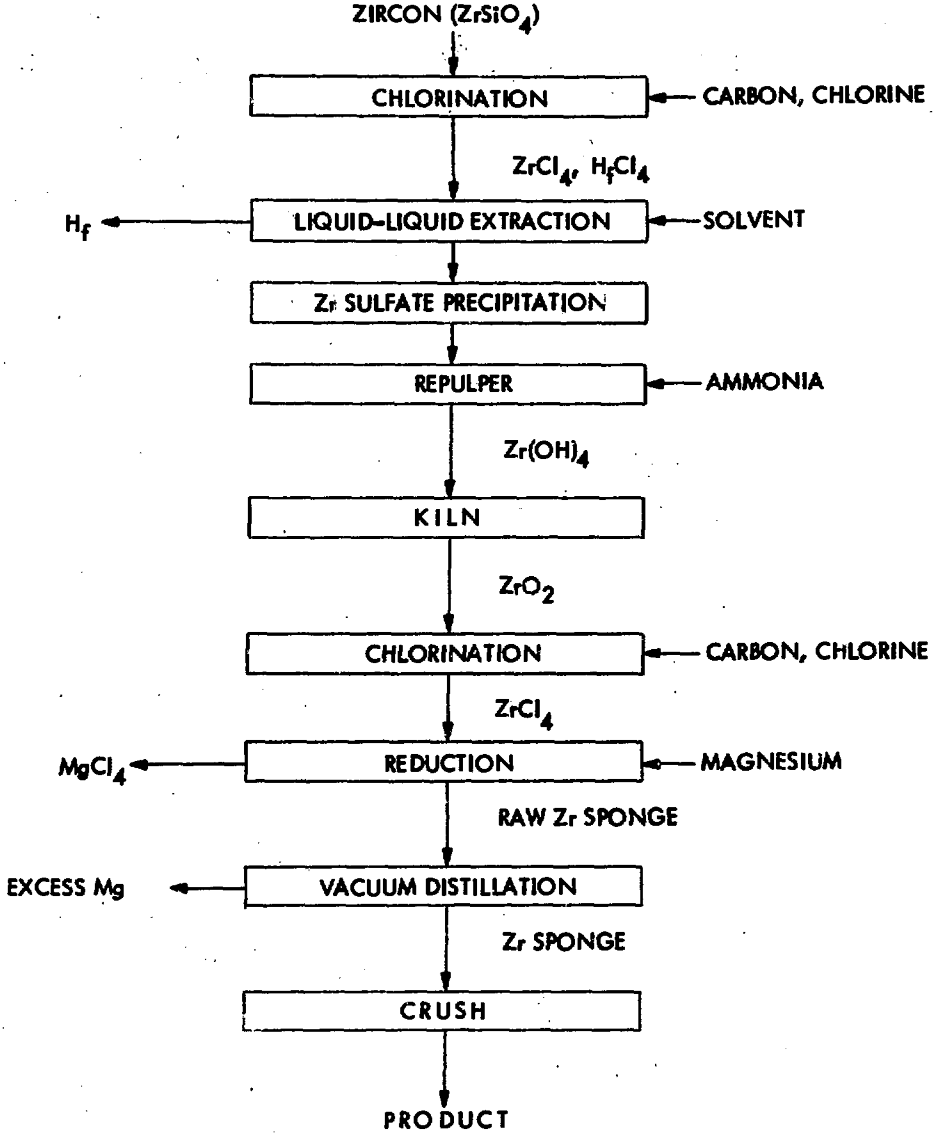

Fig. 17. Zirconium Sponge Production

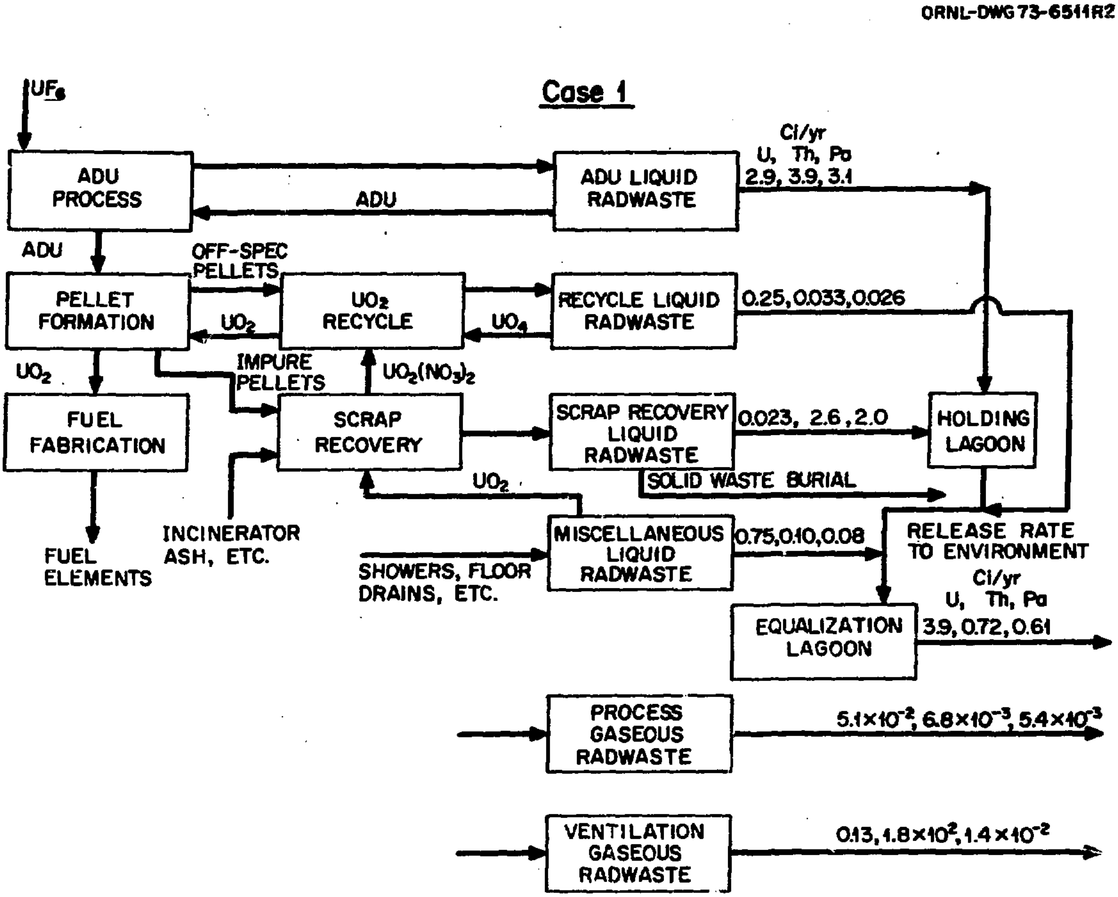

Fig. 18.

Process and Radwaste Systems for ADU Plant

ORNL-DWG 73-6504R2

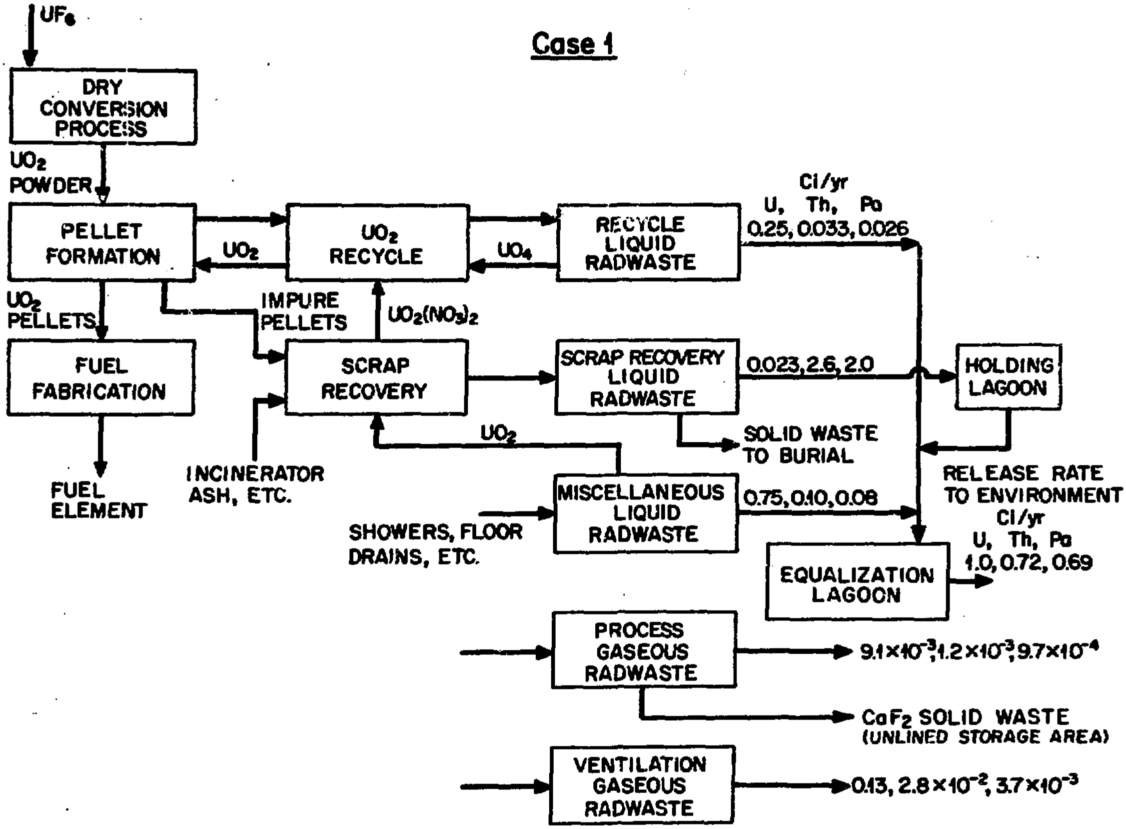

Fig. 19.

Process and Radwaste Systems for DC Plant

2. Recycle fuel

The solid radioactive plutonium wastes leaving the recycle fuel fabrication plant are given in Table 14. The gaseous radioactive wastes are given in Table 15.

C. Costs of Reducing Radiation Doses

By the addition of various treatment steps to the existing processes it is possible to reduce the release of radioactivity from the plants. Such reductions translate directly to reduced radiation doses. The basic question is How worthwhile is a given reduction in dose? Although it must be recognized that such a question is very subjective, it is possible to attach a dollar value to a given dose reduction. As mentioned earlier, such determinations are themselves dependent on the state of technology, the ingenuity of the designer, and so on. Nonetheless, using accepted or acceptable extrapolations of technology, and sound engineering principles, it is possible to make these determinations. An attempt to do so realistically has made, and the results are presented (in part) in what follows. It may be worth noting that doses of 0.1 mrem or less are scarcely discernable, and are less than one-tenth of one percent of the natural background radiation to which everyone is subjected.

1. Enriched uranium processes

ADU process

Table 16 presents a summary listing of various process steps which might be added to the ADU process to reduce releases of radioactivity. In Fig. 20 these steps are presented in terms of their annual costs and the predicted dose reductions.

DC process

Table 17 and Fig. 21 present the same type information for the DC process.

AUC process

Information similar to the above is not available for the AUC process. However, the similarity of the ADU and DU cases strongly suggests that the AUC process will exhibit about the same behavior in terms of dollars per millirem of dose reduction (i.e., about 10^5-fold dose reduction per $300,000).

2. Recycle fuel process

Table 18 and Fig. 22 present the same kinds of information for the recycle fuel fabrication plant as was given above for the ADU and DC plants.

VI. FUEL REPROCESSING

There is no commercial fuel reprocessing plant operating in the U.S. today. The plants in Great Britain and France provide the major fuel reprocessing capability for commercial power reactor fuels in the world today. Both France and Great Britain

Table 14

SOLID RADIOACTIVE PLUTONIUM WASTES FROM RECYCLE FUEL FABRICATION

(Taken from Table 4.8, ORNL-TM-4904, May 1975)

Source	Approx. wt., kg	Pu, g/day	55 gal. drums of cement	Activity, Ci/ft^3
Raffinate from oxalate process liquid radwaste treatment	95	0.04	9	8.6×10^{-3}
Clarifier and raffinate wastes from liquid radwaste scrap recovery	62	1.2	6	0.39
Low level activity solids from fuel fabrication	--	Trace		
Scrap recovery dissolver filter (MnO_2)	1.7	Trace		
TOTAL			15 drums	
AVERAGE				0.16

Table 15

GASEOUS RADIOACTIVE EFFLUENTS FROM RECYCLE FUEL FABRICATION

(Taken from Table 4.10, ORNL-TM-4904, May 1975)

	Case 1*		Case 2*		Case 3*	
Nuclide	μCi/ml	Ci/yr	μCi/ml	Ci/yr	μCi/ml	Ci/yr
^{234}U	7.1×10^{-19}	1.0×10^{-9}	7.1×10^{-21}	1.0×10^{-11}	1.4×10^{-25}	1.0×10^{-16}
^{235}U	2.3×10^{-20}	3.3×10^{-11}	2.3×10^{-22}	3.3×10^{-13}	4.5×10^{-27}	3.3×10^{-18}
^{238}U	4.9×10^{-19}	7.1×10^{-10}	4.9×10^{-21}	7.1×10^{-12}	9.7×10^{-26}	7.1×10^{-17}
^{238}Pu	3.4×10^{-14}	4.9×10^{-5}	3.4×10^{-16}	4.9×10^{-7}	6.7×10^{-21}	4.9×10^{-12}
^{239}Pu	1.8×10^{-15}	2.6×10^{-6}	1.8×10^{-17}	2.6×10^{-8}	3.6×10^{-22}	2.6×10^{-13}
^{240}Pu	3.9×10^{-15}	5.8×10^{-6}	3.9×10^{-17}	5.8×10^{-8}	7.8×10^{-22}	5.8×10^{-13}
^{241}Pu	8.8×10^{-13}	1.3×10^{-6}	8.8×10^{-15}	1.3×10^{-5}	1.8×10^{-19}	1.3×10^{-10}
^{242}Pu	2.5×10^{-17}	3.6×10^{-8}	2.5×10^{-19}	3.6×10^{-10}	5.0×10^{-24}	3.6×10^{-15}
^{241}Am	2.9×10^{-15}	4.3×10^{-6}	2.9×10^{-17}	4.3×10^{-8}	5.8×10^{-22}	4.3×10^{-13}

*The "cases" refer to various combinations of treatments for gaseous radwastes. See Table 18 "Summary of Variables for Model LWR Recycle Fuel Fabrication Plant Gaseous Radwaste Treatment Systems," for their descriptions.

Table 16

Summary of Variables for Model DWR Fuel Fabrication Plant Gaseous and Liquid Radwaste Treatment Systems

AMMONIUM DIURANATE (ADU) PROCESS

	Case 1	Case 2	Case 3	Case 4
Treatment Objective	Base Case	Reduce uranium release by 2, eliminate release of nitrate	Reduce uranium release by 15, reduce or eliminate release of ammonia and nitrate (recycle), produce low activity solid wastes [CaF_2, $Ca(OH)_2$][a]	Eliminate release of liquids (recycle), eliminate release of ammonia and nitrate (recycle), immobilize solid wastes in cement [CaF_2, $Ca(OH)_2$, residual radionuclides]
Plant Decontamination Factor for Uranium (wt U entering plant/wt U released)	1.1×10^3	2.1×10^3	1.7×10^4	4.9×10^9
ADU Liquid Radwaste				
	Filter, lagoon, release	16-hr retention, centrifuge, filter, $Ca(OH)_2$-CaF_2 precipitation, store CaF_2 in lined lagoon, release liquid waste	16-hr retention, centrifuge, filter, ion exchange, $Ca(OH)_2$-CaF_2 precipitation, volatilize and recycle NH_3, lined lagoon, release liquid waste	16-hr retention, centrifuge, filter, ion exchange, $Ca(OH)_2$-CaF_2 precipitation, volatilize and recycle NH_3, evaporate and recycle H_2O, incorporate CaF_2 waste in cement, release excess water
ADU Recycle Liquid Radwaste				
	Filter, lagoon, release	$Ca(OH)_2$ neutralization, 16-hr retention, centrifuge, filter, store $Ca(NO_3)_2$ in lined lagoon, no liquid discharge	Filter, NH_3 neutralization, 16-hr retention, centrifuge, filter, spray calcine in sand bed and recycle HNO_3, sand to scrap recovery, nitrate removal by anaerobic digestion	Same as Case 3
ADU Miscellaneous Liquid Radwaste				
	Filter, lagoon, release	Filter, lagoon, release	Evaporate and recycle water, immobilize bottoms in cement for burial	Same as Case 3
ADU Scrap Recovery Liquid Radwaste				
	Lagoon, release, ship solid waste to licensed burial ground	Store in lined lagoon, no liquid discharge, ship solid waste to licensed burial ground	Evaporate and recycle HNO_3, immobilize solid waste and bottoms in cement for burial	Same as Case 3
ADU Process Gaseous Radwaste				
	Water scrubber[b]	Water scrubber, HEPA filter (efficiency 95%)	Water scrubber, HEPA filter (efficiency 99.95%)	Water scrubbers, HEPA filters in series (efficiency 99.9995%)
ADU Ventilation Gaseous Radwaste				
	Roughing filter[b]	Roughing filter, HEPA filter (efficiency 95%)	Roughing filter, HEPA filter (efficiency 99.95%)	Roughing filter, HEPA filters in series (efficiency 99.9995%)

[a] < 1 uCi/lb, 770 ppm uranium.

[b] Part of the base plant.

ORNL DWG 74-5

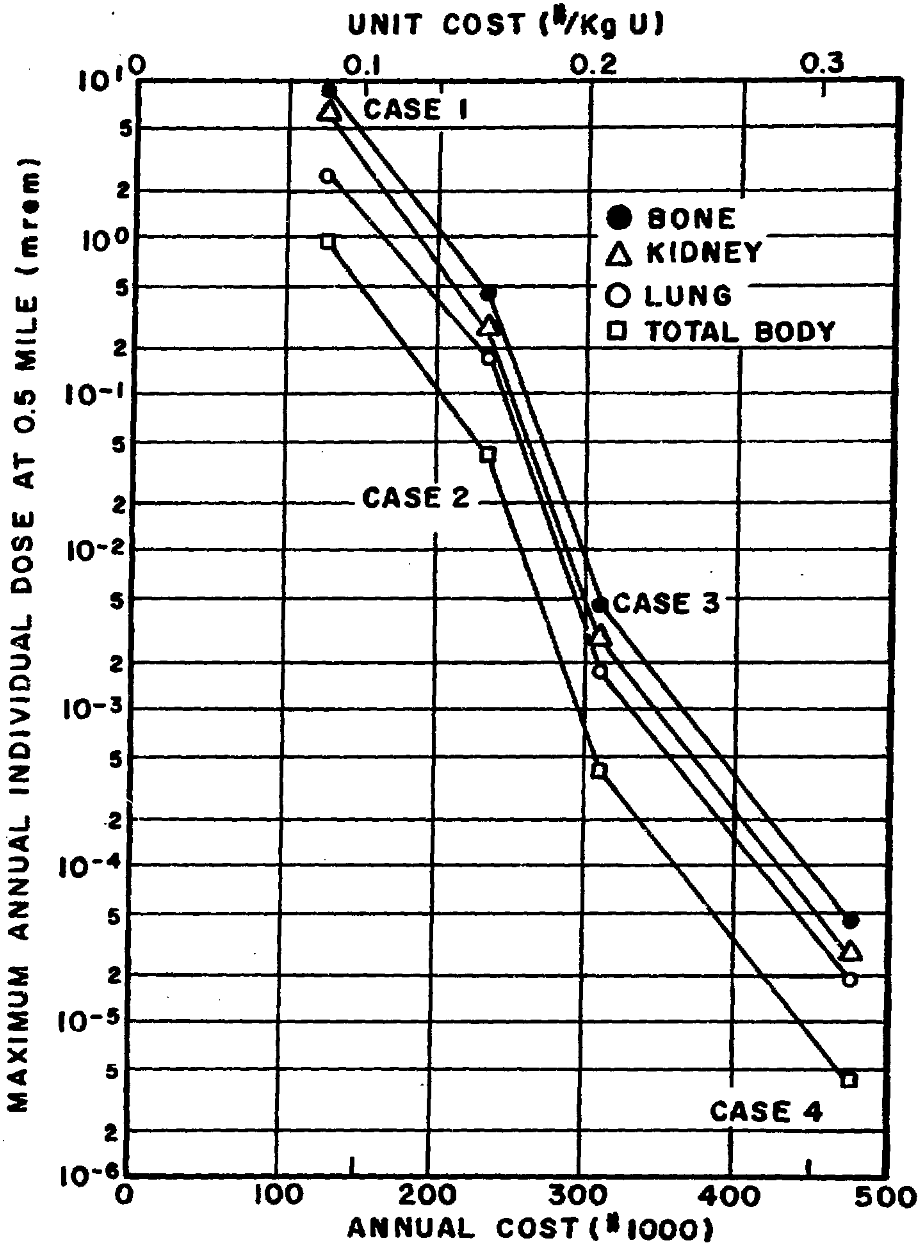

Fig. 20. Annual Cost for Reduction of Maximum Annual Dose from Gaseous Effluents at 0.5-Mile Distance from Model ADU LWR Fuel Fabrication Plant (Taken from ORNL-TM-4902, May, 1975).

Table 17

Summary of Variables for Model LWR Fuel Fabrication Plant Gaseous and Liquid Radwaste Treatment Systems

DIRECT CONVERSION (DC) PROCESS[a]

	Case 1	Case 2	Case 3	Case 4
Treatment Objective	Base Case	Reduce uranium release by 3, reduce HF release by 10^3	Reduce uranium release by 10^6, recover 90% of HF, reduce release of HF by 3×10^3, reduce or eliminate release of ammonia and nitrate (recycle), eliminate release of liquids, produce low activity[b] solid wastes [CaF_2, $Ca(OH)_2$, residual radionuclides]	Reduce uranium release by 10^7, recover 99% of HF, reduce HF release by 3×10^3, immobilize solid wastes in cement [CaF_2, $Ca(OH)_2$, residual radionuclides]
Plant Decontamination Factor for Uranium (wt U entering plant/wt U released)	3.9×10^5	6.0×10^5	6.7×10^7	6.7×10^8
		DC Recycle Liquid Radwaste		
	Filter, lagoon, release	$Ca(OH)_2$ neutralization, filter, 16-hr retention, centrifuge, store $Ca(NO_3)_2$ in lined lagoon, no liquid discharge	NH_3 neutralization, 16-hr retention, centrifuge, filter, spray calcine in sand bed and recycle NH_3, sand to scrap recovery, nitrate removal by anaerobic digestion	Same as Case 3
		DC Miscellaneous Liquid Radwaste		
	Filter, lagoon, release	Filter, lagoon, release	Evaporate and recycle water, immobilize bottoms in cement for burial, release excess water	Same as Case 3
		DC Scrap Recovery Liquid Radwaste		
	Lagoon, release, ship solid waste to licensed burial ground	Store in lined lagoon, no liquid discharge, ship solid waste to licensed burial ground	Evaporate and recycle HNO_3, immobilize solid waste and bottoms in cement for burial	Same as Case 3
		DC Process Gaseous Radwaste		
	Crushed limestone, tower, H_2 burner, store solid waste in unlined storage area	KOH scrubber, lime regeneration of KOH, store solid waste in lined storage area, H_2 dilution	Single-pass HF condenser 90% HF recovery, KOH scrubber, lime regeneration of KOH, HEPA filter (efficiency 99.95%), incorporate CaF_2 waste in cement, H_2 dilution	Multiple-pass HF condenser 99% HF recovery, KOH scrubber, lime regeneration of KOH, HEPA filters in series (efficiency 99.9995%), incorporate CaF_2 waste in cement, H_2 dilution
		DC Ventilation Gaseous Radwaste		
	Roughing filter[c]	Roughing filter, HEPA filter (efficiency 95%)	Roughing filter, HEPA filter (efficiency 99.95%)	Roughing filter, HEPA filters in series (efficiency 99.9995%)

[a] Dry process - no liquid waste for main process line.

[b] < 1 µCi/lb, 770 ppm uranium.

[c] Part of the base plant.

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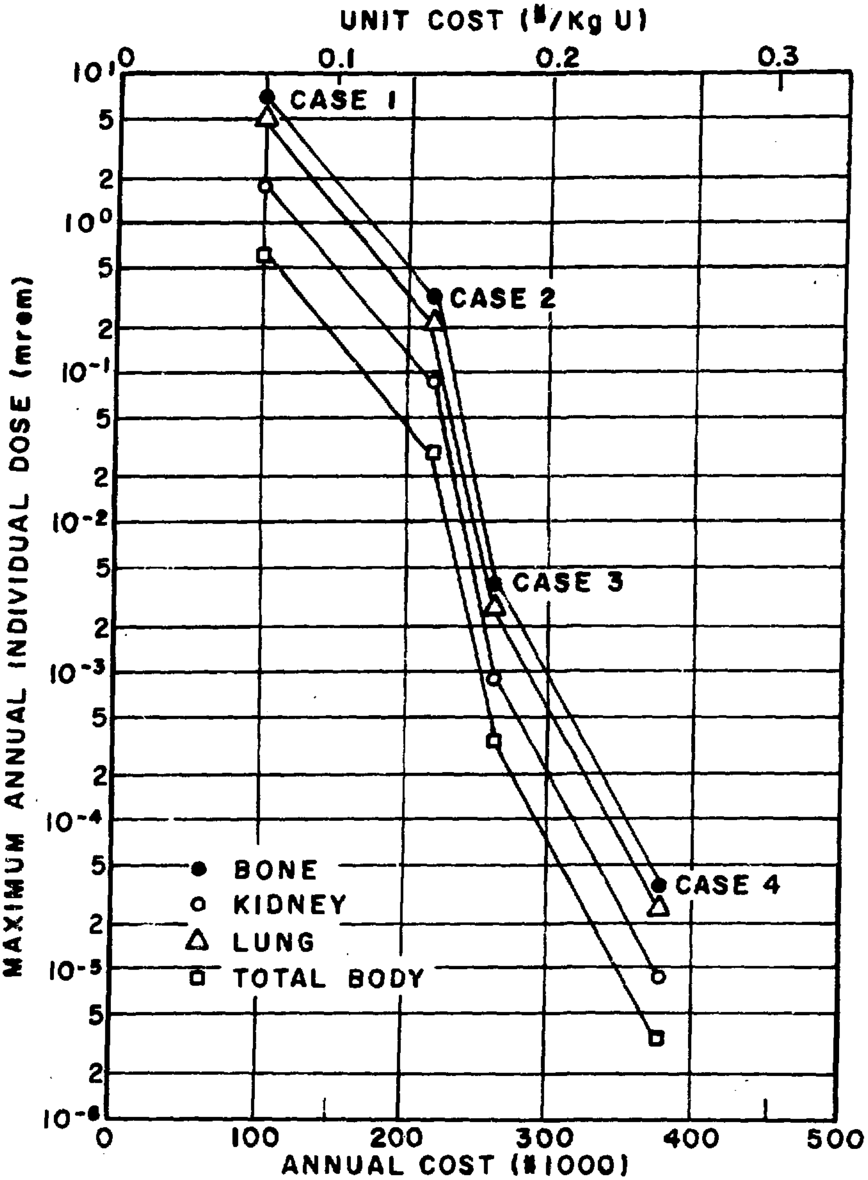


Fig. 21. Annual Cost for Reduction of Maximum Annual Dose from Gaseous Effluents at 0.5-mile Distance from Model DC LWR Fuel Fabrication Plant (Taken from ORNL TM-4902, May, 1975).

Table 18

Summary of Variables for Model LWR Recycle Fuel Fabrication Plant Gaseous Radwaste Treatment Systems

	Case 1	Case 2	Case 3
Treatment Objective	Base Case	Reduce Plutonium release by a factor of at least 100	Clean and recycle most process gaseous radwaste; extensively treat and discharge small fraction of process gaseous radwaste to minimize plutonium release
Plant DF for plutonium and uranium (Ci entering plant/Ci released in gaseous radwaste)	1.33×10^{11}	1.33×10^{13}	1.33×10^{18}
		Process Gaseous Radwaste[a]	
	Scrubber, roughing filter, HEPA filter; blend with alpha enclosure and plant ventilation air; two HEPA filters in series	Add additional bank of HEPA filters to final filtration in Case 1	Scrubber, roughing filter, HEPA filter; blend with alpha enclosure ventilation air; recycle 98% through HEPA filter; discharge 2% through two HEPA filters in series; blend with plant ventilation air; two HEPA filters in series
Rated DF of Filter Train	8.0×10^{10}	1.6×10^{14}	1.6×10^{19}
Installed DF	8.0×10^{7}	8.0×10^{9}	8.0×10^{14}
		Alpha-Enclosure Ventilation Air[b]	
	Roughing filter, HEPA filter; blend with process gaseous radwaste and plant ventilation air; two HEPA filters in series	Same as above	Roughing filter, HEPA filter; blend with process gaseous radwaste; recycle 98% through HEPA filter; discharge 2% through two HEPA filters in series; blend with plant ventilation air; two HEPA filters in series
Rated DF of Filter Train	8.0×10^{9}	1.6×10^{13}	1.6×10^{18}
Installed DF	8.0×10^{6}	8.0×10^{8}	8.0×10^{13}
		Plant Ventilation Air	
	Roughing filter, HEPA filter; blend with process gaseous radwaste and alpha enclosure ventilation air; two HEPA filters in series	Same as above	Same as Case 1

[a] Contains 0.02% of the radioactive material entering the plant before treatment.

[b] Contains 0.004% of the radioactive material entering the plant before treatment.

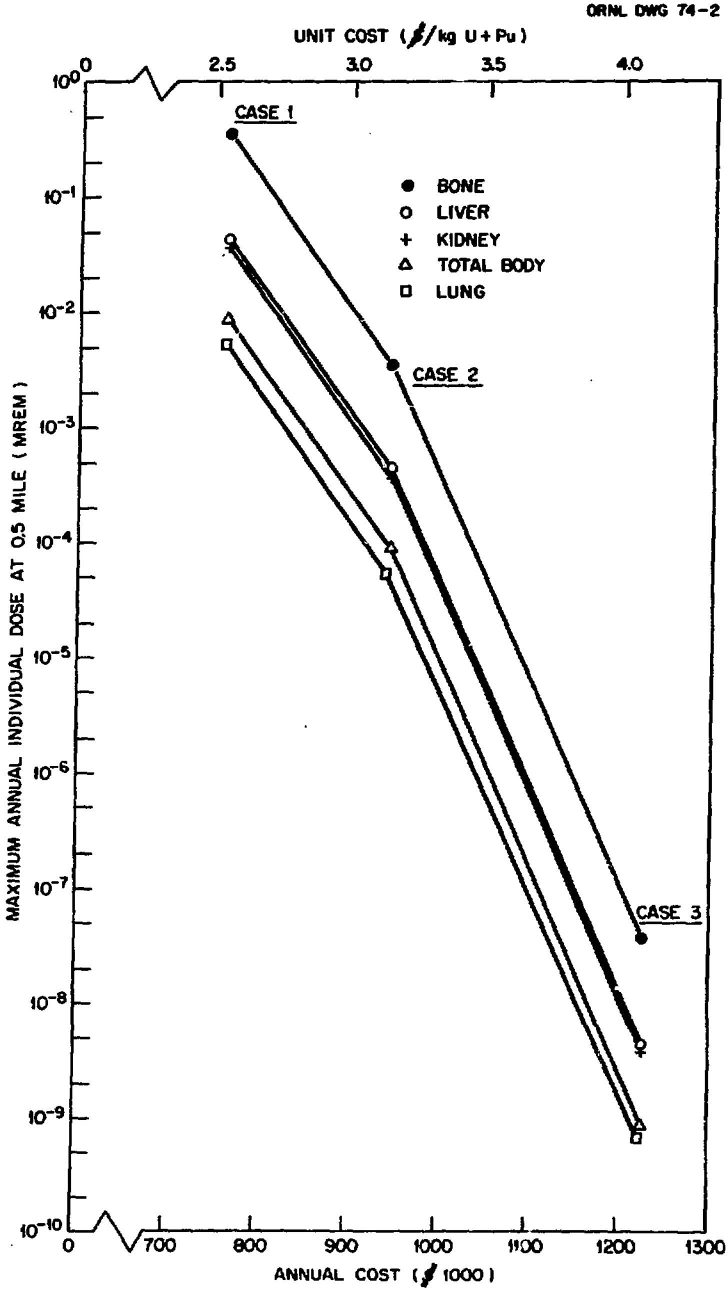


Fig. 22. Annual Cost for Reduction of Maximum Annual Dose from Gaseous Effluents at 0.5-Mile Distance from model Recycle Fuel Fabrication Plant. (Taken from ORNL-TM-4904 May 1975).

have capability and plans for substantial oxide fuel reprocessing and both are well along toward developing fast reactor fuel reprocessing capability.

All present and planned commercial fuel reprocessing plants are based on the Purex process, which involves dissolving the fuel in nitric acid and purifying it by solvent extraction using tributyl phosphate as extractant. Most oxide fuel plants also use the chop-leach head-end. As the name implies, in the chop-leach head-end the fuel is chopped, or sheared, into short pieces and leached with nitric acid. Presently planned reprocessing plants may include production of UF_6 from the purified uranyl nitrate product for use in re-enrichment steps, and may include conversion of the purified plutonium nitrate product to PuO_2.

Reprocessing plants represent a major capital investment. For example, the 1000 tonne per year plant planned for oxide fuel reprocessing in England is estimated to cost about $600 million dollars. This is consistent with what the Allied General Nuclear Services plant in South Carolina, U.S., will cost when it is completed.

Some thought is being given to removal of actinides from the high-level wastes from fuel reprocessing plants. This may have the advantage of reducing the long-term storage hazard of the wastes. However, the actinides would then have to be disposed of, presumably by recycling to reactors for conversion to fission products. Part of this actinide removal could be accomplished by reprocessing plant modifications; part would require an extensive addition to the plant. The overall feasibility of such actinide removal is yet to be established.

Because of the uncertainty in the degree of radioactive effluent containment which will be required at fuel reprocessing plants, it is most difficult to predict what they will cost to build and to operate in the future. Their rate of construction will have to be fast to keep up with the projected rate of construction of nuclear power reactors, and it is likely that effluent releases will be more strictly limited in the future than heretofore. Table 19 is a recent summary of the spent fuel reprocessing plants built, under construction or planned in the free world.

Although considerable experience exists in the U.S. and elsewhere in the reprocessing of reactor fuels irradiated in the course of producing plutonium and other materials for nuclear weapons, there is virtually no experience with fuels "burned up" (irradiated) to the extent that is planned to be routine in fuels from operating LWRs, and certainly not from LMFBRs and HTGRs. LWR fuel burnups are expected to be in the 20 to 30 megawatt-day per tonne (MWD/T) range (or slightly higher), while LMFBR fuels may experience peak burnups as high as 150 MWD/T. The significance of this observation is that no one really knows what the problems will be in reprocessing these fuels. There is already some evidence that insoluble fission products from the platinum metal group, as well as molybdenum and zirconium compounds, will form during fuel dissolution and pose solids removal problems which have not been antici-

Table 19

SELECTED SPENT NUCLEAR FUEL REPROCESSING PLANTS*

Country	Plant and Site	Capacity		Oxide Fuel Processed, Tonnes	Start-up Date
		Fuel Type	Tonnes U + Pu/yr.		
United States	Allied-General Nuclear Services (AGNS) Barnwell, S. C.	Oxide	1500		Estimated 1977 (dependent on NRC decision on Pu recycle)
	Nuclear Fuel Services (NFS) West Valley, New York	Oxide	750	222	Estimated 1983 (dependent on relicensing by NRC)
	Midwest Fuel Reprocessing Plant (MFRP) Morris, Ill.	Oxide	300		Maybe never (dependent on major revisions to plant)
Great Britain	Windscale Works (II) (BNFL) Seascale, England	Metal Oxide	2500 400	6000 tonnes put thru – total 100	1964 1969 (shut down following an incident in 1973; expected startup in 1976)
	Thermal Reactor Oxide Reprocessing Plant (THORP) (BNFL) Seascale, England	Oxide	1000		1984, with a 2nd add'n of comparable cap. in ~ 1987 being planned
	Complete Fuel Recycle Plant (CFR) Dounreay, Scotland	Oxide (fast reactor fuel)	9 to 10		1976-77
France	UP-1 Marcoule	Metal	500		1958
	UP-2 LaHague	Oxide and graphite base fuel	600 400		1975-76 1979-80
	TOP	Oxide (fast reactor fuel–Phenix)	9 to 12		Operating
Federal Republic of Germany	WAK Karlsruhe	Oxide	35	32	1971
	KEWA	Oxide	1400		1985 (full cap. 1986)
Japan	PNC Tokai	Oxide	210		1976 (full cap. operation 1982)
Belgium	Eurochemic Mol	Metal/Oxide MTR	80 40	167	1966 (Plant is shutting down) Restart ~ 1979 at ~ 75 t/yr, ultimately going to 300 t/yr in 1985.
Italy	Eurex Saluggio	MTR Oxide	5 10		1970 1975
India	Bhabha Trombay	metal	(40 – 60) metal		Operating
	Tarapur Tarapur	oxide	150		1973
	Kalpakkam Kalpakkam	Oxide	between 150 and 300 t		?
Canada	?	Oxide	~300		1985

*It is clear that fuel reprocessing plants are also operating in USSR and Mainland China.

pated.

Typical large power reactors discharge 25 to 40 tons of fuels per year in 60 to 200 fuel assemblies. The spent fuel is sent to reprocessing plants in heavy, shielded casks after storage at the reactor for about a year and a half. This time of storage allows for greater than 95% of the sources of heat and radiation to decay. In fact, with the large backlog of stored LWR fuel which will have accumulated in the U.S. before commercial reprocessing commences, it is likely that for some years to come the fuel will have been stored for 4 or 5 years before it is reprocessed.

A. Nature of LWR Fuel

All fuel from present power reactors is metal-clad. The cladding material varies depending on the reactor type. Gas-cooled reactors are clad with alloys of magnesium which, because of its chemical reactivity, can be removed chemically or mechanically. LWR and HWR fuels are clad mostly in alloys of zirconium. LMFBR fuels are clad in stainless steel. Table 20 contains a partial description of some LWR fuels. The dimensions and weights give some idea of the scale of the reprocessing operations.

LWR fuels are sheared into pieces after other head-end operations are performed to remove extraneous metal, and the sheared material is all put into a dissolver where the oxide fuel is selectively dissolved. The cladding and attendant insoluble fission products become a solid waste. Table 21 lists some important properties of LWR fuels in the context of reprocessing.

B. Separations Process

After fuel dissolution has taken place the subsequent reprocessing steps for all metal clad fuels being considered resemble each other. They are designed to separate uranium and plutonium from fission products and then from each other in a form pure enough to permit their fabrication into fuel.

1. Purex process

The basic separation process is the Purex process, which involves selective extraction of uranium and plutonium nitrates from the nitric acid solution from the dissolver (after a feed adjustment step) into an organic solution of tributyl phosphate in a hydrocarbon diluent. Uranium and plutonium are subsequently separated by changing the valence of plutonium so that it and uranium have different extractabilities. The plutonium valence may be changed either chemically as with hydrazine-stabilized hydroxylamine or ferrous sulfamate, or electrolytically. Electrolytic valence adjustment appears to be coming into favor for use in the newer plants. Fig. 23 is a simplified LWR fuel reprocessing flowsheet.

2. Waste treatment

Iodine and $^{14}CO_2$ are volatile materials which present special

Table 20

DESCRIPTIONS OF LWR FUELS

Pressurized Water Reactors (PWR)

	Westinghouse (3817 MWth)	B&W (3427 MWth)	CE (3800 MWth)
No. of assemblies in core	193	205	241
Fuel pins per assembly	264	208	236
Active length of assembly, cm	416.5	365.8	381
Weights of assembly, kg	721.9	703.5	658.2
Dimensions of assembly, cm	$(21.4)^2 \times 447$	$(\sim 20)^2 \times 421.6$	$(20.27)^2 \times 449.6$

Boiling Water Reactor (BWR)

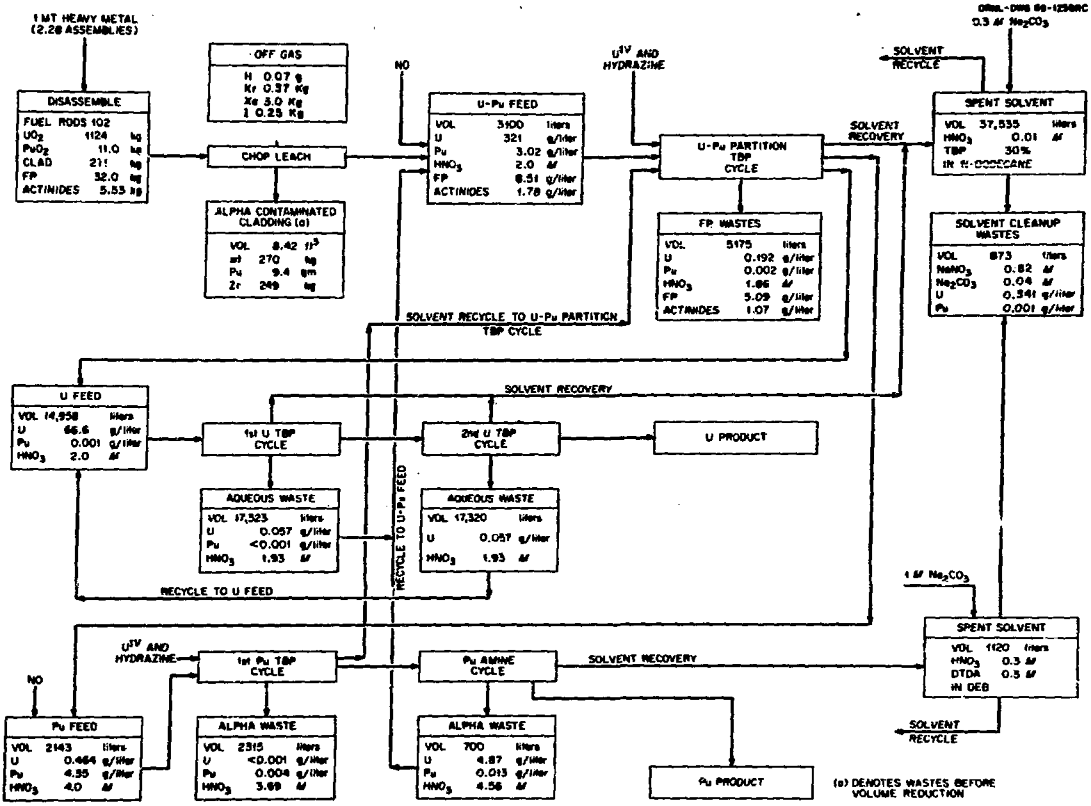
	GE (3833 MWth)
No. of assemblies in core	784
Fuel pins per assembly	64
Active length of assembly, cm	375.9
Weight of assembly, kg	279
Dimensions of assembly, cm	$(13.35)^2 \times 447.9$

Table 21

SOME PROPERTIES OF LWR FUELS IMPORTANT IN REPROCESSING

Property	150-day Cooled LWR Fuel
Fission product heat generation rate, W/kg	~ 20
Percent fissile content	1.5*
Plutonium content, g/kg	8 to 27
Insoluble fission products	6820 W/tonne
Ru, Pd, Rh, Mo, Zr	7390 g/tonne
Fuel element design	~ 0.5 kg of metal per kg of fuel
Elements per tonne of fuel	2 BWR, 3 PWR

*This is the approximate value for PWRs fueled with ^{235}U. If plutonium is recycled to LWRs, the percent fissile material (U + Pu) will approach 1.7% at equilibrium in reactors in which Pu produced in a reactor is returned to that reactor (the so-called self-generated reactor). In the case of a reactor fueled solely with recycled plutonium, the fissile material content would approach 2.2% at equilibrium.



(a) DENOTES WASTES BEFORE VOLUME REDUCTION

Fig. 23. FUEL REPROCESSING FLOWSHEET FOR LWR FUEL. FUEL EXPOSURE: 33,000 MEGAWATT-DAYS PER TONNE AT A SPECIFIC POWER OF 30 MEGAWATTS PER TONNE.

problems to the fuel reprocessor because of their volatility and their biological importance. Iodine is a fission product (^{129}I is the isotope of importance because of its long half life), and ^{14}C is formed during reactor operation by the transmutation of impurity ^{14}N to ^{14}C by n,p reaction. The ^{14}C is expected to be oxidized to $^{14}CO_2$.

carbon-14 dioxide

The presence of ^{14}C in the CO_2 may necessitate fixing the CO_2 rather than releasing it to the environment. Scrubbing processes based on (1) sorption in sodium hydroxide solution (caustic) or (2) sorption in a calcium hydroxide slurry may be used. In the first (caustic) process the caustic-carbonate solution is treated with calcium hydroxide, precipitating $CaCO_3$ and releasing the caustic for re-use.

3. Advanced methods for specific isotopes

Certain radioisotopes either are especially important health hazards, or are difficult to remove from reprocessing plant effluents -- or both. (Iodine-129 and tritium are among these, as is ^{14}C.) For these radioisotopes, special additions will be made to the reprocessing plants to achieve the desired degree of removal from the effluents of the plants. Krypton-85 may be added to these isotopes, not because it is particularly toxic - its relatively short half-life (~12 years) and the fact that it undergoes no chemical reactions to speak of make it quite innocuous --, but because it is an isotope for which removal processes are well under development, and it probably can be removed easily. (It is, in fact, rather interesting how a sort of historical inertia sustains development of certain technologies well beyond their demonstrable need.)

Some types of processes under development which may be added to reprocessing plants are discussed below.

iodox

The iodox process is an advanced method for removing elemental iodine and organic iodides from gaseous effluents. The process is suitable for use either as a primary step for removing the bulk of the iodine from the dissolver off-gas stream or as a polishing unit for removing small amounts of iodine from off-gas streams. The iodine can be isolated as a solid, anhydriodic acid which may be suitable for storage, perhaps in concrete.

The steps in the iodox system are (1) oxidation of the iodine species to the soluble, nonvolatile iodate form using 19-20 M HNO_3 in a bubble-cap or packed column; (2) concentration of the iodine-bearing nitric acid scrub solution in an evaporator; (3) recycle of iodine-free nitric acid condensate from the evaporator to the plant nitric acid system; (4) transfer of the iodine--nitric acid concentrate from the bottom of the evaporator to a second evaporator where it is evaporated to dryness to form HI_3O_8. The condensate from the second evaporator is recycled to the first evaporator. In plants in which the high-activity wastes are stored in tanks, the concentrated acid required for the iodox process would be purchased and the excess acid recycled to the dissolver. In plants where the high-level wastes are solidified, the acid is recovered at low concentrations and an extra fractionation system is required to produce the concentrated acid for recycle to the dissolver and iodox systems. Very little fresh acid would be purchased for this type of plant.

The principal advantages of the iodox process are (1) the high removal of iodine achieved for either elemental or organic iodides; (2) the feasibility of handling large amounts (mass) of iodine; (3) no new chemicals are introduced into the system; and (4) conventional processing equipment is used. Disadvantages include: (1) corrosion problems that may require the use of titantium or zirconium equipment as materials of construction; and (2) the requirement for internal plant production of concentrated nitric acid in plants where the high-activity wastes are solidified and nitric acid is recycled.

voloxidation

Tritium remaining in metal-clad fuel after it leaves the reactor may be removed by shearing the fuel and then tumbling the sheared pieces in a heated device called a voloxidizer to drive off the tritium and tritiated water. The temperature will be between 400 and 600°C, and an oxidizing atmosphere will be employed. Thus, the tritium will be released as tritiated water. The advantage to this operation is that it removes the bulk (~90-95%) of the tritium before fuel dissolution, and prevents excessive tritium contamination of a large volume of water.

The process is still in early developmental stages, and many difficult mechanical problems remain to be solved.

Freon sorption

Removal of ^{85}Kr from off-gas may be required in future reprocessing plants. An attractive means for achieving this is to be selectively sorb the krypton in one of the Freons (relatively short-chain, halogenated hydrocarbons) after other chemical impurities and radioactive materials have been removed. This process has seen commercial application at reactors, and its adaptation to fuel reprocessing plant off-gas cleanup is in a fairly advanced stage of engineering development. Figure 24 is a schematic representation of a Freon sorption system.

actinide removal

If it turns out to be desirable to remove actinides from the high-level reprocessing plant wastes to a higher degree than is presently planned, it may be possible to do so by an addition to the fuel reprocessing flowsheet. The possible advantages of such additional removal are discussed more fully later in the section under Waste Management, but the basic motivation derives from the observation that if the small amounts of Am, Cm Np, and Pu which will be present in the high-level wastes from the Purex flowsheet are removed more completely, the length of time that wastes remain significantly toxic is dramatically reduced. Figure 25 is a flow diagram for a possible advanced process for actinide removal.

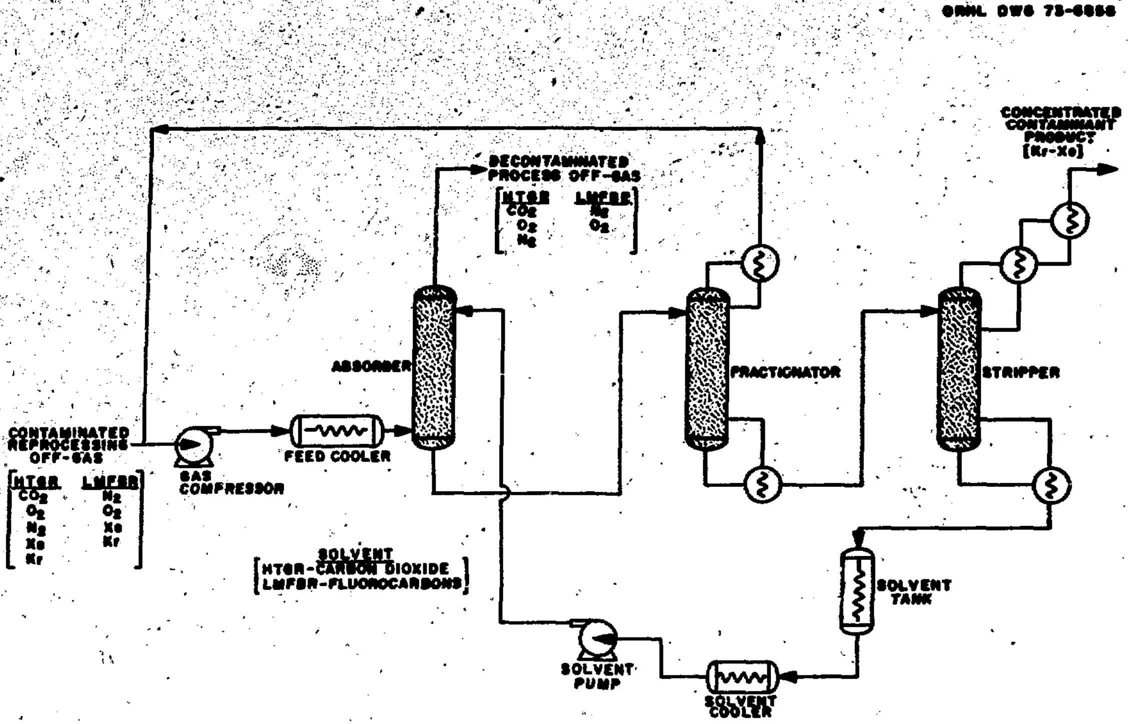


Fig. 24. SELECTIVE ABSORPTION SYSTEM FOR KRYPTON REMOVAL

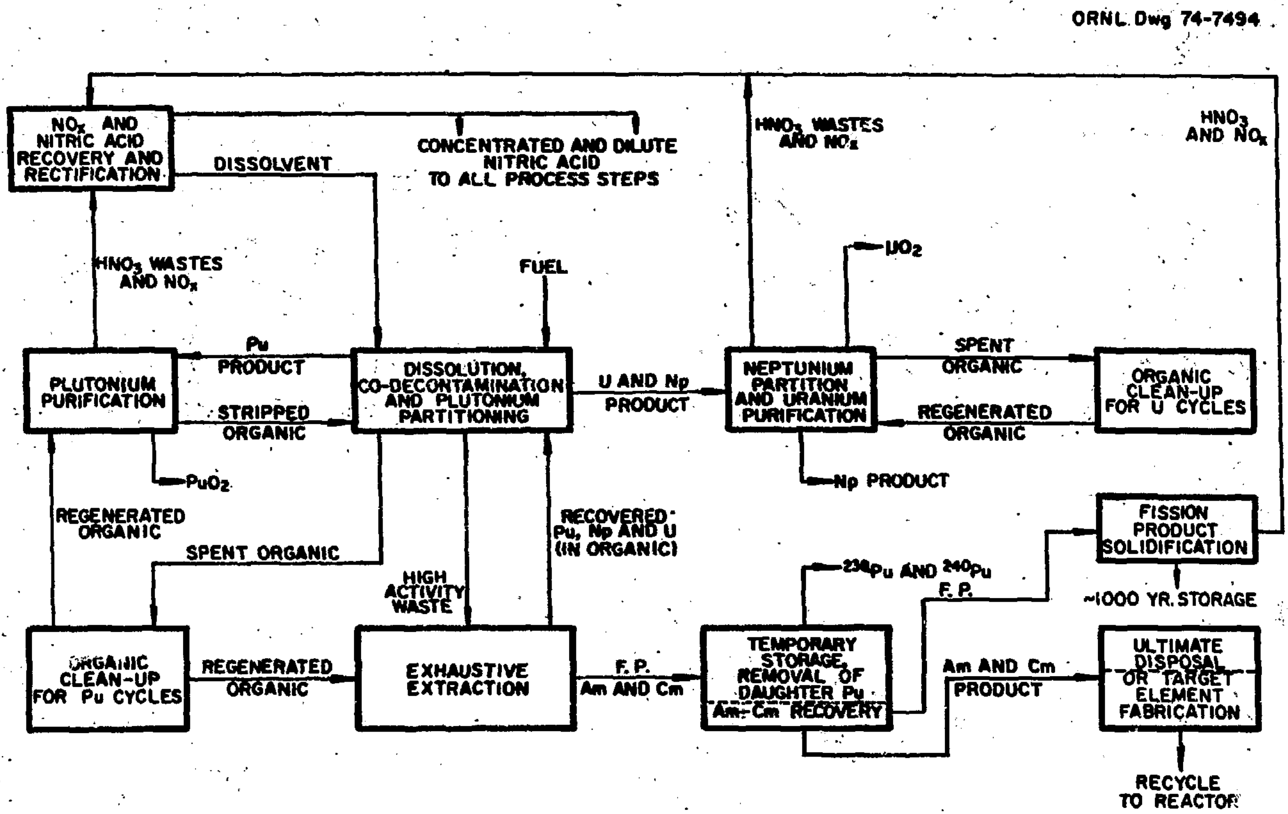


Fig. 25. Flow Diagram for an Advanced Process for Additional Actinides Removal from Plant Wastes

C. Fuel Reprocessing Plant

Figure 26 is a schematic representation of the major processing components in a model LWR fuel reprocessing plant. It is based on current technology, i.e., on process steps which have been demonstrated. The plant decontamination factors for the radioisotopes shown are defined in terms of the ratio of curies or mass of a specified radioisotope which enters the plant to the curies or mass of that radioisotope which leaves the plant. Thus, the in-process time, or plant hold-up contributes to the decontamination factor of the ^{131}I, whose half-life is only about 8 days, while the hold-up has no effect on the 10^7 year half-life ^{129}I. This difference is reflected as a factor of ten in their plant decontamination factors. As can be seen, there is no plant decontamination factor for ^{85}Kr or tritium, because current practice does not remove them. Figure 27 gives at least a little idea of the types of equipment which may be used in the fuel reprocessing operations. Figure 28 shows one concept of part of a fuel reprocessing plant. Because of the extremely radioactive material being handled, heavy shielding is required, and nearly all major operations are carried out totally remotely.

D. Radioactivity Released

A summary of the radioactive waste streams from LWR fuel reprocessing is presented in Table 22. It is planned that no radioactive liquid wastes will be released to the environment at the reprocessing plant. What radioactivity is released will be sent up the plant stack. In order to achieve this goal, a 5-tonne of fuel per day reprocessing plant may vaporize up to 25,000 gallons of water per day. This water vapor will join the true gases from the various plant ventilation and off-gas systems which are also sent to the stack for discharge to the atmosphere.

There is some commercial fuel reprocessing plant operating experience already available which may be taken as a sort of practical baseline in deciding what can be accomplished in effluent cleanup. This experience is from the Nuclear Fuel Services reprocessing plant in West Valley, New York. The plant is presently shut down for modifications and an increase in capacity. The operating experience is shown in Table 23.

E. Costs of Reducing Radiation Doses

There are various modifications and additions to the fuel reprocessing plant which might be made to reduce the amount of radioactivity released. These are presented in terms of annual operating costs and equipment costs in Tables 24 and 25 and Figure 29.

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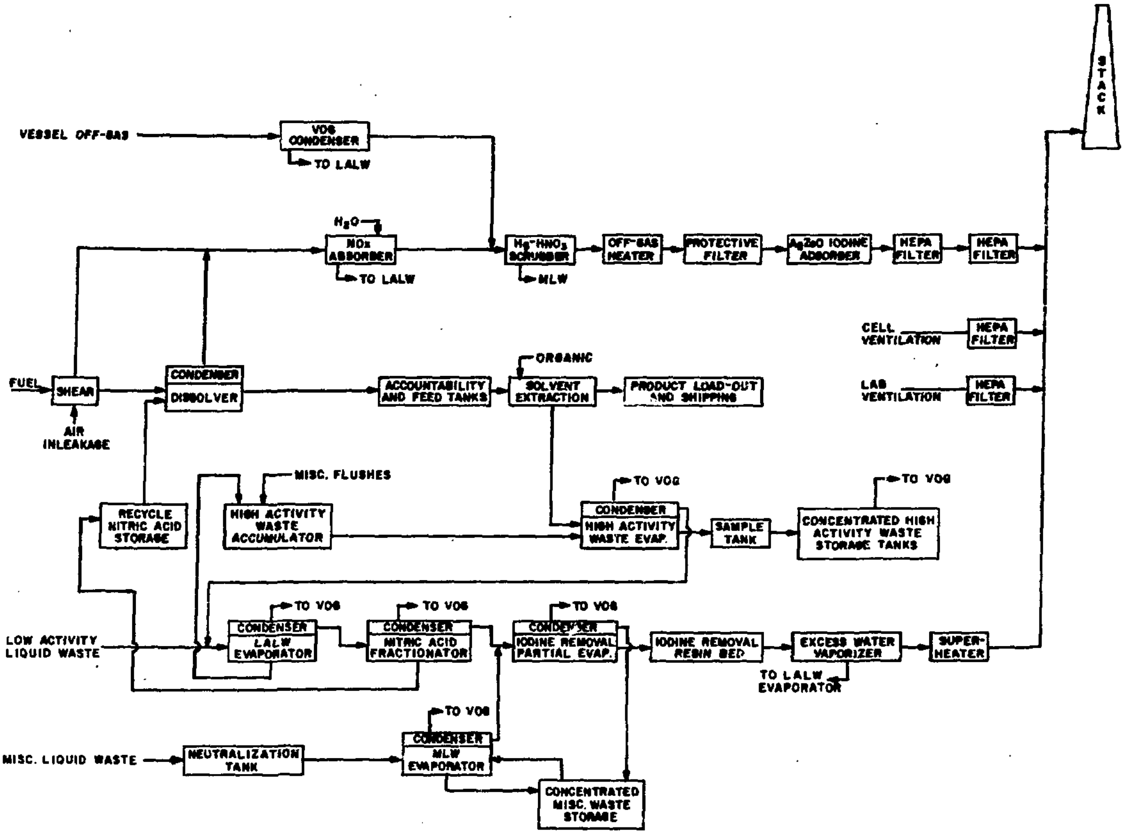

PLANT DECONTAMINATION FACTORS

IODINE-131	7.5×10^2	PLUTONIUM	2×10^8
IODINE-129	7.5×10	URANIUM	5×10^7
KRYPTON-85	1.0	SEMI-VOLATILES	1×10^8
PARTICULATES	5×10^8	TRITIUM	1.0

Fig. 26. Model LWR Fuel Reprocessing Plant

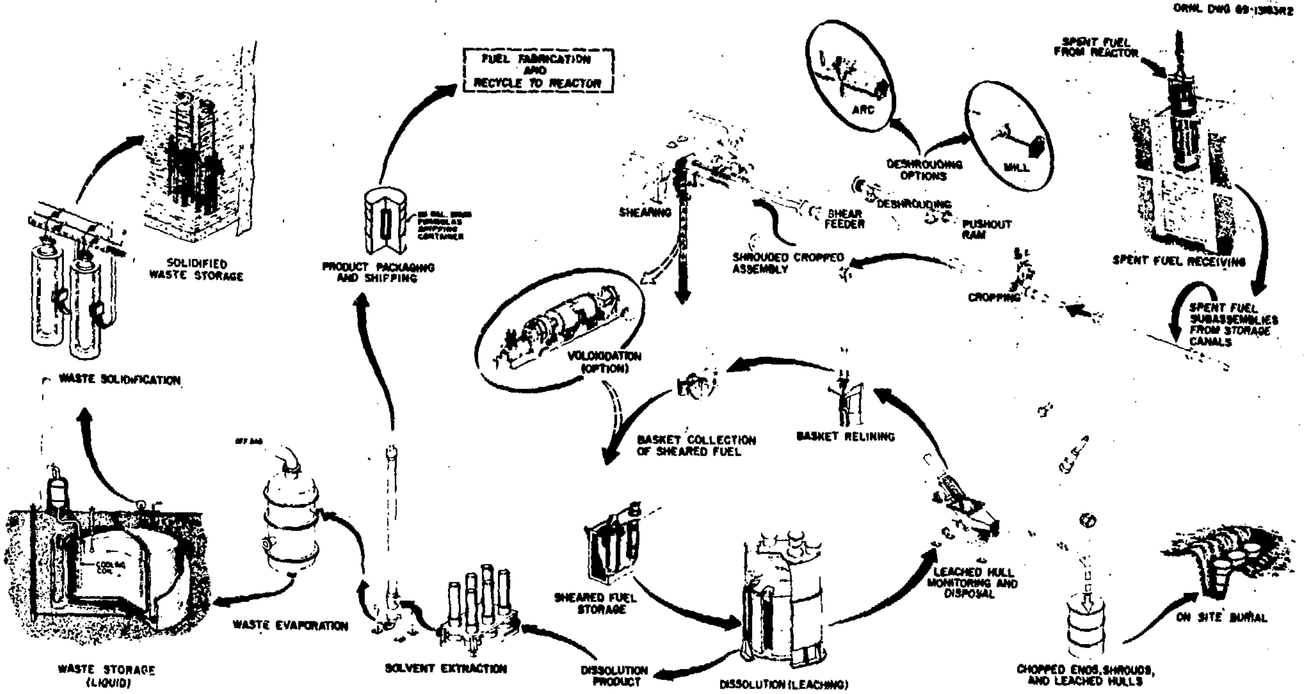

Fig. 27. Pictorial Representation of Typical Spent Fuel Reprocessing Operations

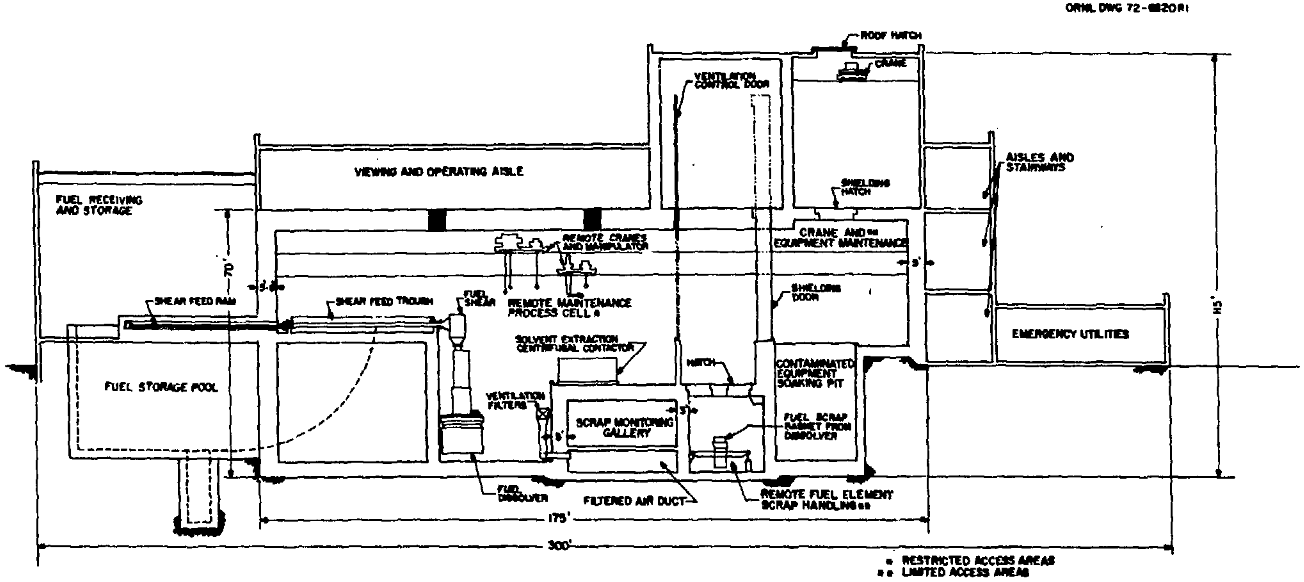

Fig. 28. Cross Section in Elevation of a Representative LWR Fuel Reprocessing Plant.

Table 22

LWR Fuel Reprocessing Radioactive Waste Streams

Item	Type of Radioactive Waste Stream				
	Liquids		Solids		Gases
	High Level	Intermediate Level	Hulls	Process	Stack
1. Source of waste stream	High activity aqueous waste stream – first cycle solvent extraction	Miscellaneous sources – see Fig. 1	Residue after sheared fuel is dissolved	Misc. plant operations, failed equipment	Dissolver off gases and other streams
2. Fission product distribution	99.7	<0.05	<0.1	Very low	<0.1
3. Fission product content	$>10^9$ curies/year	Minor	$>10^7$ curies/year	Minor	10^7 curies/year
4. Acidity and reason	~4M HNO because nitric acid is used to dissolve uranium.	~2M HNO, for compatibility with HLLW	~ neutral	Variable	~ neutral
5. Current legal requirement for storage and disposal	Solidify within 5 yrs after formation; ship off site to Federal repository in < 10 yrs.	None	None[*]	None[*]	None
6. Processing method before storage	Concentration, denitration, dilution to adjust pH	Concentration, denitration to adjust pH	Immerse in HNO_3, rinse monitor, pour into concrete container, attach lid.	Variable	Iodine scrubber and HEPA filter
7. Short-term storage method	Stainless steel tank equipped with extensive cooling system	Stainless steel tank	Locate in soil; compact soil above container.	Locate in trench or container if required.	None
8. Annual volume generated	Up to 450,000 gals. at 300 gal/MTU for 160-day fuel decay	Up to 100,000 gals., depends on maintenance, decontamination.	30,000 ft^3 at 15,000 MTU/yr	105,000 ft^3, depends on maintenance and decontamination work.	---
9. Treatment and handling for long-term storage	Convert to solid; ship to Federal repository	Probably mix with HLLW.	Probably ship[*] to Federal repository ($>10^5$ nCi of TRU/g)	Variable and not specified	None
10. Possible future addition	---		---	Shipment of transuranium waste to a Fed. repository is a possibility	Additional scrubbing and gas-processing

---

[*] A proposed addition to ERDA Manual – Chapter 20,306 (September 1974) states that transuranium (TRU) waste will be solidified (if liquid) as soon as practicable and transferred to ERDA within 5 years of formation. The specific activity of a transuranium waste (e.g., 10 nanocuries per gram) is specified for ERDA facilities is not included in this proposal.

Table 23

NFS FUEL REPROCESSING PLANT EXPERIENCE

Fuel Processed*	1968	1969	1970	1971
Reactor exposure, MWth	5.1×10^5	9.5×10^5	7.2×10^5	7.9×10^5
Gross beta, curies	3.4×10^7	6.4×10^7	4.8×10^7	5.3×10^7
^{85}Kr, curies	1.6×10^5	3.0×10^5	2.3×10^5	2.5×10^5
^{129}I, curies	0.46	0.85	0.65	0.71
^{90}Sr, curies	1.4×10^6	2.6×10^6	2.0×10^6	2.2×10^6
<u>Annual Release, curies**</u>				
Particulates	1.1	0.12	0.18	0.01
^{85}Kr	1.9×10^5	3×10^5	1.8×10^5	2.2×10^5
^{131}I	<0.06	<0.06	<0.06	<0.06

*Based on reactor power data and typical LWR fuel decayed one year.

**Measured effluent data.

Table 24

Summary of Variables for Model Nuclear Fuel Reprocessing Plant[a] Gaseous and Liquid Radwaste Treatment Systems

	Radwaste Treatment Case No.								
	1	2a	2b	3	4	5	6	6c	7
Treatment Objective	Base Case	Reduce iodine release by 10	Reduce iodine release, DF – 10^4	Reduce krypton release by 100	Reduce particulate, uranium and plutonium release by 10	Reduce semi-volatile release by 10	Reduce tritium release by 100	Cumulate reduction of releases, summation of Cases 2 – 6	Further reduction in releases, overall DFs: Iodine – 5×10^6 Krypton – 10^4 Particulates and Semi-volatiles – 10^{12} Tritium – 10^3
				Overall Plant Decontamination Factor[b]					
Iodine-131	750	7500	1×10^4	750	750	750	750	1×10^4	5×10^4
Iodine-129	75	750	1×10^4	75	75	75	75	1×10^4	5×10^4
Krypton-85	1	1	1	100	1	1	1	100	1×10^4
Particulates	5×10^8	5×10^8	5×10^8	5×10^8	5×10^9	5×10^8	5×10^8	5×10^9	1×10^{12}
Plutonium	2×10^8	2×10^8	2×10^8	2×10^8	2×10^9	2×10^8	2×10^8	2×10^9	1×10^{12}
Uranium	5×10^7	5×10^7	5×10^7	5×10^7	5×10^8	5×10^7	5×10^7	5×10^8	1×10^{12}
Semi-Volatiles	1×10^8	1×10^8	1×10^8	1×10^8	1×10^8	1×10^9	1×10^8	1×10^9	1×10^{12}
Tritium	1	1	1	1	1	1	100	100	1×10^3
				Equipment Unit or Function and Flowsheet Reference					
Iodine									
Gaseous	$Hg(NO_3)_2$–HNO_3 scrubber, AgZeO adsorber, HEPA filters	Iodine evolution, $Hg(NO_3)_2$–HNO_3 scrubber, AgZeO adsorber, HEPA filters	Iodine evolution, Iodox, $Hg(NO_3)_2$–HNO_3 scrubber, AgZeO adsorber, HEPA filters	Same as Case 1	Same as Case 1	Same as Case 1	Same as Case 1	Same as Case 2b	Reduced volume net off-gas release, recycle, process and cell off-gas, 2 stages of Iodox, 2 stages of AgZeO adsorbers, HEPA filters
Liquid	Evaporation, iodine removal on resin bed, evaporation and vaporization	Same as Case 1	Same as Case 1	Same as Case 1	Same as Case 1	Same as Case 1	Same as Case 1	Same as Case 2b	Evaporation, iodine removal on resin bed, evaporation and recycle, storage for excess water, no release of water or water vapor
Solid	None	Hg recycle, $NaIO_3$ recovery and storage	Same as Case 2a	Same as Case 1	Same as Case 1	Same as Case 1	Same as Case 1	Same as Case 2b	Isolate NaI for storage
Krypton	None[a]	Same as Case 1	Same as Case 1	Selective absorption	Same as Case 1	Same as Case 1	Same as Case 1	Same as Case 3	Reduced volume net off-gas release, recycle process and cell off-gas, recycle cell off-gas through selective absorption unit
Particulates, Uranium and Plutonium	HEPA filters	Same as Case 1	Same as Case 1	Same as Case 1	HEPA filters, sand filter	Same as Case 1	Same as Case 1	Same as Case 4	Reduced volume net off-gas release, recycle process and cell off-gas, improved filtration efficiency on a small volume of final off-gas
Semi-Volatiles	Acid scrubbers, HEPA filters	Same as Case 1	Same as Case 1	Same as Case 1	Same as Case 1	Acid scrubbers, caustic scrubber, HEPA filters	Same as Case 1	Same as Case 5	Reduced volume net off-gas release, recycle process and cell off-gas, caustic scrubber on process off-gas, improved adsorption efficiency on small volume of final off-gas
Tritium	None[a]	Same as Case 1	Same as Case 1	Same as Case 1	Same as Case 1	Same as Case 1	Voloxidation, recombiner, Drierite, molecular sieve, cold trap, storage	Same as Case 6	Reduced volume net off-gas release, recycle process and cell off-gas, same as Case 6, dry off-gas by cooling to –100°F
Cell Ventilation	HEPA filter	Same as Case 1	Same as Case 1	Same as Case 1	HEPA filter, sand filter	Same as Case 1	Same as Case 1	Same as Case 4	Recycle, no release
Lab Ventilation	HEPA filter	Same as Case 1	Same as Case 1	Same as Case 1	HEPA filter, sand filter	Same as Case 1	Same as Case 1	Same as Case 4	HEPA filter, roof vents

---

[a] Model nuclear fuel reprocessing plant has a nominal capacity of 1500 metric tons per year; reference fuel is 3.3% enriched uranium irradiated at an average specific power of 30 MW/metric ton to an exposure of 33,000 MWd/metric ton and decayed 160 days. No credit is taken for decay during processing. All gaseous and water vapor releases are discharged through a 100-meter stack.

[b] Decontamination factor (DF) is amount entering plant/amount released in waste effluents.

Table 25

Estimated Annual Costs, Reprocessing Cost, and Contribution to Power Cost for the 1500-Metric Ton/Year Model Fuel Reprocessing Plant and Radwaste Treatment Cases
(Adapted from Table 6.1 of ORNL-TM-4901, May 1975)

Radwaste Treatment Case	Capital Cost[a] ($1000)	Annual Fixed Charges ($1000)	Annual Operating Cost[b] ($1000)	Total Annual Cost ($1000)	Reprocessing Cost[c] [$/kg(U)]	Contribution to Power Cost[d] (mills/kWhr)
1[e]	base cost	---	---	---	---	---
			Additional Cost for Radwaste Treatment Systems			
2a	753	196	78	274	0.18	0.000711
2b	2,071	538	215	753	0.50	0.00196
3	3,871	1,006	403	1,409	0.94	0.00366
4	1,059	275	28	303	0.20	0.000786
5	340	88	35	123	0.08	0.000319
6	2,744	713	285	998	0.67	0.00259
6c	10,085	2,622	1,049	3,671	2.45	0.00954
7[f]	125,000	32,500	13,000	45,500	30.33	0.12

[a] System and structure capital cost consists of direct and indirect cost. The interest during construction is included as an indirect cost.

[b] Annual operating costs are estimated at 40% of annual fixed charges with the exception of the sand filter in Case 4 which is estimated at 10%.

[c] The reprocessing cost equals the annual cost divided by the 1.5×10^6 kg per year of uranium charged to the reactor.

[d] The contribution to power cost is computed on the basis of a 1500-metric ton/year reprocessing plant servicing a nuclear economy of fifty-five 1000-MW(e) LWRs (irradiation level, 33,000 MWd/metric ton; load factor, 80%; thermal efficiency, 32.5%). The costs include the direct charges but do not include the effect of carrying charges on fuel working capital.

[e] Case 1, the base case, represents a complete model nuclear fuel reprocessing plant which produces uranium nitrate and plutonium nitrate products and stores high-level liquid waste. Radwaste treatment Cases 2a-6 are additions to the base case. The total capital cost for Case 6c is the cost of Case 1 plus the cost of Cases 2b through 6.

[f] Case 7 represents the advanced concept of a "near zero release" plant. The capital cost is taken as twice the base case. The difference in the capital cost between the base case and Case 7, $125,000,000, is taken as the added cost of radwaste treatment for Case 7 as compred to Case 1.

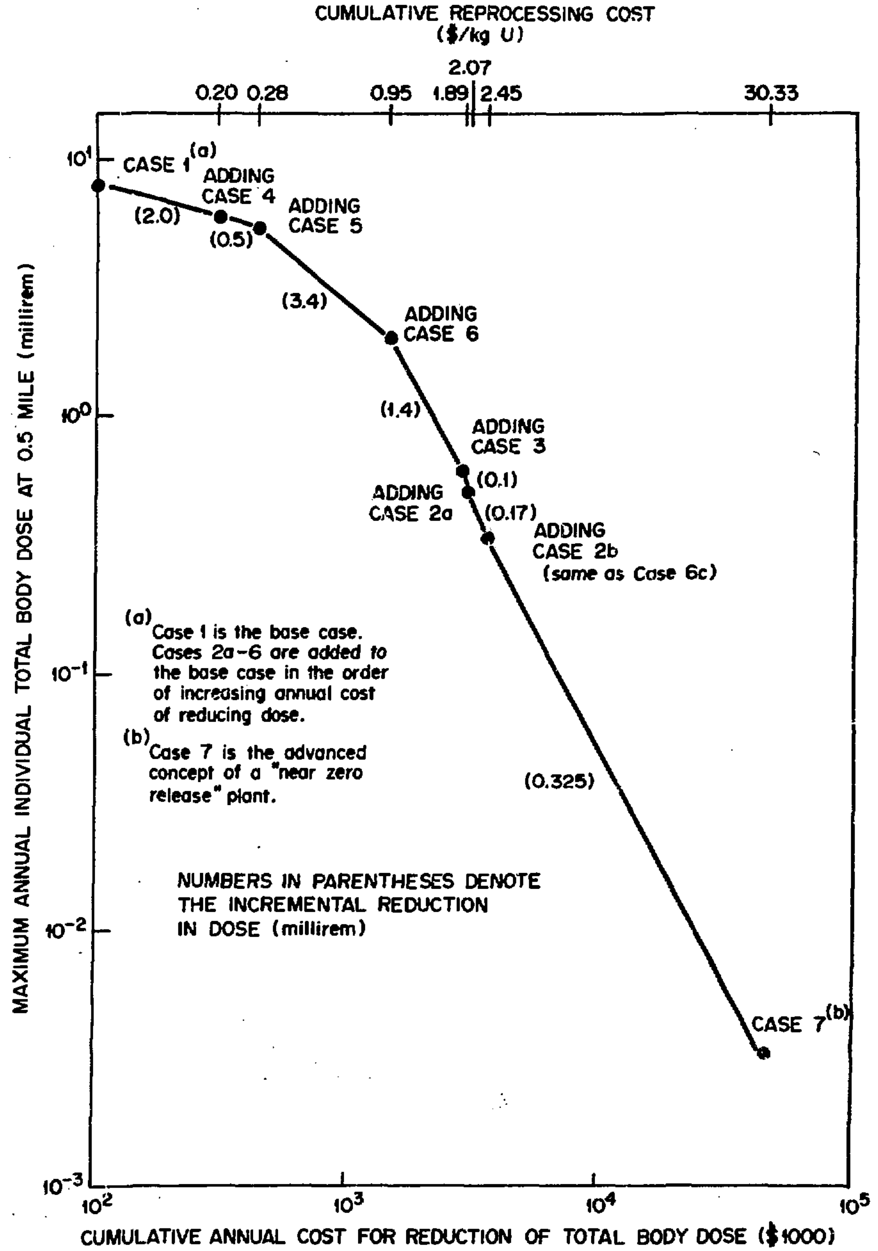
CUMULATIVE REPROCESSING COST
($/kg U)
0.20
0.28
0.95
1.89
2.07
2.45
30.33
CASE 1(a)
ADDING CASE 4
ADDING CASE 5
ADDING CASE 6
ADDING CASE 3
ADDING CASE 2a
ADDING CASE 2b (same as Case 6c)
CASE 7(b)
(2.0)
(0.5)
(3.4)
(1.4)
(0.1)
(0.17)
(0.325)
(a)Case 1 is the base case. Cases 2a-6 are added to the base case in the order of increasing annual cost of reducing dose.
(b)Case 7 is the advanced concept of a "near zero release" plant.
NUMBERS IN PARENTHESES DENOTE THE INCREMENTAL REDUCTION IN DOSE (millirem)
MAXIMUM ANNUAL INDIVIDUAL TOTAL BODY DOSE AT 0.5 MILE (millirem)
10^1
10^0
10^-1
10^-2
10^-3
10^2
10^3
10^4
10^5
CUMULATIVE ANNUAL COST FOR REDUCTION OF TOTAL BODY DOSE ($1000)

Fig. 29.

VII. TRANSPORTATION

The wide variety and levels of radioactivity of the nuclear materials transported lead to a wide range of solutions to the problems presented. Thus, there is the low-activity-level (but relatively high-bulk) milled ore which is shipped to the conversion plant on the one hand, and the intensely-radioactive (but relatively low-bulk) high-level radioactive waste which must be shipped to a waste repository on the other. Between these extremes are solids, gases and liquids of various volumes and radioactivity levels: spent reactor fuel; natural and enriched UF_6; fabricated fuel elements; fission product gases, e.g., ^{85}Kr; and solutions of fission products. Methods of transportation of these materials depend on volume, weight and radioactivity levels, and include shipment by truck, rail, air and water. Packaging is similarly related to size, weight, physical form, and radiation level.

The subject of safeguards, which is intimately related to transporting nuclear materials, will not be discussed here. Safeguards has to do with the protection and accountability of fissile materials, wherever they are. Certainly one of the most important steps in the fuel cycle from the point of view of safeguards is that of transportation of the fissile materials. However, the subject of safeguards is very complex and has both subjective and objective components. Many of its problems are not even clearly defined, let alone solved. There are, in fact, potential solutions to some of the safeguards problems which might effectively remove much of the subject of radioactive materials transport from consideration. These involve the relation of transportation to siting, and involve collecting several fuel cycle operations on a single site. The implications of the safeguards problems are important enough that the subject merits special and separate discussion beyond the brief mention of them in this essay.

All the activities of man are subject to accidents, that is, to the unexpected or unanticipated adverse happening. Transportation is no exception, and in fact, includes our best known, most widely publicized examples of accidents. So some mention of accidents is in order. Since by their nature they are random events, accidents are best discussed statistically and probabilistically, and such a treatment is beyond the scope of this essay. However, the subject will be mentioned briefly later.

The nuclear fuel cycle encompasses major processes and facility operations which are directly related to and necessary for power production using nuclear reactors. Materials transportation connects the fuel cycle steps. Figure 30 is one of many representations of the way the nuclear fuel cycle steps are related. It pertains to the fuel cycle for light water reactors, and includes recycle of plutonium, which is an important element in the long-term commercialization of nuclear power. As intimated above and mentioned briefly later, collecting several of these steps--especially fuel reprocessing and fabrication--onto a single site would have a profound effect on the need for and nature of the transportation operations.

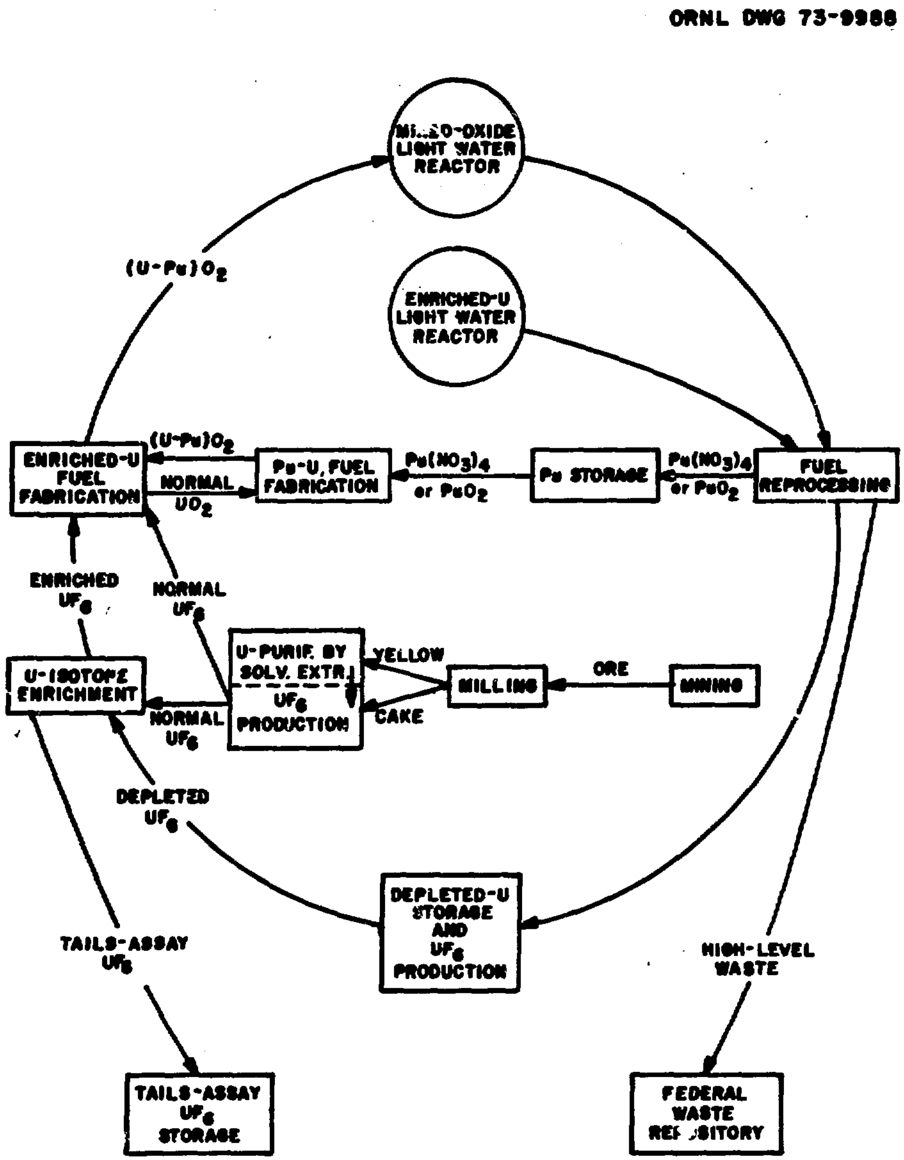

Fig. 30. The LWR Nuclear Fuel Cycle (Showing Plutonium Recycle).

At present the nuclear fuel cycle in the U.S. is devoted virtually solely to light water reactors (LWRs). There is a small component of reactor fuel cycle work devoted to high-temperature gas-cooled reactors (HTGRs) which may become significant over the next several decades. The essential differences between the LWR and HTGR fuel cycles derive from the use of thorium and highly enriched uranium (~90% ^{235}U) in HTGRs [instead of the slightly enriched uranium (2 to 5% ^{235}U) in LWRs], and the planned recycle of ^{233}U (produced from the thorium) to augment the ^{235}U [instead of ^{239}Pu (produced from the ^{238}U) to augment the ^{235}U which is planned for LWRs]. Table 26 summarizes transportation operations in the nuclear fuel cycle.

If nuclear power is to be a major factor in the nation's economy over a large number of years, then the breeder reactor must be developed. The essential new element introduced by the breeder is the use of plutonium rather than uranium as the primary fissile material (assuming that the breeder chosen operates in the uranium-plutonium cycle). The impact of the breeder on the nuclear fuel cycle is felt in the greatly reduced amount of uranium which must be handled in mining and in the subsequent steps leading to enriched uranium production for each unit of power produced. Thus, transportation requirements in related fuel cycle steps would be proportionately lessened. Conversely, there is the increased requirement for plutonium processing and shipment.

(It should be remembered that a successful long-term nuclear power industry will entail plutonium processing and transporting even with the LWR, which produces about a fourth as much plutonium as the ^{235}U it consumes.)

Finally, there are two important facts to consider in regard to near-term transportation in the nuclear fuel cycle: (1) While there are a number of LWR fuel fabrication plants in operation and under construction, there is no operating commercial fuel reprocessing plant in the U.S., nor will there by for one, and perhaps not for two or three, years. Further, the reprocessing plant likely to come on stream first (the Allied-General Nuclear Services plant) will be too small to handle the projected LWR fuel reprocessing load virtually the day it opens its doors for business. The implication of this fact with regard to transportation is that there are likely to be interim spent fuel storage facilities required to which the spent fuel must be shipped from the reactors when their reserve storage areas are full. (2) There is at present no available way to dispose permanently of high- and intermediate-level commercial solid radioactive wastes. Only interim tank storage of liquid wastes is possible at the present time. It appears that the solution to this problem is 5 to 10 years away. The implication of this fact with regard to transportation is that high-level solid waste shipments will likely start with a surge rather than more slowly, and more nearly in step with the growth of the nuclear industry. This appears likely because of the immediate necessity to relieve the constipation which will have occurred in the disposal of wastes by the time permanent disposal is possible.

A. Uranium Concentrate

Table 26

Transportation of Radioactive Materials in the Nuclear Fuel Cycle

Radioactive Material	Point-to-Point Movements	Mode of Transport	Required Packaging
Uranium or thorium ore	Mine to mill	Open truck	None
Ore concentrates (Uranium or thorium products)	Mill to refining and conversion plant	Truck	Drums
Thorium nitrate[a]	Refining plant to materials processing plant	Truck	Drums
Natural UF_6	Refining and conversion plant to enrichment plant	Truck	Pressurized cylinders
Enriched UF_6	Enrichment plant to materials processing plant	Truck	Pressurized cylinders and protective packaging
Uranium (233[a] or 235) or plutonium oxides[b] (fissile)	Materials processing plant (or fuel reprocessing plant) to fuel fabrication plant (may be at same site)	Truck (if offsite)	Steel pails or sealed metal cans within gasketed steel containers supported inside steel drums
Thorium oxide[a] (fertile)	Materials processing plant to fuel fabrication plant	Truck	Drums
New fabricated fuel assemblies	Fuel fabrication plant to nuclear power reactors	Rail[c] or truck	Special fuel element shipping containers
Transuranic wastes	Fuel fabrication plant (or mixed oxide fuel reprocessing plant) to Federal repository[d,e]	Rail[c] or truck	Drums and protective packaging
Irradiated fuel	Nuclear power reactor to fuel reprocessing plant	Rail[c] or truck	Specially designed and approved shielded casks
Recovered thorium[a]	Fuel reprocessing plant to storage	a	a
Recovered enriched UF_6 (recycle)	Reprocessing plant to enrichment plant (or materials processing plant)	Truck	Pressurized cylinders and protective packaging
Recovered uranyl nitrate	Fuel reprocessing plant to fuel fabrication plant or conversion plant (or materials reprocessing plant)	Tank trucks or tank cars	Protective packaging
High-level solid wastes	Fuel reprocessing plant to Federal repository[d]	Rail[c] or truck	Specially designed and approved shielded casks
Low- and intermediate-level wastes (beta-gamma)	From essentially all parts of the fuel cycle to commercial burial grounds	Truck	Drums and protective packaging

---

[a] To the present there has been limited experience in shipping uranium-233 and thorium compounds; this will become important if a large number of HTGRs become operational.

[b] To the present there has been limited experience in shipping plutonium compounds; this will become important when plutonium recycle in LWRs and LMFBRs is in wide use.

[c] Trucking to railhead may be necessary.

[d] The federal repository is at present nonexistent.

[e] Currently shipped to burial grounds.

Uranium mines and mills are generally located on a single site, or near each other, so transportation between mine and mill is confined to short distances. However, transport of the uranium concentrate from the mill to the conversion plant involves large distances. Since the mines and mills are in the western states, and the refineries and conversion plants are in the Midwest, it is clear that long shipping distances are involved. However, since it is natural uranium that is being shipped, there is little or no problem caused by radioactivity during shipment. As is apparent from the fact that uranium ore averages about 0.21% U_3O_8, while concentrate is 98% (or greater) U_3O_8, by far the largest amount of material is transported (on-site) between mine and mill. The U_3O_8 (or diruanate) concentrate is packaged in standard 55 gallon drums for shipment by truck or rail to the conversion plant.

uranium conversion plants

Uranium conversion plants (refineries) convert the relatively impure concentrate from the mill to a very pure uranium hexafluoride product suitable for use in enrichment plants.

The recent trend is to combine the fluorination step with the solvent extraction step at the refinery (or to eliminate solvent extraction altogether, as with the dry hydrofluor process.) Thus, the two types of refineries are not so very different today, and the shipping problems are tending to become virtually the same, namely those associated with shipping UF_6. There is also a move in the direction of putting UF_6 production steps at the fuel reprocessing plants as the last step prior to shipment of the recovered uranium (which may still be more enriched in ^{235}U than the enrichment plant "tails") to the enrichment plant. So it is apparent that shipment of UF_6, both as natural and as enriched uranium is assuming ever-increasing prominence in the nuclear fuel cycle. Figure 31 shows typical natural uranium UF_6 shipping containers.

B. UF_6 To and From Enrichment Plants

As Fig. 32 suggests, UF_6 may be shipped both to and from the uranium isotope enrichment plants. The physical properties of UF_6 are such that at usual ambient temperatures the UF_6 may be either gaseous or solid, depending on the pressure. Under ordinary conditions of shipment it is solid. (If it is vented to the atmosphere it reacts with moisture in the air to form uranyl fluoride and hydrofluoric acid.) Either normal, slightly depleted, or very slightly enriched uranium may be received at the gaseous diffusion plant, depending on whether the uranium has been freshly mined or is being recycled from a fuel reprocessing plant. The ^{235}U content of the entering recycled uranium will depend on the specific reactor type and recycle mode employed. Low-enrichment (2-4%) or high-enrichment (~90%) uranium as UF_6 may be shipped from the enrichment plant. Since the standard shipping containers hold either 10 or 14 tonnes of UF_6 (natural uranium), or 2-1/2 tonnes UF_6 (>5% enriched uranium), the number of shipments may be estimated. Beyond the shipments indicated above, there is at present interplant shipment among the Oak Ridge, Paducah and Portsmouth enrichment

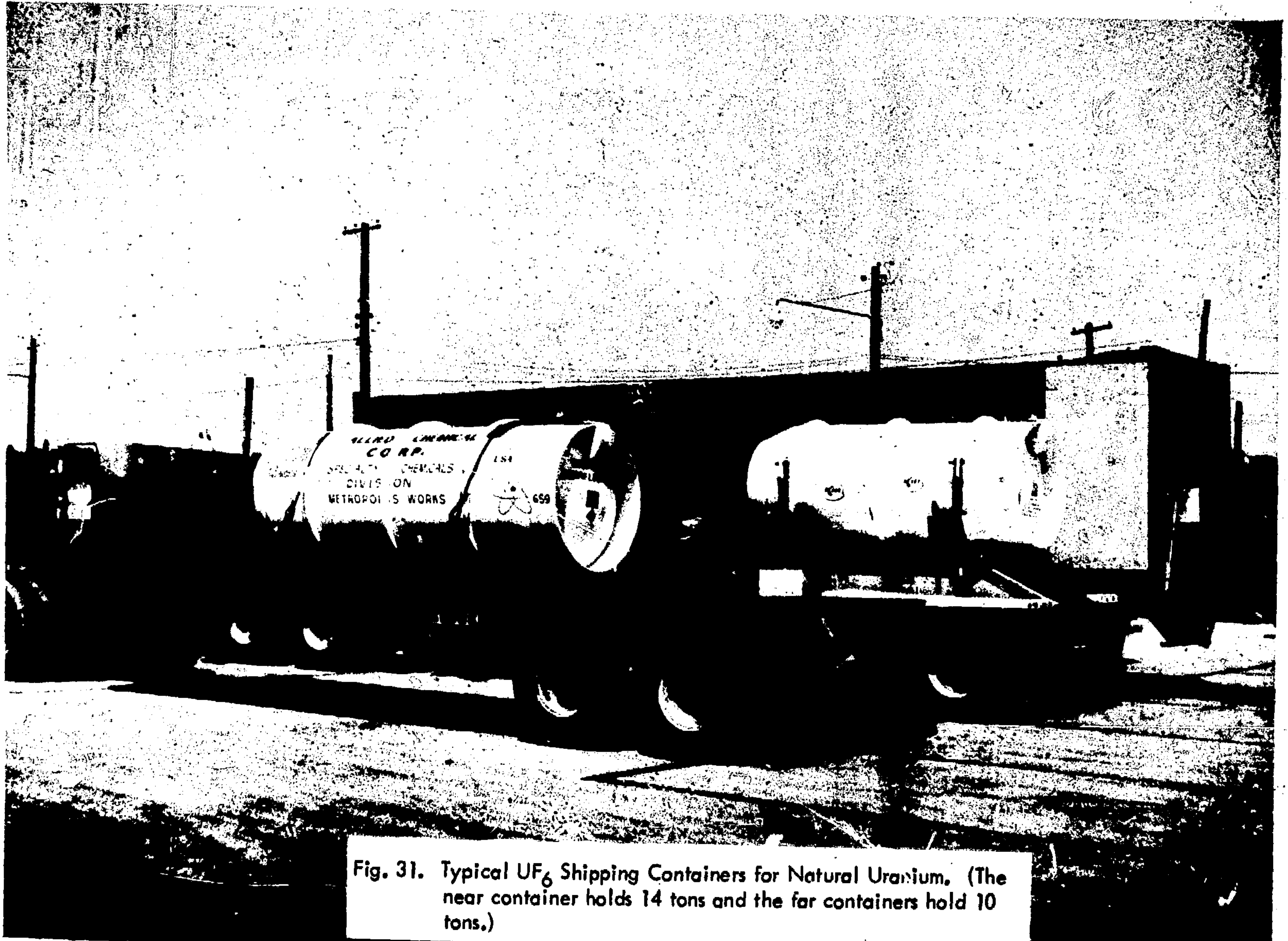

Fig. 31. Typical UF_6 Shipping Containers for Natural Uranium. (The near container holds 14 tons and the far containers hold 10 tons.)

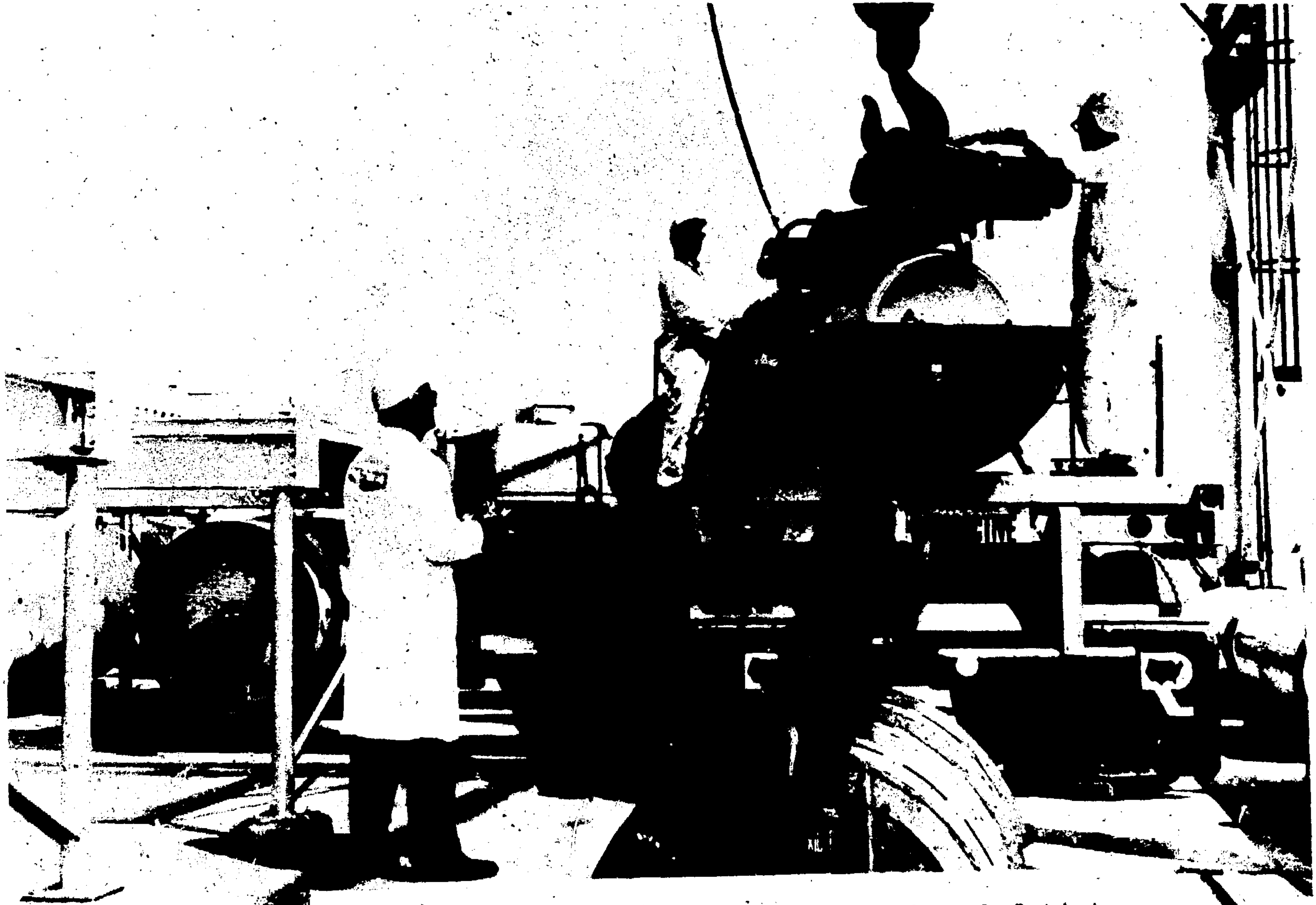

Fig. 32. Typical UF_6 Shipping Container and Protective Carrier for Enriched Uranium. (Capacity: 2 1/2 tons of $\leq$ 5% Enriched UF_6.)

plants.

C. Fabricated Fuel

The uranium received at the LWR fuel fabrication (usually as UF_6) is converted to pellets of UO_2 which are usually 2 to 4% enriched in ^{235}U. The pellets are loaded into metals tubes of an alloy of zirconium (which has a low thermal neutron absorption cross section), which are in turn assembled into fuel assemblies. These fuel assemblies are shipped to the reactors. The number of assemblies required for a reactor core depends on the type of reactor. Typically, a 1000 MWe PWR requires 193 assemblies, while a 1080 MWe BWR requires 764 assemblies.

Use of recycled plutonium in LWRs would require shipping plutonium (required by regulation to be as PuO_2 after June 17, 1978) from the fuel reprocessing plant to the fuel fabrication plant. The amount of plutonium shipped from the reprocessing plant to the fabrication plant would be about one-third the amount of ^{235}U shipped from the enrichment plant to the fabrication plant, so a plutonium shipping requirement would exist. (However, since the uranium would be, on the average, only about 3% ^{235}U, whereas plutonium is roughly equivalent to 60-70% enriched uranium, the relative masses of plutonium to uranium would be of the order of 1 to 70.)

[To avoid shipping pure PuO_2, with its attendant safeguards problems, it has been suggested that the uranium and plutonium be mixed at the reprocessing plant before shipment to the fabrication plant. This would reduce the fissile material (Pu plus $\leq$ 1% enriched U) content of the material to be shipped to a level well below that which could be used for making an explosive device. It would, however, somewhat complicate the fuel fabrication steps, which more and more are based on receiving UF_6, not a mixture of uranium and plutonium oxides which may prove to be difficultly soluble, and which would require a difficult assay of total fissile material content prior to fabrication.]

Fabricated fuel (with the exception of possible future HTGR recycle fuel) is relatively non-radioactive, and the transportation problems associated with it are more those of protecting it from damage than protecting the public from it. (HTGR recycle fuel is an exception, since it will contain ^{232}U, whose decay chain daughters are intensely radioactive, requiring heavy shielding.) There will be, however, a small amount of neutron emission, especially from future LWR recycle fuels which contain plutonium. Care will be necessary to protect workers from the neutron radiation. Because of the value of the fabricated fuel assemblies, only two are entrusted to a single container, and the containers are carefully packaged in shock-absorbant carriers. Figure 33 shows a typical shipping arrangement for fabricated LWR fuel assemblies. These fabricated fuel containers are shipped mainly by truck.

D. Spent Fuel and Reprocessing Wastes

Reactors will ship their spent fuels to the reprocessing plants where the uranium and plutonium (and thorium) will be separated from fission products and made available for fuel

Fig. 33. Fabricated LWR Fuel Assembly Shipping Containers.

fabrication. Fuel element burnup (a measure of the fraction of fissile material that has been consumed), decay time (the time between discharge from the reactor and shipment to the reprocessing plant) and size determine the nature of this transportation problem. Besides spent fuel shipments, other major transportation considerations at the reprocessing plant are those associated with the separated fission products and fertile and fissile materials.

1. Spent fuel

Transportation of spent fuel from the reactor to the fuel reprocessing plant is a major step in the nuclear fuel cycle. The fuel is laden with radioisotopes which necessitate both heavy shielding and very high integrity containment. The nature of the problem is such as to require a major expenditure of money to produce a container which is acceptable for shipping a single spent fuel assembly, and only a fractional cost increase is required to produce a container which will accommodate additional assemblies. Thus, there is a strong incentive to produce a container, or cask, which holds as many assemblies as possible. Opposing this incentive for increased size is the fact that each additional assembly imposes a requirement for additional shielded volume, i.e., for additional weight. There comes a point where the cost of the handling equipment for the cask, as well as its sheer size and weight, limit the number of assemblies that it is practical to transport in a single carrier. In general, this limit is reached at a size beyond the load limits for trucks, necessitating rail shipment. However, about half the reactors are without rail siding, so truck-rail (intermodal) shipments are required. Figure 34 shows a typical carrier for LWR fuel. Shipping containers may carry up to 10 PWR fuel assemblies or up to 24 BWR assemblies, and weigh up to 100 tons or more. The total amount of fuel material or fission products per cask is about the same for both PWR and BWR, even though the number of assemblies differs by a factor of about two to three in the sizes of their assemblies. Table 27 summarizes shipping modes for spent fuel shipping casks. Table 28 summarizes the status of spent fuel transportation equipment.

An additional factor to consider in the shipment of spent fuel is the heat that is generated by the fission product decay. In general, this is not a serious problem with LWR fuel, amounting to up to about 10 kw per PWR assembly, and 5 kw per BWR assembly at the time of shipment. [The problem of heat production may be quite important in the case of LMFBR fuel, where it is proposed that shipping take place after much shorter decay times than those used for LWRs (perhaps as low as 90 days or less vs the 150 days to nearly a year of decay planned for LWRs).]

The accidental release of fission products during shipment of spent fuel must be guarded against carefully. Apart from consideration related to safeguards, there is perhaps no part of the nuclear power fuel cycle with greater potential to cause a serious threat than that of spent fuel shipment. For this reason elaborate precautions are taken in cask design and construction. Further, extensive testing procedures are prescribed and carried out on casks and their prototypes to ensure structural

Table 27

Spent Fuel Shipping Cask Transportation Modes

Capacities and Dimensions	Mode of Transportation				
	Legal Weight Truck	Overweight Truck	Rail	Water	Intermodal (heavy haul to railhead)
Cask capacity, assemblies	1 PWR or 2 BWR	2-3 PWR or 4-7 BWR	10 PWR or 24 BWR	10 PWR or 24 BWR	10 PWR or 24 BWR
Loaded weight, tons	25 (max.)	30-40	100	--	--
Overall dimensions	4' diam x 19'	5' diam x 19'	8' diam x 19'	--	--
Vehicle dimensions	8' x 55'	8' x 55'	10.5' x 75'	10' x 105'	10' x 105'
Gross vehicle weight, tons	36.5	45 to 55	200	175	175
Shipping package dimensions	--	--	--	10' x 40' x 13' high	10' x 40' x 13' high

Taken from Proceedings of the Third International Symposium on Packaging and Transportation of Radioactive Materials, "Spent Fuel Transportation - State of the Art," by R. W. Peterson, CONF-710801, Vol. 1, pp. 415-436 (August 1971).

Table 28

Spent Fuel Transportation Equipment Status--December 1974

OWNER	CASK DESIGNATION	CAPACITY FUEL ASSY'S	CASK WEIGHT-LB	MODE OF TRANSPORT	LICENSE STATUS	OPERATIONAL STATUS	PRIMARY COOLANT	FAILED FUEL CAPABILITY	REDUNDANT YOKE
G. E.	IF-100	1 PWR/4 BWR[1]	45,000	LWT[3]	Issued	3 Units Operating	Water	No	No
G.E.	IF-200	2 PWR/4 BWR[2]	55,000	OWT[3]	Issued	3 Units Operating	Water	Yes	No
NFS	NFS-4	1 PWR/2 BWR	48,000	LWT	Issued	2 Units Operating	Water	Yes	No
NAC	NAC-1	1 PWR/2 BWR	48,000	LWT	Issued	4 Units Available	Water	Yes	No
NLI	NLI 1/2	1 PWR/2 BWR	48,000	LWT	Issued	1 Unit Operating 2 More Mid'75	Air-He	Yes	Yes
NFS	NFS-5	2 PWR/4 BWR	51,000	LWT	Application submitted 6/73	Unknown	Water	Yes	No
Trans-Nuclear	TN-8	3 PWR	80,000	OWT	Issued	2 Units Under Construction	Air-He	Yes	No
Trans-Nuclear	TN-9	7 BWR	80,000	OWT	Issued	2 Units Under Construction	Air-He	Yes	No
G.E.	IF-300	7 PWR/17 BWR	140,000	Rail/Water	Issued	4 Units Operating, 2 More Ordered	Water	No	Design Completed None Ordered
NLI	NLI-10/24	10 PWR/24 BWR	200,000	Rail/Water	Fall '75	18 Units Under Construction	Air-He	Yes	Yes

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[1] 138" Maximum Length -- No Neutron Shielding.

[2] 140" Maximum Length -- No Neutron Shielding.

[3] LWT means legal weight truck; OWT means overweight truck.

Taken from Proceedings of Joint Topical Meeting on Commercial Nuclear Fuel Technology Today, "Shipment of Spent Fuel and Recovered Products," by Reuben W. Peterson, CNS ISSN 0068-8517, and 75-CNA/ANS-100 (April 28-30, 1975).

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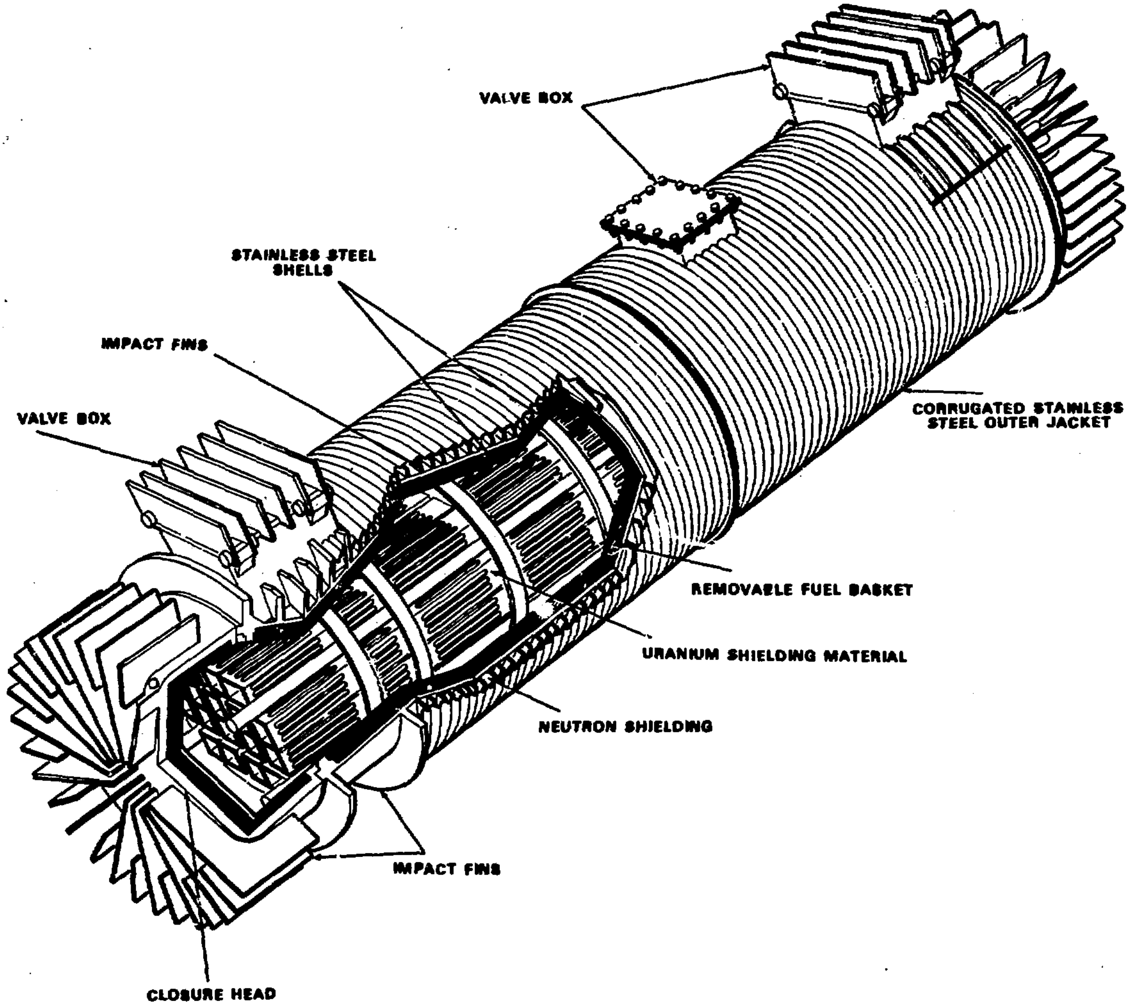

Fig. 34. Typical Spent LWR Fuel Cask for up to 10 PWR or up to 25 BWR Fuel Assemblies

integrity and virtual infallibility of sealing devices for the few openings such casks have. These tests include several kinds of impacts, in addition to stringent fire and water resistance tests. Also, extensive analyses of the likely consequences and remedial actions associated with accidents are carried out, and Nuclear Regulatory Commission approvals are required.

2. Reprocessing wastes

After fuel reprocessing, the fission product wastes solutions may be stored in underground tanks for up to five years before solidification preparatory to shipment to a federal repository. There is at present no federal repository for waste, and (as mentioned earlier) no commercial fuel reprocessor for spent fuel. Nonetheless, the broad outlines of how the wastes will be handled are clear, and certainly the amounts of waste to be handled can be predicted accurately from an assumed size of nuclear power industry and relative number of power reactor types, i.e., LWR, HTGR and LMFBR. The size of container used for storing these wastes will be set by the rate of heat release during the first few years of storage, as well as by the nature of the storage facility and of the shielded carrier. The containers will have to be shielded for shipment, and shipment may be by truck or rail. Since they are not to be re-opened, the inner containers may be welded shut before shipment, and it is extremely unlikely that any accident could breach the containment and release the fission products during transport. It is more likely that a container might lose shielding during an accident, but this too is not probable, and even if it occurs, appears to be a manageable problem. A typical waste storage inner container, may be a 12-inch-diameter cylinder about 10 feet long. About ten such cannisters may be required to hold the high-level waste from a year's operation of 1000 MWe reactor. Figure 35 shows a possible arrangement of such cannisters and their shipping cask.

E. Relationship of Shipping to Siting

The locations of the various parts of the fuel cycle with respect to each other are very important in determining the nature of the transportation problems. Because the mine and mill are always near each other, the great bulk of ore need not be shipped far before it is concentrated over 100-fold. The concentrate is not a radiation hazard, and is of relatively low value, so its transport to the conversion plant is not a significant shipping problem. Further, shipment of natural uranium as UF_6 does not appear to pose many problems, though as has been pointed out, there will be quite a significant amount of this material shipped annually.

Extraordinary attention and precautions are required when uranium enriched to a level suitable for making weapons is shipped, or when plutonium is shipped. Special treatment and handling are also required when highly radioactive materials, such as spent fuel assemblies or high-level wastes, are shipped. If, for example, reactors, fuel reprocessing plants, and fuel fabrication plants were all on the same site, both spent fuel shipment and undiluted plutonium shipment off-site would be obviated. However, while this arrangement would take care of

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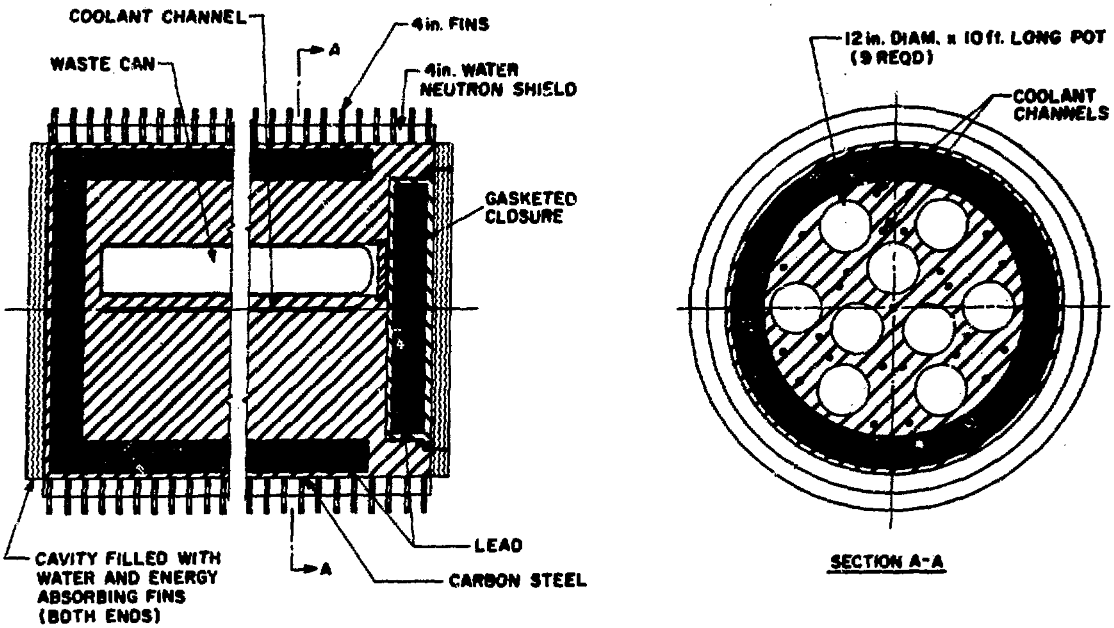

Fig. 35. Schematic Representation of a Possible High-Level Waste Storage Cannister and Shielding Shipping Cask Arrangement.

many of the potential shipping problems, it would create problems of its own. One of the most important problems is that a five tonne per day fuel reprocessing plant, which is the size plant under construction by Allied-General Nuclear Services, and being planned by Exxon Nuclear (and is about the minimum size planned for future plants) will take care of fuel from about 55 LWRs. Locating this many reactors on a single site would pose rather enormous problems of electrical energy distribution, and perhaps also of waste heat dissipation. There would also have to be a high-level waste solidification plant on-site, but this is no different from the requirement for any large fuel reprocessing plant. A more reasonable approach appears to be to locate only the reprocessing and fabrication operations on a single site. This would necessitate spent fuel and fabricated fuel shipment, but would minimize plutonium shipment. Table 29 compares transportation requirements in the year 2000 for dispersed versus co-located fuel recycle facilities. Co-location of reactors with the recycle facilities is not included. The reactors are considered to be distributed about the country near the load centers, as they are today.

F. Transportation Accidents

The subject of transportation accidents is complex, and deserves a separate essay devoted solely to it. Nevertheless, some mention of accidents is in order. Because accidents are by their nature statistical, there is always an element of uncertainty about them, and despite the odds against one occurring, a critic can always say "Yes, I know the odds are very large against one, but what if one happens?" Such questions may lead to subjective responses and to expensive and even unreasonable precautions.

There is a fair body of statistical information on rail and truck accidents. This information may be used to calculate the probable frequency and severity of accidents during the transport of the most important materials in the nuclear fuel cycle. The usual measures of severity of an accident are in terms of human injury and life lost, and in dollar value of property damaged or destroyed. When considering the nuclear fuel cycle there must be added the somewhat different factor of spread of radioactive materials which may lead to a persistent and serious long-term pollution of a large area, or to the possibility of an unacceptable spread of radioactivity over a large region. This factor is in many ways similar to the spread of toxic chemicals. In both cases there is a continuing hazard from accidentally released material. In both cases it is possible to clean up the area, though it must be admitted that nature is more forgiving, i.e., better able to assimilate and reduce the hazard to an acceptable level, in the case of chemical spills than in radioactive materials spills. In the former case, dispersion, dilution, and assimilation return the area of the accident to near-normal in months, or at most years. In the case of the most toxic radioactive materials, e.g., the actinides, and especially plutonium it may be impractical to rely on dispersion and dilution to ameliorate the problem, as decades or centuries may be required. The material must be quantitatively recovered. This could be very expensive in some cases. However, on the other side of the ledger, the radioactive materials would be much more carefully and securely packaged than many

Table 29

Comparison of Transportation Requirements in the Year 2000 for Dispersed *versus* Co-Located (Integrated) Fuel Recycle Facilities.

	Dispersed Facilities	Integrated Facility
Fresh Fuel		
Number of shipments	9601	9601
Vehicles in transit	26.3	145
Mass heavy metal in transit, tons	80	440
Spent Fuel		
Number of shipments	15,987	15,987
Vehicles in transit	88	307
Radioactivity in transit, MCi	659	2258
93% $^{235}UF_6$[a]		
Number of shipments	70	70
Vehicles in transit	0.4	1.3
Mass U in transit, tons	0.3	1.0
Plutonium Oxide[b]		
Number of shipments	722	0
Vehicles in transit	2.0	0
Mass Pu in transit, tons	1.0	0
HTGR-Uranium Oxide[c]		
Number of shipments	50	0
Vehicles in transit	0.14	0
Mass U in transit, tons	0.07	0
40% ^{235}U Oxide[d] (recycled U from HTGRs)		
Number of shipments	23	0
Vehicles in transit	0.06	0
Mass U in transit	0.03	0
High-Level Solidified Waste[e]		
Number of shipments	252	0
Vehicles in transit	5.0	0
Radioactivity in transit, MCi	56	0
Alpha Solid Wastes[f]		
Number of shipments	1144	0
Vehicles in transit	25.1	0
Mass actinides in transit, tons	0.06	0
All Other Wastes[f]		
Number of shipments	83,770	0
Vehicles in transit	367	0
Radioactivity in transit, MCi	8.3	0

[a] Isotopic composition is 1.0% ^{234}U, 93.1% ^{235}U, 0.2% ^{236}U, 5.7% ^{238}U.

[b] Isotopic composition is 1% ^{238}Pu, 59% ^{239}Pu, 24% ^{240}Pu, 12% ^{241}Pu, 4% ^{242}Pu.

[c] Isotopic composition is 0.041% ^{232}U, 59.6% ^{233}U, 26.3% ^{234}U, 8% ^{235}U, 6.1% ^{236}U.

[d] Isotopic composition is 1.4% ^{234}U, 40.7% ^{235}U, 43.9% ^{236}U, 14% ^{238}U.

[e] High-level waste is shipped ten years after it is generated in reprocessing.

[f] Wastes are shipped one year after their generation.

[Taken from J. Blomeke, C. W. Kee and R. Salmon, Projected Shipments of Special Nuclear Material and Wastes by the Nuclear Power Industry, ORNL-TM-4631 (August 1974), Table 1.]

toxic chemicals are today, and would be much less likely to be released in an accident.

Experience will tell where an acceptable trade-off lies between the risk of accident and the cost of accident prevention. Certainly at the present time there is a totally different public attitude toward acceptance of "familiar" transportation risks on the one hand, and acceptance of those associated with transporting nuclear materials on the other.

VIII. WASTE MANAGEMENT

Of all the problems associated with nuclear energy, probably none is so chronic and its solution so elusive and controversial as that of "permanent" disposal of the radioactive wastes produced by fission and transmutation reactions. The technical problems arise from the effectively infinite radioactive lifetime of some of the wastes, and from the fact that an appreciable fraction of the earth's air, crust and water would be required to dilute the wastes to concentrations considered to be acceptable. Together these factors impose a requirement either of disposing of wastes in a manner permitting and ensuring indefinitely long surveillance and attention to ensure their confinement or of disposing of them in a place so free from natural disturbance or remote from man that such attention is not required. A few moments' reflection on the nature of man and on his history strongly suggests the second course of action, which, if it is possible, relieves mankind of long-term responsibility. Another alternative method of permanent waste disposal is simply to destroy the very long-lived radioactive isotopes. While all attempts to accelerate significantly the process of radioactive decay have failed so far, there is a way which may be practical to destroy a very significant part of the radioactive wastes. This will be discussed later on.

A. Sources of Radioactive Wastes

Man lives in a "sea" of radioactivity, both outside and within his body. Typically, man is subjected to 120 to 140 millirems per year from naturally occurring radioactivity in and around him. A millirem is a relatively very small amount of radiation. For comparison it may be noted that about 450 rems absorbed by a man over a relatively short time would have about a 50-50 probability of killing him. Radiation commonly around and in man comes from such varied sources as ^{40}K, ^{14}C, ^{3}H, $^{219,220,222}Rn$ and cosmic rays. There are, of course, significant amounts of ^{238}U, ^{235}U and ^{232}Th, and of the radioactive elements in their decay chains, also present in the earth's crust and water, but these are mostly fixed in minerals, such that with the exception of the Rn isotopes they are not commonly in the biota of which man is a part. Since Rn is a gas, it is motile, and if it is inhaled by a man before it decays to its solid daughters, the subsequent decay chain is likely to run its course in that man. The relatively short half-lives of ^{14}C (∿5600 yrs) and ^{3}H (∿12.3 yrs) preclude the possibility that they persist from their creation in the primordial past. They are made continuously through nuclear reactions induced by cosmic rays. The amount of ^{14}C, though relatively small (∿2.8 x 10^{8} curies world wide in steady state, about 97% of which is deep in the oceans), is adequate to make practical the technique of "carbon dating" used successfully by archeologists, historians, and others to determine the ages of carbonaceous things a few tens of thousands of years old. The amount of ^{3}H is still less ($\sim 2.8 \times 10^{7}$ curies worldwide in steady state, about 90% of which is in water, 10% in the stratosphere, and 0.1% in the troposphere). The very long half-life of ^{40}K ($\sim 1.3 \times 10^{9}$ yrs) suggests that it could have been around at the generally accepted time the earth was formed (4-6 billion years ago) and still be there at 5 to 10 percent of its original amount. The amount of ^{40}K may be calculated to be about 4×10^{23} curies in a layer of the earth about 10 miles thick. The average man contains about 0.02 gram of ^{40}K, or about 0.14 microcuries.

In the context of radioactive wastes, tritium, ^{14}C and radon isotopes are the radioisotopes of greatest interest from among those mentioned. Actually, only the radon isotopes are truly important "natural" wastes. The tritium and ^{14}C are only of consequence as they are produced artifically in concentrations far in excess of their natural concentrations.

1. Mills

The nuclear fuel cycle starts at the mines and nearby mills where uranium (or thorium) ores are taken from the ground and a first separation of the desired element from the unwanted waste dirt is carried out. And it is here that the first significant radioactive waste problem arises. Typical "good" uranium ore contains only about 0.21% U_3O_8; thus, it is apparent that a great deal of the material present in the ore is left at the uranium mill after the uranium has been removed. The present practice is to dispose of this waste material or "tailings" as it is called, by simply dumping it into "monumental" tailings piles at the mills. Radon is continuously emitted from such piles, and is a potential source of harmful radiation. Methods have been suggested for limiting the amount of radon evolved from tailings piles; these methods are based on putting layers of dirt or spreading asphalt membranes on the piles to inhibit diffusion of the radon long enough for it to decay substantially to its non-volatile daughters. Guides for disposing of uranium milling wastes have been published, and continuing attention is being given to this waste idsposal problem.

2. Fabrication plants

After mining and milling, the uranium concentrates typically are refined (a process which further purifies the concentrate suitable for the uranium enrichment plant), enriched in the isotope ^{235}U at a gaseous diffusion plant, and the enriched uranium is fabricated into fuel. Uranium enrichment produces two streams of material: enriched UF_6 product, and depleted UF_6 "tails." The tails are far and away the larger of the streams, and could be considered a radioactive waste. (However, it appears likely that the LMFBR, which uses depleted uranium in its blanket to breed plutonium, will put this material to good use.)

Reactor fuel fabrication plants, by their nature, produce wastes which are mainly alpha-contaminated. Light water reactor (LWR) fuel fabrication involves uranium of low enrichment (typically, about 3% ^{235}U), and may involve plutonium as well. If recycle fuel is fabricated, the waste disposal problem will be significantly more troublesome than it is at present because of the much greater toxicity of plutonium than of low-enrichment uranium.

High temperature gas-cooled reactor (HTGR) fuel fabrication involves highly enriched uranium (about 93% ^{235}U) and thorium. Thorium decay produces ^{220}Rn, which has been mentioned previously in connection with natural radiation, and with some uranium milling wastes. Delaying the emission of ^{220}Rn, whose half-life is just under one minute, permits it to decay to its solid daughters, which may be disposed of as moderately radioactive wastes. In the steady state, HTGRs must be fueled partly with ^{233}U produced by nuclear reactions from the ^{232}Th. The disposal problem becomes more acute when fuel is fabricated from ^{233}U. This is true partly because of the presence of ^{232}U in the ^{233}U. ^{220}Rn is produced in the decay chain of ^{232}U, in amounts dependent on the ^{232}U content. It is also true partly because ^{233}U is itself more toxic than ^{238}U or ^{235}U.

Liquid metal fast breeder reactor (LMFBR) fuel fabrication involves uranium and plutonium. The exceptional toxicity of plutonium has already been noted. Fuel fabrication plant wastes include all manner of solids and sludges that arise from decontamination operations, liquid waste stream treatment, and off-gas cleanup. Uncompacted wastes may vary in density from 2 to 200 lbs/ft^3, with uranium, plutonium and thorium contents of from trace amounts to several grams per cubic foot. About 1/2 to 2/3 of the waste volume is combustible, and volume and weight reductions of 50 and 20, respectively, may be obtained with these fractions. It has been estimated that about 20,000 ft^3 of alpha waste will be generated per tonne of plutonium or ^{233}U fabricated, and that these wastes will contain about 0.5% of the plutonium or ^{233}U.

3. Reprocessing Plants

The basic, large problems in radioactive waste disposal arise from operation of the spent fuel reprocessing plants. In general, the spent fuel is chopped (LWR and LMFBR fuel) or burned (HTGR fuel) to make the fissile and fertile materials available for dissolving in acid. The resulting acidic solutions are treated by solvent extraction to extract uranium and plutonium (and in the case of HTGRs, thorium), leaving the fission products in an aqueous waste stream. It is this waste stream that poses the outstanding waste disposal problem of the nuclear power industry. Fuel reprocessing plants also have other sources of radioactive wastes.

The aqueous waste stream mentioned above is certainly the most important, but gaseous wastes such as krypton, xenon, tritium or tritiated water vapor, and volatilized iodine and solid wastes are also important reprocessing wastes requiring disposal. An especially important solid waste is the chopped up pieces of fuel cladding left after the fuel has been dissolved. These may be contaminated with difficult-to-remove plutonium.

The various important kinds of wastes generated during fuel reprocessing are given in Table 30 for LWR, HTHR and LMFBR fuels. These wastes are defined as high-level wastes, and federal regulations call for them to be solidified with 5 years of their

Table 30

Calculated Curies in Spent Fuel per Tonne of Heavy Metal Charged to the Reactor

Source of Radioactivity	Curies Present at Indicated Days after Discharge					
	0 day	30 days	90 days	160 days	365 days	3653 days
LWR[a]						
Cladding	1.42×10^5	8.03×10^4	4.52×10^4	2.62×10^4	1×10^4	2.4×10^3
Fission Products	1.38×10^8	1.08×10^7	6.19×10^6	4.19×10^6	2.22×10^6	3.18×10^5
Actinides	3.91×10^7	1.83×10^5	1.33×10^5	1.26×10^5	1.14×10^5	7.2×10^4
HTGR[b]						
Light Elements	6.52×10^3	3.55×10^3	3.49×10	3.4×10^3	3.26×10^3	1.76×10^3
Fission Products	2.96×10^8	2.32×10^7	1.32×10^7	9.1×10^6	4.55×10^6	1.01×10^6
Actinides	1.04×10^8	2.18×10^7	4.77×10^6	1.0×10^6	3.81×10^4	2.80×10^4
LMFBR[c]						
Cladding	1.34×10^6	6.06×10^5	3.99×10^5	2.8×10^5	1.32×10^5	5.98×10^3
Fission Products	1.96×10^8	1.68×10^7	9.56×10^6	6.7×10^6	3.31×10^6	3.15×10^5
Actinides	8.05×10^7	7.16×10^5	6.79×10^5	6.6×10^5	6.21×10^5	4.10×10^5

[a] Burnup: 33,000 megawatt-days/tonne; power: 30 megawatts; flux: 2.92×10^{13} neutrons/cm^2·sec.

[b] Burnup: 94,271 megawatt-days/tonne; power: 64.57 megawatts; flux: 8.04×10^{13} neutrons/cm^2·sec.

[c] Burnup: 37,118 megawatt-days/tonne; power: 49.28 megawatts; flux: 2.49×10^{15} neutrons/cm^2·sec.

generation, and for the resultant stable solids to be shipped to a federal repository within 10 years of their generation.*

Beyond the problem of the wastes produced by the reprocessing plants during their life times, there is the problem of "decommissioning" the fuel reprocessing plants when they reach the end of useful life. However, it is not so clear that the option exists to cut up the contaminated parts of the reprocessing plants and remove them to a central waste storage facility. The activity of the reprocessing plant is, by the nature of the operations, in a variety of chemical and physical forms as it passes through the plant and the process equipment. Thus, extensive "loose" contamination will be present in the plants, and this will pose a major obstacle to its complete removal from the plant site. For this reason it is likely that the "perpetual care" approach to disposal after decommissioning will be the one chosen for spent fuel reprocessing plants. Of course, there will be fewer spent fuel reprocessing plants to decommission than there will be reactors. Seven of eight 5 tonnes per day plants should be adequate to handle the LWR spent fuel reprocessing load in the year 2000.

B. Waste Treatment

Radioactive wastes are treated prior to their disposal to put them in chemical and physical forms suitable for the intended method of disposal. There are liquid, gaseous and solid wastes, and these contain alpha, beta and gamma emitters. The waste treatment method chosen depends on all of these factors. Thus, low activity level aqueous wastes are often treated by ion exchange and evaporation, so that the decontaminated water may be disposed of in environmental water. The radioactivity is concentrated in a sludge or other solid, e.g., the ion exchange resin itself. These solid wastes are treated to make them more compact, if possible, and are commonly incorporated in a solid matrix whose function is to prevent their subsequent release in a dispersible form.

Gaseous wastes are composed largely of non-radioactive gases such as air, helium, carbon dioxide or nitrogen contaminated with relatively small amounts of radioactive gases such as ^{85}Kr, xenon isotopes, and tritium, or vapors such as tritiated water vapor, and the iodine isotopes ^{131}I and ^{129}I. Such wastes are usually treated by preferential sorption of the radioisotopes onto materials such as charcoal (for Kr and I), silica gel (for tritated water), molecular sieves (for tritiated water) and silver-impregnated high-specific-surface-area solids (for I_2). The gaseous radioactives wastes are thus to be put into the form of solid wastes, or in the case of krypton, are to be put in metal cylinders as compressed gas, and the decontaminated gaseous wastes may be disposed of in the earth's atmosphere.

Because of the special hazard presented by ingested or inhaled alpha emitters, and the highly specific uptake of iodine in the thyroid gland, these materials require special attention. Alpha

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* These regulations are given in "Siting of Fuel Reprocessing Plants and Related Waste Management Facilities", Federal Register 35, No. 222, 17530 (Nov. 14, 1970). There is at present no federal repository, so there is something of a dichotomy implicit in the regulations.

emitters are largely actinide elements, and when half lives are taken into account, the elements uranium, neptunium, plutonium, americium and curium emerge as the elements of principal concern. Highly specialized methods for their treatment are being studied. These were mentioned in section VI on reprocessing. Iodine, primarily the isotope ^{129}I when the wastes are allowed to decay a year or more before treatment (^{131}I, while the predominant fission product iodine isotope, has a half-life of only 8.05 days), is a special problem because its many chemical valence states, its proclivity to add to organic compounds and the volatility of many of its common forms give it a troublesome ubiquity. Both ^{129}I and ^{131}I are beta emitters.

1. Decay

There is a form of preliminary waste "treatment" which is widely used that is highly effective in reducing waste disposal problems. The treatment is simply to wait for the wastes to decay before final treatment prior to disposal. The principal radioisotope providing incentive for extended waiting, or "decay" periods is ^{131}I. Table 31 shows how the amounts of ^{131} and ^{129}I change with time. Clearly there is no incentive to wait more than a year from the point of view of radioiodine decay because the very long half-life isotope ^{129}I (the half-life is 1.6 x 10^{7} yrs!) dominates after about 200 days.

Radioactive decay heat is another important problem in waste treatment which is ameliorated by delay. Although only a few percent of the energy released by fission is not released virtually instantly as kinetic energy of the fission products during the fission process, the few percent released more slowly by radioactive decay of the fission products is not negligible. For example, the fission product decay heat production rates for the fission products (exclusive of Kr, Xe, ^{3}H and I) present in 1 tonne of heavy metal charged to an LWR and irradiated to a level of 33,000 megawatt-days/tonne are 1.92 x 10^{4} watts 0.411 years after discharge from the reactor, 2.93 x 10^{3} watts 3.41 years after discharge, 1.01 x 10^{3} watts 10.42 years after discharge, and 1.05 x 10^{2} watts 100.5 years after discharge. Since the weight of the fission products being considered is about 28.8 kilograms, the specific heat generation rates range from 0.67 watts per gram 150 days after discharge to 0.035 watts per gram 10.42 years after discharge. The factor of nearly 20 decrease in specific power gained by a 10 year delay makes a very significant difference in how the wastes may be treated.

Typically, after fuel reprocessing the liquid fission product wastes are stored in underground, shielded tanks as a method of interim disposal. Figure 36 is a cross section drawing of a representative modern waste storage tank.

Liquid waste storage tanks are located at fuel reprocessing plants to accommodate the high-level liquid wastes (for up to five years) prior to their solidification and shipment off-site for more permanent disposal.

Modern high-level liquid waste storage tanks are made of stainless steel and may contain 300,000 gallons of waste. Air may be used to circulate the liquid in the tank to avoid solids settling out during storage. It also provides dilution of radio-

Table 31

Amounts of Radioiodine from One Tonne of Irradiated Heavy Metal from an LWR

(Basis: 33,000 megawatt-days/tonne; 2.92×10^{13} neutrons/cm^2-sec)

Isotope	Curies Present at Indicated Days after Discharge					
	0 day	30 days	90 days	160 days	365 days	3653 days
^{131}I	8.61×10^5	6.71×10^4	3.83×10^2	9.23×10^{-1}	1.99×10^{-8}	0
^{129}I	3.71×10^{-2}	3.73×10^{-2}	3.74×10^{-2}	3.74×10^{-2}	3.74×10^{-2}	3.74×10^{-2}
TOTAL	8.61×10^5	6.71×10^4	3.83×10^2	9.60×10^{-1}	3.74×10^{-2}	3.74×10^{-2}

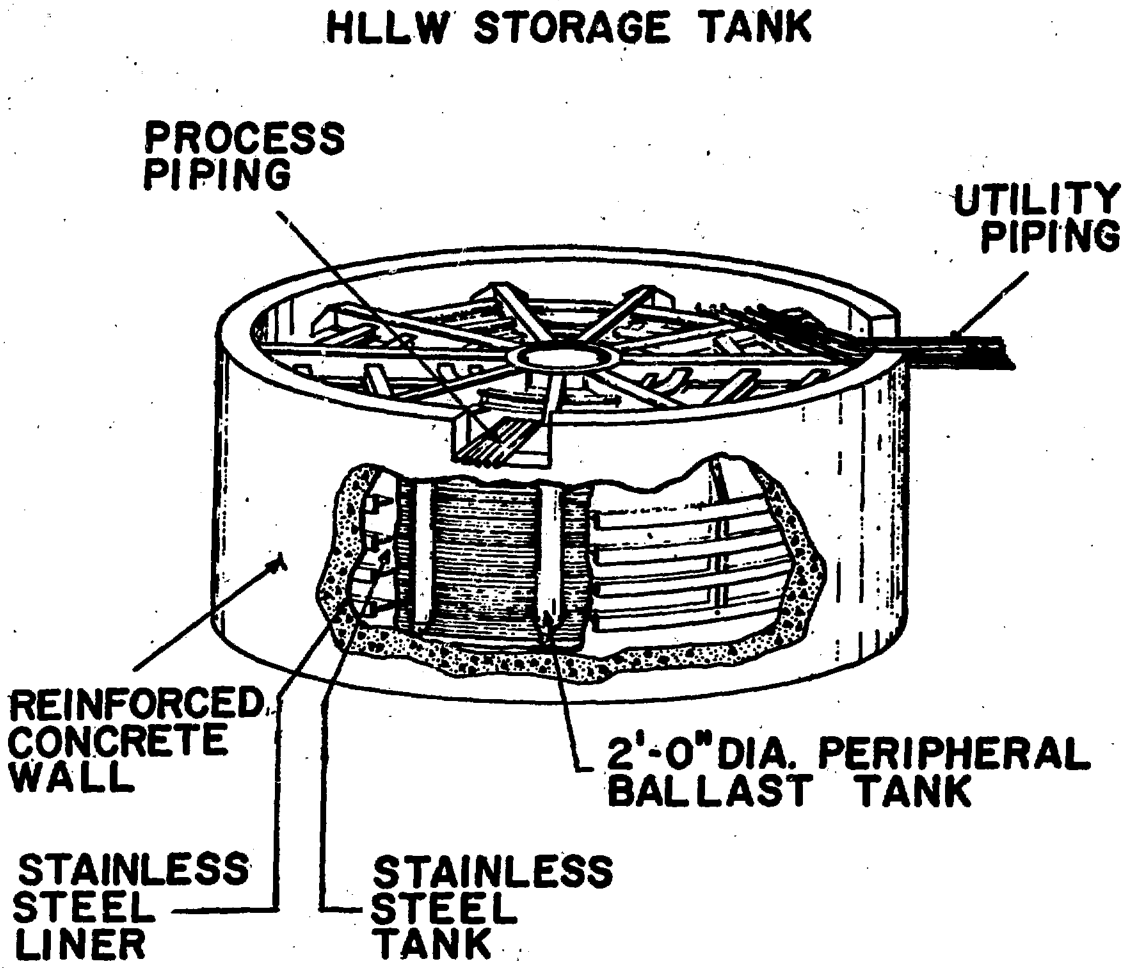

Fig. 36. Liquid Waste Storage Tank. (Courtesy of the Barnwell Nuclear Fuel Plant, Separations Facility, Allied-Gulf Nuclear Services, Barnwell, South Carolina).

lytically produced hydrogen. In general, the liquid waste is transferred progressively to tanks of lower heat removal capacity as decay occurs, thus making the tanks with highest heat removal capacity available for the freshest waste, which has the highest power density.

Requirements appear to be getting more stringent for high-level liquid waste storage tanks. Leaks in existing tanks, coupled with increased concern over the possible effects of tornadoes or earthquakes, have led to increased concern over their integrity, and certainly to increased cost of liquid waste storage.

High-level radioactive wastes* will probably be stored after solidification in several different geographical locations in bedded or domed salt deposits. Lower-level wastes may be stored in several different types of suitable, geologically stable formations at a number of different locations. In any event, attention will be paid to both geological suitability and geographical convenience to the principal sources of waste production, i.e., fuel reprocessing plants.

Storage of high-level wastes has been practiced for 30 years, and almost 340 thousand cubic meters (90 million gallons) of acid and alkaline solutions and sludges have been accumulated in about 300 tanks at ERDA (AEC) reprocessing sites over this period. Of these, about 26 carbon-steel tanks are known to have developed leaks, releasing about 235,000 Ci of ^{137}Cs in 430,000 gallons of alkaline waste. It is also of interest to note that until at least the year 2000 by far the most waste will be from ERDA rather than commercial fuel reprocessing.

2. Solidification

Regardless of the form of the wastes initially, they are finally treated to incorporate or contain them in solids for disposal, or they are reduced to such low levels of activity that they may be released to the environment. Tables 32, 33, and 34 summarize the projected characteristics of solidified aqueous wastes from reprocessing three kinds of reactor fuels.

Solidification of high level wastes from reprocessing plants is a very important process step, since it bears directly on the disposal step which follows. For this reason methods of solidification have received a great deal of attention. Methods range from incorporation in glasses made from calcined wastes with appropriate additives, to calcination in fluidized beds to produce a granular powder which is stored in steel containers.

fluidized bed calcination

In this process liquid waste is atomized into a heated, fluidized bed where it is deposited and calcined on particles in the bed. The resultant granular particulates may themselves be

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*High level wastes are defined in the Federal Register, 35, No. 222, Nov. 14, 1970, p. 17530, as "those aqueous wastes resulting from the operation of the first cycle solvent extraction system or equivalent, and the concentrated wastes from subsequent extraction cycles, or equivalent, in a facility for reprocessing irradiated reactor fuels".

Table 32

Projected Characteristics of Solidified LWR Aqueous Reprocessing Wastes and Cladding

(Based on a tonne of heavy metal reprocessed)

Characteristic	Individual Waste Streams Characteristics					Possible Combined Waste Streams Characteristics		
	(1) F.P. Waste	(2) Alpha Waste	(3) Solvent Cleanup Waste	(4) Caustic Scrubber Waste	(5) Cladding	(1)+(2)+(3)	(1)+(2)+(4)	(1)+(2)+(3)+(4)
Composition, kg/tonne								
U_3O_8	1.17	0.001	0.348	--	1.1[a]	1.52	1.17	1.52
PuO_2	0.011	0.011	0.001	--	0.01[a]	0.023	.022	0.023
$Na_2B_4O_7$	--	--	79.3	31.6	--	79.3	31.6	111
Fe_2O_3	1.07	0.016	--	--	--	1.09	1.09	1.09
Cr_2O_3	0.15	0.002	--	--	--	0.15	0.15	0.15
NiO	0.13	0.001	--	--	--	0.13	0.13	0.13
P_2O_5	0.09	--	Trace	--	--	0.09	0.09	0.09
F.P. oxides	31.5	Trace	Trace	--	0.02[a]	31.5	31.5	31.5
Actinide oxides	6.28	Trace	Trace	--	--	6.28	6.28	6.28
Zircaloy-4, Inconel	--	--	--	--	270	--	--	--
Total weight, kg/tonne	40.4	0.031	79.6	31.6	271	120	72.0	152
Volume, ft^3/tonne	0.74[b]	0.001[b]	1.18[c]	0.47[c]	2.12[d]	1.41[c]	0.69[c]	1.88[c]
Thermal conductivity, BTU hr^{-1} ft^{-1} °F^{-1} at 500°C	0.26	0.26	0.55	0.55	3.6[e]	1.02	1.48	0.96
Density, g/cc	1.92[b]	2.07[b]	2.37[c]	2.37[c]	4.5[d]	3.01[c]	3.67[c]	2.86[c]

[a] Assumes 0.1% Pu and U, and 0.05% of the fission products (F.P.s) are lost to the cladding.

[b] Product is assumed to be 70% voids.

[c] Product is assumed to be a void-free dispersion of solids in $Na_2B_4O_7$.

[d] Cladding is compressed to 70% of theoretical density.

[e] Conductivity at 100°C.

Table 33

Projected Characteristics of Solidified HTGR Aqueous Reprocessing Wastes and SiC Fuel Particle Coatings.

(Based on a tonne of heavy metal reprocessed.)

Characteristic	Individual Waste Streams Characteristics (1) ^{235}U Recycle Particle Waste	(2) Clarifier Wastes	(3) Combined Thorex & TBP Fission Product Wastes	(4) Combined Thorex & TBP Alpha Wastes	(5) Solvent Cleanup Wastes	Possible Combined Waste Streams Characteristics (3)+(4)+(5)	(1)+(2)+(3)+(4)+(5)
Composition, kg/tonne							
C	15	2.3	--	--	--	--	17.3
SiC	18	27.3	--	--	--	--	45.3
$Na_2B_4O_7$	--	--	113[a]	--	51.4[b]	155[c]	240[d]
Na_2SO_4	--	--	--	34.3[e]	--	34.3	34.3
Na_3PO_4	--	--	--	3.90	--	3.90	3.90
Li_2SO_4	--	--	1.21	--	--	1.21	1.21
AlF_3	--	--	2.73	--	--	2.73	2.73
Al_2O_3	--	--	10.4	--	--	10.4	10.4
Fe_2O_3	--	--	2.16	--	--	2.16	2.16
NiO	--	--	0.53	--	--	0.53	0.53
Cr_2O_3	--	--	0.39	--	--	0.39	0.39
SiO_2	--	--	0.40	--	--	0.40	0.40
MoO_3	--	--	0.06	--	--	0.06	0.06
CuO	--	--	0.05	--	--	0.05	0.05
UO_2	8.52	--	--	--	--	--	8.52
U_3O_8	--	0.047	0.045	0.258	0.096	0.398	0.446
ThO_2	--	0.569	0.991	0.964	2.06	3.99	4.56
PuO_2	0.567	0.002	1.20	0.112	0.002	1.31	1.88
F. P. Oxides	4.80	7.2	91.30	Trace	Trace	91.30	103.3
Actinide Oxides	0.794	Trace	1.633	Trace	Trace	1.633	2.427
Total weight, kg/tonne	47.7	37.4	226	39.5	53.5	309	460
Volume, ft^3/tonne	1.14[f]	0.79[f]	2.41[g]	0.51[h]	0.77[g]	3.56[g]	5.79[g]
Thermal conductivity, BTU hr^{-1} ft^{-1} $°F^{-1}$	0.41	0.41	1.42	1.5	0.60	1.13	1.39
Density, g/cc	1.48	1.68	3.30	2.73	2.44	3.07	2.93

[a] 1.05 kg of sodium added per tonne to balance the boron chemically. 108 kg of $Na_2B_4O_2$ added per tonne to give 50 wt % waste solids in the $Na_2B_4O_7$.

[b] 35.5 kg of B_2O_3 added per tonne to balance the sodium chemically.

[c] 10.7 kg of B_2O_3 added per tonne to balance the sodium chemically. 135 kg of $Na_2B_4O_7$ added per tonne to give 50 wt % waste solids in the $Na_2B_4O_7$.

[d] 10.7 kg of B_2O_3 added per tonne to balance the sodium chemically. 220 kg of $Na_2B_4O_7$ added per tonne to give 50 wt % waste solids in the $Na_2B_4O_7$.

[e] 5.50 kg of sodium added per tonne to balance the sulfate chemically. 1.64 kg of sodium added per tonne to balance the phosphate chemically.

[f] Product is assumed to be 50% voids.

[g] Product is assumed to be a void-free dispersion of solids in $Na_2B_4O_7$.

[h] Product is assumed to be a void-free dispersion of solids in Na_2SO_4 + Na_3PO_4.

Table 34

Projected Characteristics of Solidified LMFBR Aqueous Reprocessing Wastes and Cladding
(Based on a tonne of heavy metal reprocessed.)

Characteristic	Fission Product Wastes								Cladding		Possible Combined Waste Streams Characteristics			
	Without Boron		With Boron											
	(1) 1% of Cladding Dissolved	(2) 10% of Cladding Dissolved	(3) 1% of Cladding Dissolved	(4) 10% of Cladding Dissolved	(5) With $Fe(NO_3)_2$ Reductant	(6) With U^{4+} Reductant	(7) Solvent Cleanup Wastes	(8) Caustic Scrubber Wastes	(9) Alpha-Contaminated	(10) Induced Activity Only	(1)+(5)+(7)+(8)	(2)+(5)+(7)+(8)	(3)+(5)+(7)+(8)	(4)+(5)+(7)+(8)
Composition, kg/tonne														
Fe_2O_3	3.75	37.5	3.75	37.5	8.52	--	--	--		--	12.27	46.02	12.27	46.02
Cr_2O_3	1.01	10.1	1.01	10.1	--	--	--	--		--	1.01	10.1	1.01	10.1
NiO	.42	4.17	0.42	4.17	--	--	--	--		--	0.42	4.17	0.42	4.17
PuO_2	0.11	0.11	0.11	0.11	0.02	0.02	0.02	--	0.03[a]	--	0.15	0.15	0.15	0.15
U_3O_8	1.02	1.02	1.02	1.02	--	0.02	0.10	--	0.3[a]	--	1.12	1.12	1.12	1.12
$Na_2B_4O_7$	--	--	86.5	86.5	--	--	67.9	95.8	--	--	164	164	164	164
F.P. oxides	34.2	34.2	34.2	34.2	Trace	Trace	Trace	Trace	0.02[a]	--	34.2	34.2	34.2	34.2
Actinide oxides	0.91	0.91	0.91	0.91	Trace	Trace	Trace	Trace	--	--	0.91	0.91	0.91	0.91
Stainless Steel	--	--	--	--	--	--	--	--	650	700	--	--	--	--
Total weight, kg/tonne	41.4	88.0	128	175	8.54	0.04	68	95.8	650	700	214	260	214	260
Volume, ft^3/tonne	0.81[b]	1.84[b]	1.53[c]	1.84[c]	0.19[b]	0.0003[b]	1.01[c]	1.43[c]	4.17[d]	4.50[d]	2.74[c]	3.05[c]	2.74[c]	3.05[c]
Thermal conductivity, BTU hr^{-1} ft^{-1} $°F^{-1}$ at 500°C	1.26	0.26	1.02	1.41	0.26	0.26	0.55	0.55	9.0[e]	9.0[e]	0.9	1.13	0.9	1.13
Density, g/cc	1.81[b]	1.69[b]	2.95[c]	3.35[c]	1.56[b]	2.90[b]	2.37[c]	2.37[c]	5.50[d]	5.50[d]	2.75[c]	3.02[c]	2.75[c]	3.02[c]

[a] Assumes 0.3% Pu and U, and 0.05% of the fission products (F.P.s) are lost to the cladding.

[b] Product is assumed to be 70% voids.

[c] Product is assumed to be a void-free dispersion of solids in $Na_2B_4O_7$.

[d] Cladding is compressed to 70% of theoretical density.

[e] Conductivity at 100°C.

the final waste form, or they may be incorproated into crystalline or glassy solids. Figure 37 shows schematically a fluid bed calciner and glass maker.

spray calcination

In this process the liquid waste is atomized into a heated chamber where flash evaporation produces solid oxide particles. The product of spray calcination is not completely stabilized chemically, and requires additional heating to produce an inert product. Suitable materials, e.g., phosphoric acid or glass making solids, may be added to produce glass which may be canned for final isolation from the biosphere.

pot calcination

In this process liquid is introduced into the processing vessel continuously and evaporated continuously in a vessel which is to be the storage cannister. When the cannister is full the solid is held at about 900°C to complete removal of water and nitrates. Feed additives can be used to make a glass.

phosphate glass formation

In this process liquid waste and phosphoric acid are mixed and concentrated to a thick sludge in an evaporator. The sludge is then dried and the nitrates are decomposed in a melter. The molten phosphate glass is dropped into the storage cannister.

In some countries wastes are incorporated in asphalt (tar). Because these wastes must be shipped to a repository, and because the shipping container must be able to tolerate "design basis accidents" it does not appear that asphalt will be much used in the U. S. It appears unnecessarily restrictive to design a container which will withstand a fire while it contains asphalt, which is relatively much less stable than the various calcined materials.

iodine

Iodine is a semi-volatile fission product having complex physical and chemical properties, and an extraordinary tendency to concentrate in the thyroid gland of man. Thus, it requires special attention to ensure it is safely managed.

Several dry and wet processes for removing iodine from the various off-gas streams of a nuclear fuel reprocessing plant have been used and studied. Dry processes use beds containing solids such as charcoal (either at room temperature or liquid nitrogen temperature) and silver zeolite. Wet processes use scrubbing columns filled with solution such as 10$\underline{M}$ NaOH, nitric acid plus mercuric nitrate, and 20$\underline{M}$ HNO_3 (the iodox process). The final solid form to be used for disposal of iodine has not been determined. It may be practical to incorporate it in cement.

gaseous wastes

Gaseous wastes are the noble gases xenon and krypton, and tritium. Typically, from 5 to 6 kg of noble gases are present in

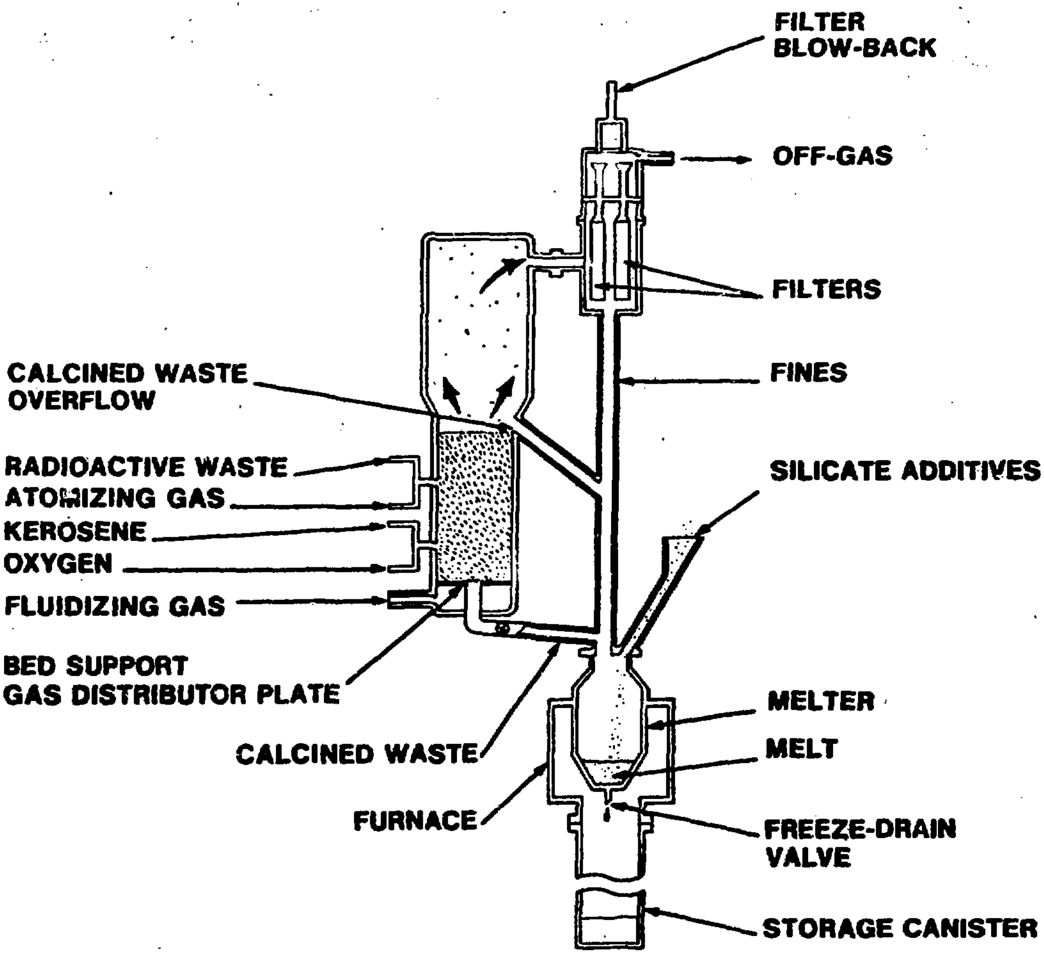

Fig. 37. Fluidized Bed Calciner and Continuous Silicate Glass Melter.

each ton. of spent fuel from LWRs and LMFBRs. Xenon comprises about 95% of the weight of the noble gas mixture, but the only radioisotope remaining after 160 days decay is 10.8 year ^{85}Kr. At present these gases are discharged to the atmosphere following interim holdup for decay. In the future their recovery is likely in the framework of the "as low as reasonably achievable" (ALARA) guidelines. Concentration and storage in high-pressure gas cylinders are likely. This is not exactly a "solidification" method, but it is as close as current technology comes.

Tritium is produced at a rate of about 0.02 to 0.03 Ci per MWdth in the reactors. Most of the tritium is retained in LWR fuels and is released during the dissolution step of reprocessing, and most is released in water vapor to the atmosphere. (More than 90% of the tritium in LMFBR fuels will leave the fuel while it is in the reactor, and will be trapped in the sodium coolant cleanup systems. It will be removed from these systems as solid and may be packaged for disposal as solid. The remainder will be released during reprocessing, and handled as in the case of tritium from LWR fuel.) Future plants having head-end operations like voloxidation should be able to separate and concentrate the tritium, perhaps in a volume as small as a few liters of tritiated water per day. This concentrate could be fixed in a solid and disposed of.

3. Partitioning of actinides

The special problem posed by long-lived alpha wastes deserves separate discussion. The elements of greatest concern are uranium, neptunium, plutonium, americium and curium. If these actinide elements could be removed from the wastes (primarily from the fission product wastes from fuel reprocessing plants, but also from fuel fabrication and refabrication plants), the period of significant radioactive hazard at the disposal sites may be reduced from millions of years to less than 1000 years. (It might also be necessary to remove ^{99}Tc and ^{129}I.) However, the required degree of removal of these actinides from the fission products to achieve this extraordinary change in the nature of the waste disposal problem is such that only about one part in 10^4 of the actinides may remain with the fission products. Further, once separated from the fission products and the inert, confining solid matrix containing the fission products, the actinides are more hazardous than before because now they are much more concentrated, and any release is correspondingly more toxic. So the problem has two major facets: (1) partitioning the actinides away from the fission products or other radioactive wastes with an unprecedented (and in a practical sense, perhaps unattainable) degree of separation, and (2) completely and positively removing the actinides from the biota essentially forever. The second part of the problem, while seemingly impossible of attainment, may not be impossible. It may be possible to recycle the separated actinides back to the reactors where, after many cycles, they would ultimately be converted to fission products. It seems clear that reactors with a large flux of high energy neutrons, i.e., fast reactors, will be better suited to this job than thermal reactors.

The first part of the problem is being studied conceptually and experimentally. Fig. 38 is a conceptual processing sequence

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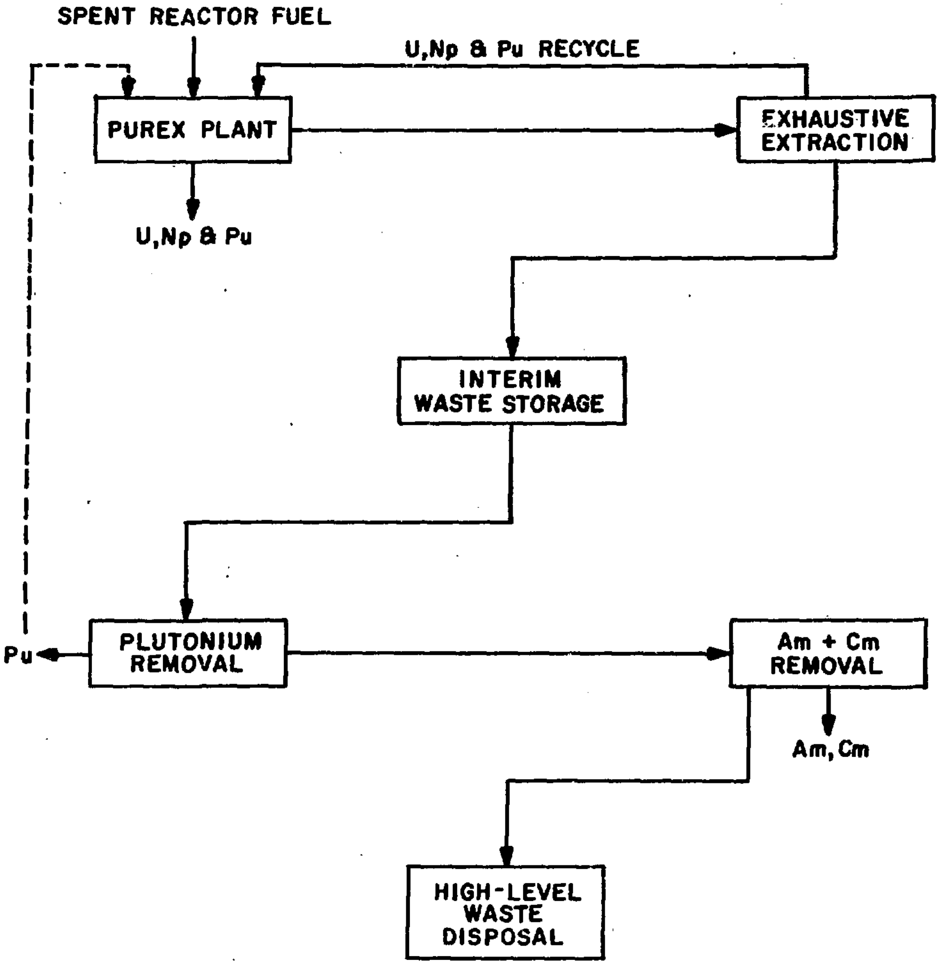

Fig. 38. Conceptual Processing Sequence for the Removal of Actinides.

to remove the actinides. This part of the problem is extremely difficult because of the very high degree of separation required, and because additional contaminated materials are produced in the course of carrying out the partitioning. Thus, the very real danger exists that the solution to the problem does not "converge." The actinides may be more dispersed at the end of the process than at the beginning, or the volume of wastes containing the fission products may be unacceptably large -- or both. Also, it should be noted that during interim waste storage, radioactive decay leads to the buildup of additional plutonium which must be removed in an additional step.

C. Geologic Isolation

After appropriate treatment, the solidified high-level wastes could be stored in metal containers in an underground repository with a high degree of assurance of containment. A great deal of study has gone into the question of what is the most suitable type of repository, and for a variety of reasons (not the least of which is that their very existence bespeaks great temporal stability) salt deposits appear to be the optimum choice. Fig. 39 shows where some of the major salt deposits are in the U. S. Those in the south and southwest appear most promising. Fig. 40 presents various high-level radioactive waste isolation options in the form of an alternatives diagram.

D. Other Disposal Options

There is at present a hiatus in the progress toward selection of a federal repository for permanent high-level waste disposal. Until this selection is made, and the myriad other problems attending "ultimate" disposal are solved, some sort of interim waste storage plan must be put into action. The projected total volumes of various wastes to be stored one way or another at a federal repository are large. Far and away the largest volume is from intermediate-level (alpha-beta-gamma) wastes. However, the largest number of curies in the repository is associated with the high-level wastes.

Beyond the interim storage "option" there are a large number of other "options". These include disposal at sea (probably best reserved for relatively low-level activity wastes); disposal into space (probably best deferred until a time when less uncertainty and cost attend a launch into space); disposal in ice beds (probably best avoided until more is known about the long-term behavior of such beds).

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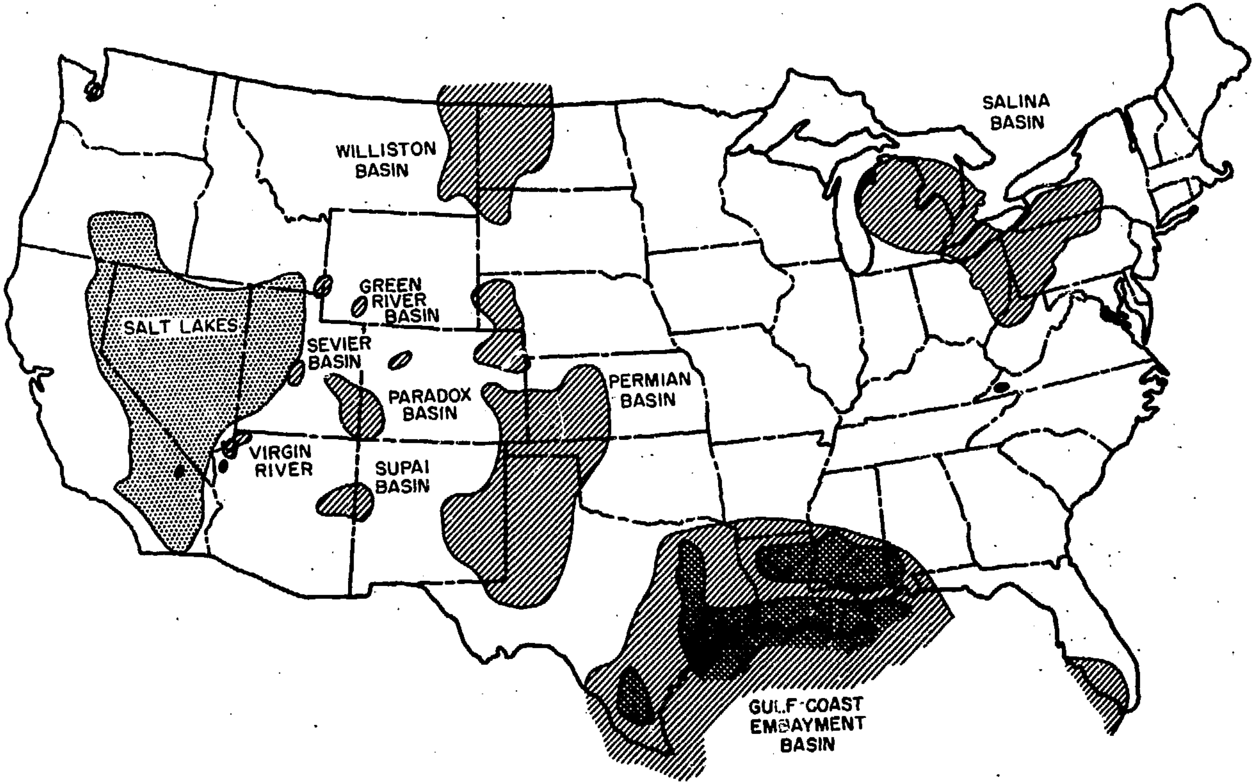

Fig. 39. Rock Salt Deposits in the United States.

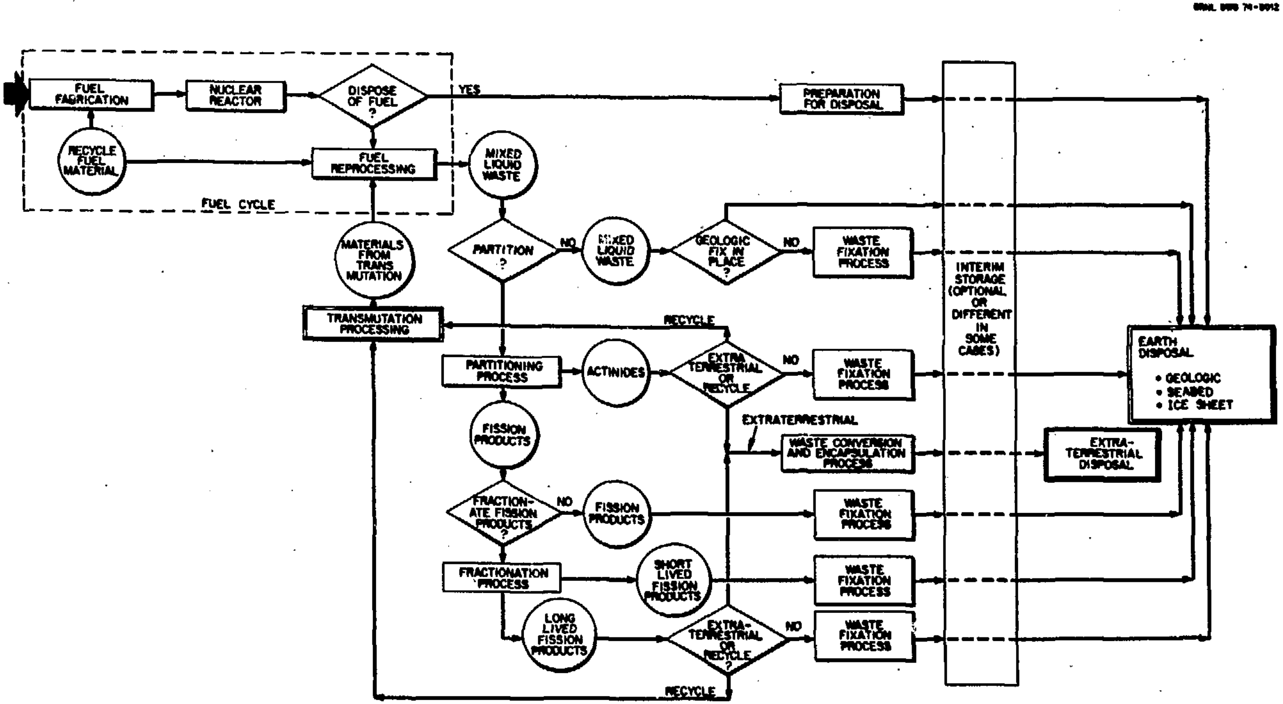

Fig. 40. HIGH-LEVEL RADIOACTIVE WASTE MANAGEMENT AND Isolation Option Diagram.
(TAKEN FROM WASH-1297)

IX. APPENDIX-Standards for Release of Radioactive Materials from Nuclear Fuel Cycles

General Standards

NRC

(1) 10 CFR 20
Maximum permissible release-10 CFR 20, Appendix B,
Table II (Pages 71-75)

(2) "As Low As Reasonably Achievable"

EPA

(1) Proposed 40 CFR 90
Maximum dose to individual
25 mrem/yr total body
75 mrem/yr thyroid
25 mrem/yr organs other than thyroid

Total release by entire fuel cycle per gigawatt year of power

^{85}Kr - 50,000 curies
^{129}I - 5 millicuries

Pu and ohter alpha emitting transuranics with half lives greater than one year - 0.5 millicurie total (Radon, ^{14}C, tritium-under study)

(2) "Best Practical Control Technology Currently Available"

(3) "Best Available Technology Economically Achievable"

Natural Background

~100 millirem/yr at sea level
~130 millirem/yr at 5,000-ft elevation (Denver)

LWR reactor guides (per reactor)-10 CFR 50, Appendix I

(1) Maximum dose to individual
Liquid 3 mrem/yr total body
10 mrem/yr bone

Gases 5 mrem/yr total body
15 mrem/yr skin
15 mrem/yr organ (iodine and particulates)

(2) Population dose (based on cost-benefit)
$1000/total body-man-rem (50 mile radius)
$1000/man-thyroid-rem (50 mile radius)

Uranium Mines

NRC - No jurisdiction

Ore is not legally a source material until beneficiation begins.

State - Set regulations

Bureau of Mines - Set occupational radon exposure level

EPA - 40 CFR 440 (Nov. 6, 1975), interim final rules and proposed rules

(1) Liquid effluent limitation

^{226}Ra 10 p Ci/l maximum any one day
3 p Ci/avg over 30 days

U 4 mg/l maximum any one day
2 mg/l avg over 30 days
(Also sets standards for chemical releases)

(2) "BPCTCA" guides
- Settling ponds
- Lime precipitation
- Ion exchange (for uranium removal)
- Barium chloride coprecipitation (for radium removal)
- Secondary settling

Uranium Mills

NRC

(1) Maximum permissible concentration - 10 CFR 20
Airborne
Yellow cake dust Unat* $= 5 \times 10^{-12}$ μCi/ml at the fence post
Ore dust Unat* $= 2 \times 10^{-12}$ μCi/ml at the fence post

Liquid
^{226}Ra $= 3 \times 10^{-8}$ μCi/ml (30 Ci/l)
^{230}Th $= 2 \times 10^{-6}$ μCi/ml
Unat* $= 3 \times 10^{-5}$ μCi/ml (44 mg/l)

(2) No "ALARA" guides have been proposed

EPA - 40 CFR 440 (Nov. 6, 1975), interim final rules and proposed rules

(1) No discharge of liquid pollutants (exception if annual precipitation exceeds annual evaporation.

(2) "BPTCA" guides
- No discharge of waste water
- Liquid recycle to mill

Other Segments of Nuclear Fuel Cycle

(1) 10 CFR 20 standards

(2) Proposed 10 nanocurie/g transuranic rule on waste (Sept. 12, 1974) has not been promulgated

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*Specific activity Unat $= 6.77 \times 10^{-7}$ Ci/g.

(3) "ALARA" guides-none proposed

(4) EPA-None

Transportation

Dept. of Transportation - 49 CFR 73 - maximum permissible doses

General shipments - 10 mrem/hr 3 ft from package
Exclusive use vehicle
(1) 1000 mrem/hr 3 ft from package (closed vehicle)
(2) 200 mrem/hr on outside surface of vehicle (closed vehicles)
(3) 10 mrem/hr 6 meters from vehicle
(4) 2 mrem/hr to driver

NRC - 10 CFR 71

Design criteria for shipping casks, permissible releases in the event of accidents.

The Safety of Nuclear Power Plants

by

W. B. Cottrell

Engineering Technology Division, Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830

ABSTRACT

The safety of nuclear reactors is a national concern, as reflected both by the annual expenditures for government-sponsored research and the antinuclear cries of a conglomeration of individuals and groups ranging from Nobel prize winners to professional activists. The position of the majority is that nuclear reactors may be safely built and operated by the conservative application of proven technology and that ongoing research will serve to define the degree of conservatism and extend the technology. On the other hand, the antinuclear forces contend that the existing nuclear technology imposes an unacceptable level of risk on our society, and they propose a variety of solutions ranging from the outright banning of nuclear power to various limitations on its application. This article examines several controversial issues concerning nuclear power, including (1) occupational health impacts of electrical generation by various power plants; (2) routine releases from nuclear power plants; (3) abnormal occurrences in reactor operations; (4) risk of fatalities due to both natural and man-caused events; (5) operating availability and capacity of various types of electrical generating plants; (6) safeguards — plutonium diversion; and (7) radioactive waste disposal.

I feel that nuclear power is essential to our national interest and that the nuclear reactors now being built and operated are acceptably safe. While it is the privilege, if not the responsibility, of all persons concerned with the development of nuclear power to advance their own divergent views of acceptable safety, it appears to me that the Nuclear Regulatory Commission (as well as its predecessor, the AEC) has performed commendably — if not perfectly — in fulfilling its responsibility for the safe regulation of nuclear energy.

INTRODUCTION

The safety of nuclear reactors is a national concern, as evidenced both by the annual expenditure for government-sponsored research and the antinuclear cries of a number of individuals and groups ranging from Nobel prize winners to professional activists. In this article I will first review the design and safety features of typical light-water power reactors and then consider briefly the present environment in this country that continues to encourage the growth and development of nuclear power. This growth, in turn, has led to increasingly vocal opposition. I will identify the issues being raised by those opposing nuclear power and discuss several of the more prominent of these issues.

DESIGN AND SAFETY FEATURES OF LIGHT-WATER REACTORS

In accordance with the basic laws of physics, nuclear energy is produced when an atom of certain heavy elements is "hit" by a neutron and splits in the so-called fission process, releasing more energy (as well as more neutrons) than is required to effect the split. In the proper surroundings, this fission process may sustain itself. There are many reactor types in which this fission process is controlled and the heat it generates is converted into electricity. The power reactors in most common use in this country are two light-water reactor types, commonly referred to as the pressurized-water reactor (see Fig. 1) and the boiling-water reactor (see Fig. 2). While these two types differ significantly in detail, they are characterized by the same concern for safety which is reflected in the same basic safety philosophy and analogous plant safety features.

The safety philosophy has been codified in the Commission's regulations and regulatory standards which govern the licensing of nuclear facilities.[1] Implicit in these regulations is the concept of defense in depth, in which one may identify three levels of safety:

1. "design for maximum safety in normal operation..."

2. "assume incidents will occur...[and] provide safety features to protect operators and the public..."

3. "provide additional safety features as appropriate... where some safety systems are assumed to [also] fail..."

This safety philosophy has led to the incorporation of numerous safety features — both large and small — in the design of a nuclear power plant. Three of the more significant — in terms of both plant design and cost — of these safety features are (1) containment, (2) emergency core-cooling systems, and (3) emergency power.

Containment

The only significant potential hazard to the public in the event of a major accident at a nuclear power plant lies in the possible escape of radioactivity in either liquid or gaseous form. In order to reduce these accident consequences to safe levels, all nuclear power plants are provided with comprehensive containment systems, which in effect isolate the radioactivity within a nominally leaktight enclosure[2] as shown for a pressurized-water reactor (PWR) in Fig. 3. In addition to the dominating concrete structure which characterizes most nuclear power plants, the containment systems include valves to seal off lines penetrating the containment, cooling systems to reduce the containment temperature and pressure, filter systems to reduce the radioactivity in the containment atmosphere, and other related and/or supporting equipment. These containment systems are continuously tested to assure their performance under accident conditions and will leak less than 0.2%/day.

Pressurized water reactor (PWR)

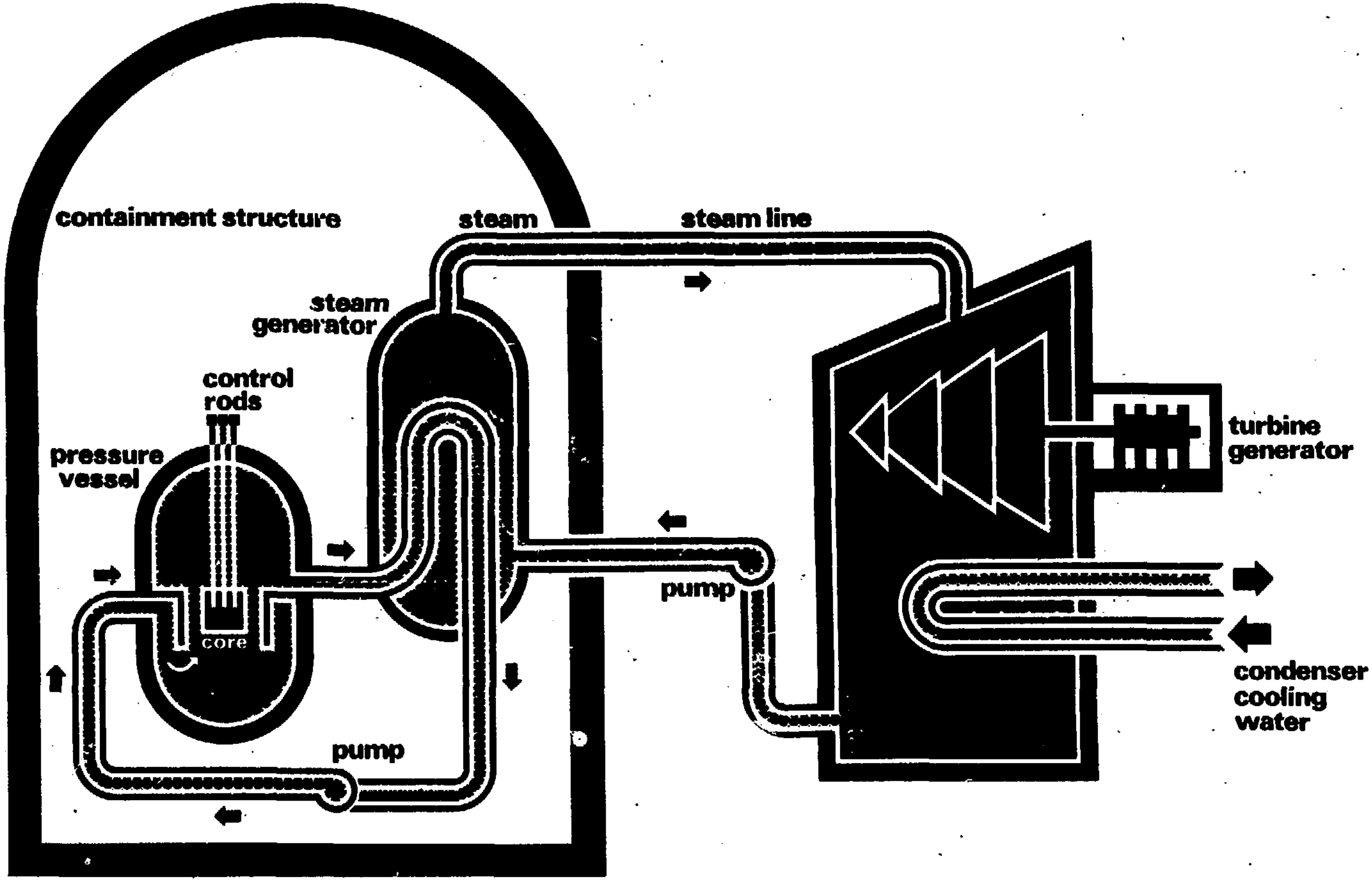


Figure 1

Boiling water reactor (BWR)

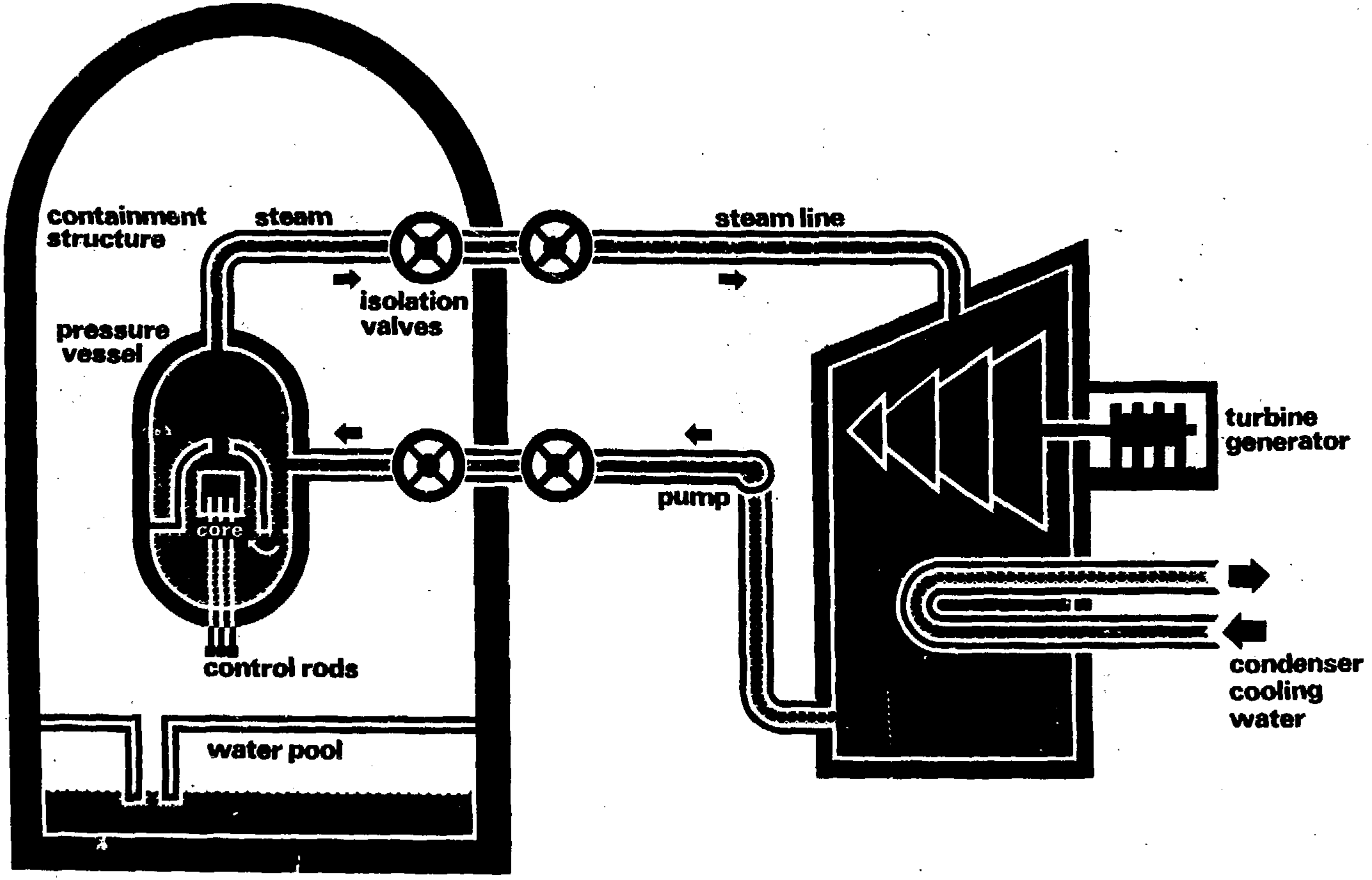
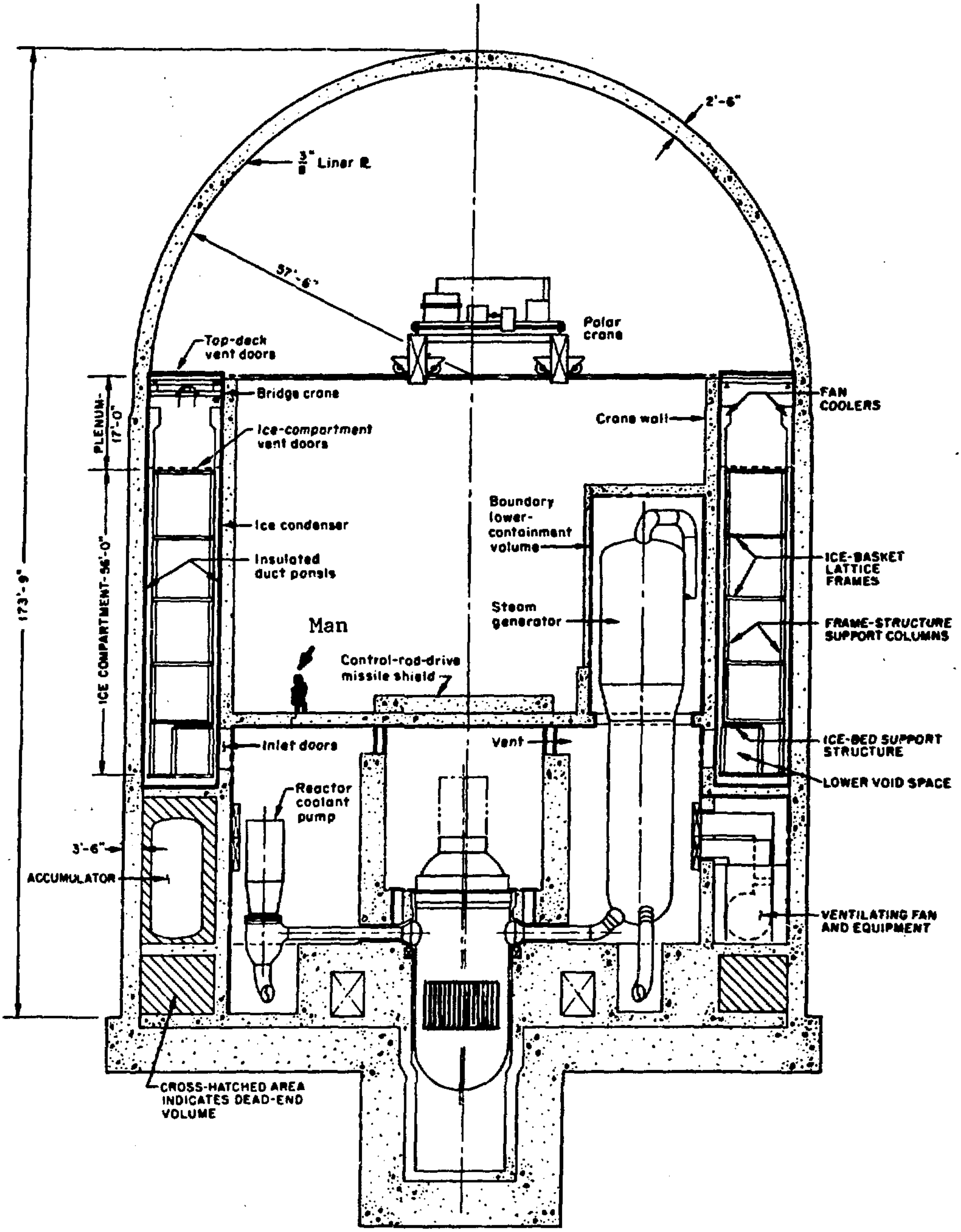


Figure 2



Typical Primary Coolant System and Containment
for a Large PWR System

Figure 3

Emergency Core-Cooling Systems

Significant quantities of fission products can be released from the reactor fuel elements if the reactor fuel is allowed to reach temperatures substantially above operating fuel temperatures. Inasmuch as accidents in which normal core cooling is impaired are readily conceivable, all water-cooled power reactors are provided with multiple capability for introducing water into the reactor core. The collection of systems which perform this function is known as the emergency core-cooling system (ECCS). The ECCS for a pressurized-water reactor is shown schematically in Fig. 4. The component systems of the ECCS include (1) a high-pressure low-volume system, (2) pressurized accumulator tanks for intermediate-pressure large-volume requirements, and (3) a low-pressure intermediate-volume system for long-term requirements. Each of these systems exists in duplicate and has multiple components connected to emergency power to assure performance when and if needed.[1]

Emergency Power

Electrical power is essential for normal operation of a nuclear power plant and for the operation of certain equipment in the event of various potential accidents. In order to assure that electrical power is always available for vital services, nuclear plants not only have several connections to the external electrical grid but also have their own emergency power units capable of supporting emergency functions at the plant for extended periods of time. In typical 1000-MW(e) nuclear plants, this emergency power would be provided by two or more diesel units each capable of >4000 kW each.[3]

THE NEED FOR NUCLEAR POWER

No one can adequately appreciate the need for nuclear power without first understanding the importance of energy in our society and the limitations of alternative forms of energy. Our population, our energy consumption and, most importantly, our energy consumption per individual, all continue to increase. Furthermore, there is a direct correlation between our Gross National Product (an indicator of our economic health) and energy consumption (see Fig. 5).[4] Although neither the GNP or our energy consumption are increasing at the rate projected a few years ago, unless our economy experiences a severe setback, both GNP and energy consumption may be expected to increase. Furthermore, both our existing sources of energy, as well as most of the novel energy sources now being developed, have serious problems and limitations which will force us to increase our dependence on both coal and nuclear power over the next 50 years.

In fact if one considers the likely impact of all but coal and nuclear energy sources in terms of their ability to contribute to our national electrical needs by the year 2000, the maximum estimated contribution from most government documents is less than 15%. A typical breakdown is presented in Table 1.

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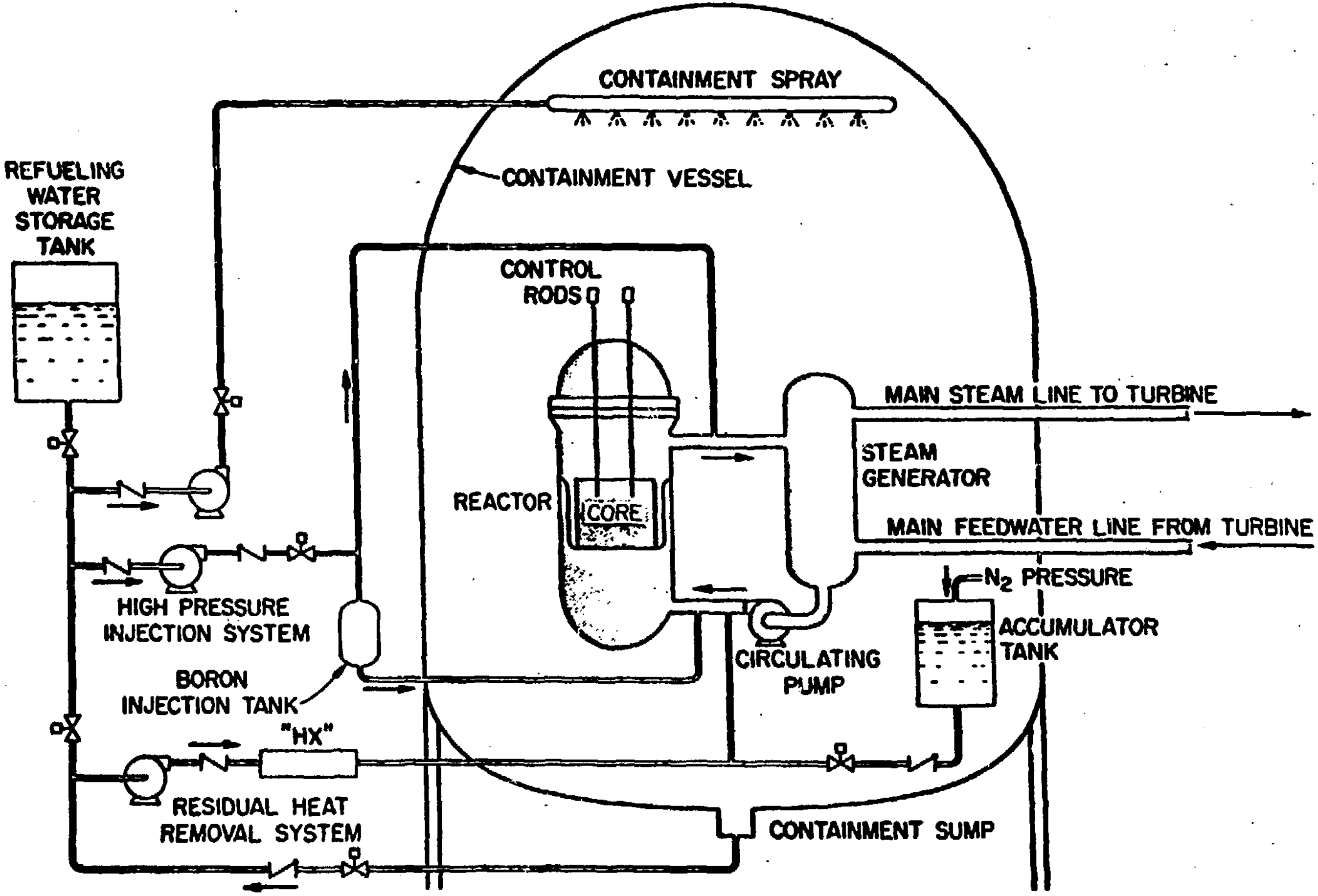


Figure 4 PWR Emergency Cooling Systems.

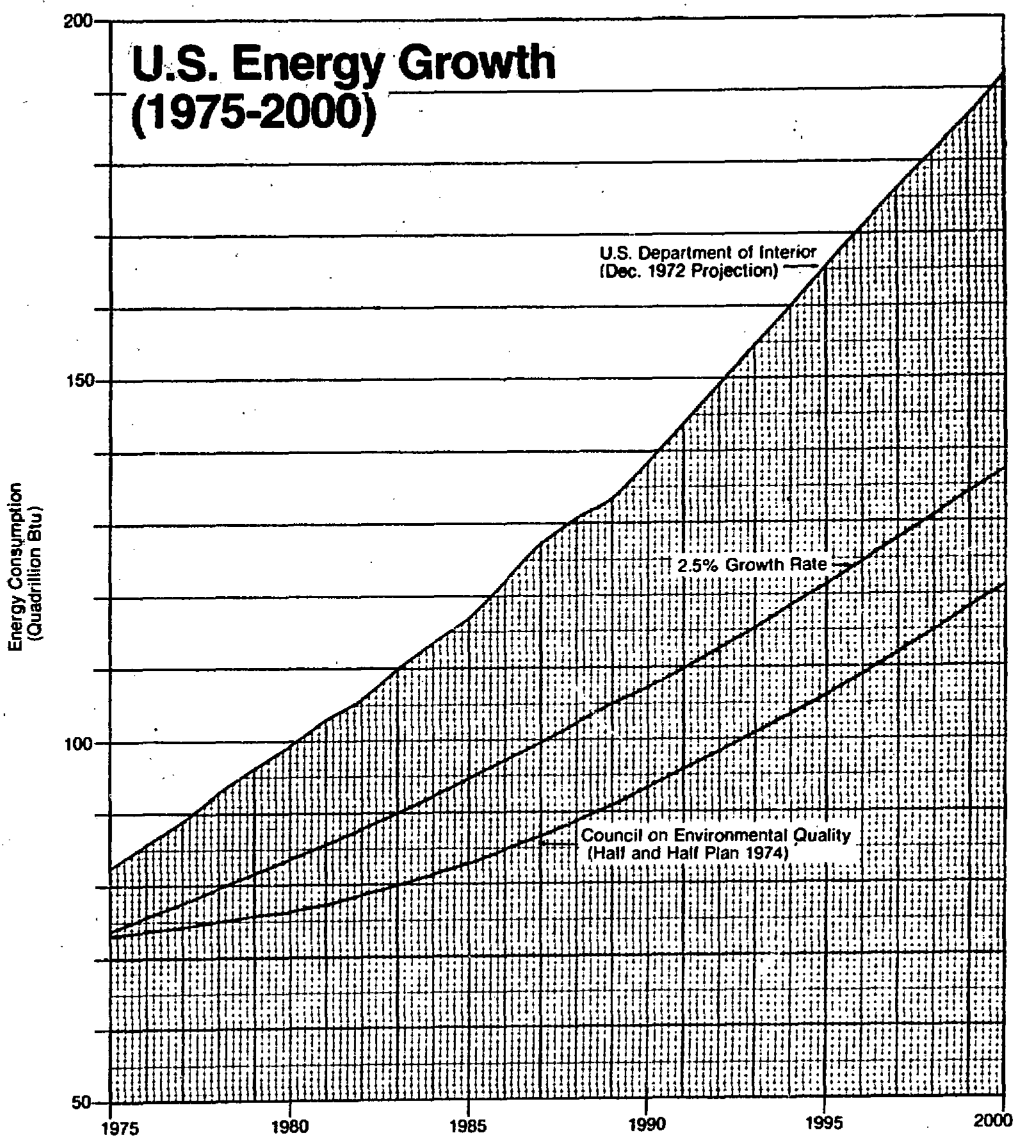

U.S. Energy Growth
(1975-2000)
Energy Consumption
(Quadrillion Btu)
200
150
100
50
1975
1980
1985
1990
1995
2000
U.S. Department of Interior
(Dec. 1972 Projection)
2.5% Growth Rate
Council on Environmental Quality
(Half and Half Plan 1974)

Figure 5

Table 1. Percent of Total Electrical Energy: Year 2000[5]

	Percent
Solar	2 - 5
Hydro	3
Tidal	less than 1
Geothermal	less than 1
Ocean Gradients	negligible
Wind	less than 1
Fusion	0
Natural Gas	0
Oil	3
	11 - 14%

Although there is much debate as to what our energy needs will be by the year 2000, most predictions predict a 100 ±30% increase (see Fig. 6).[4] Given the limitations of the energy sources listed in Table 1, we have left only coal and nuclear. While recent studies[6] have indicated that we could provide this additional energy to the year 2000 with coal only, the cost whether measured in terms of dollars, environmental degradation, or depletion of our natural resources would be many times that of the nuclear-coal mix.

Many people continue to advocate one or both — slower growth and energy conservation. However, it should be recognized that both have indeed been incorporated into our energy planning and are a part of — not a substitute for — most current projections of energy demand. The most explicit and detailed expression of our national energy policy incorporating the above considerations is in the National Plan for Energy Research, Development and Demonstration (ERDA-48),[7] which was submitted to President Ford and Congress in June 1975. It was revised and reissued in 1976 as ERDA 76-1.[8] These policy statements specifically identify the near-term need for light-water reactors (i.e., PWRs and BWRs) and the long-term need for the breeder reactor, for which the Clinch River Breeder Reactor in Oak Ridge is the demonstrative project. Furthermore, both of these needs were assigned the highest priority along with the development and use of other technologies.

THE NUCLEAR CONTROVERSY

In our complex technological society, no major change can be implemented without dislocating some segments of that society. Since the late sixties, it has become increasingly apparent to all concerned that nuclear power was destined to play an important role in our national energy picture, and starting with the environmentalist movement at about the same time, nuclear power has been subjected to extensive criticism from many sides. Some of this criticism was warranted, and has resulted in changes in the technology. Other criticism was found to be without merit and — much to the chagrin of its advocates — was not acted upon.

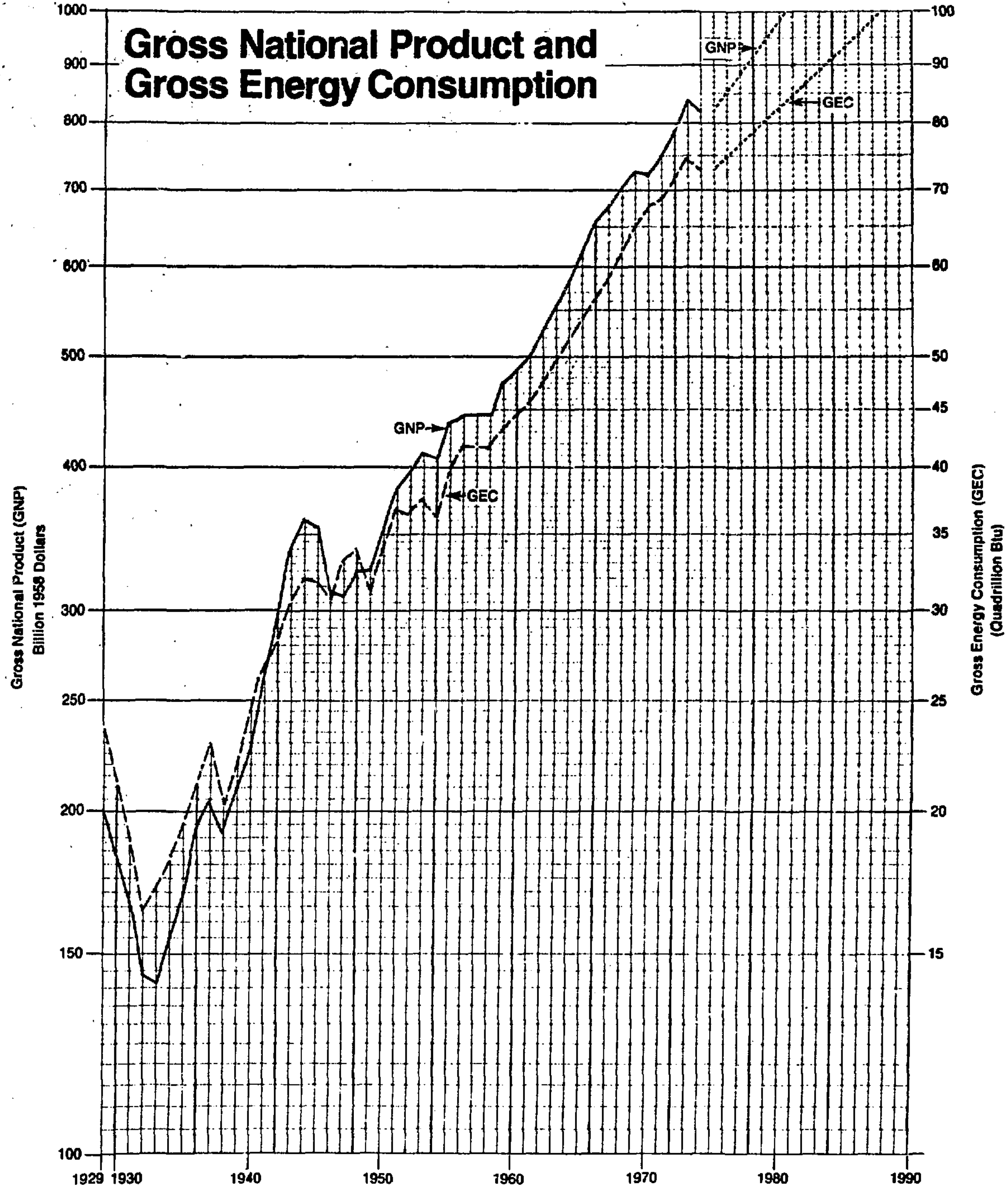

Gross National Product and Gross Energy Consumption
GNP
GEC
GNP
GEC
Gross National Product (GNP) Billion 1958 Dollars
Gross Energy Consumption (GEC) (Quadrillion Btu)
1000
900
800
700
600
500
400
300
250
200
150
100
100
90
80
70
60
50
45
40
35
30
25
20
15
1929
1930
1940
1950
1960
1970
1980
1990

Figure 6

Those opposed to nuclear power range from individuals who have specific concerns regarding the features of one reactor to organized groups who are opposed to nuclear power in general. The latter includes such groups as the Sierra Club, the National Resources Defense Council, the Union of Concerned Scientists, and Ralph Nader's organization, to mention some of the more outspoken in this regard.

I do not propose to deal here with the objectives or motivation of any individual or group. I would, however, like to identify some of the major issues involved and discuss the impact of these issues. In the following portions of this article, we will address ourselves to the merits of several of these issues.

The nature of the issues raised against nuclear power run the gauntlet from the real and valid to the imaginary and incredible. In 1970, following the first substantial signs of widespread nuclear opposition, *Nuclear Safety*, a journal I edit, commissioned an article[9] to evaluate the nature and attitude of approximately 800 articles dealing with nuclear safety which were published that year. Some of the results of that study are given in Table 2, which shows the relative concern (ratio of unfavorable to favorable articles) for each of some 11 general issues and the number of articles published on each issue.

It is of interest to compare this 1970 analysis with a recent public opinion poll[10] by Louis Harris and Associates under the sponsorship of Ebasco Services, Inc. In one of the questions in this poll, a representative 1537 adults were asked to identify safety issues that concerned them. Table 3 gives estimates of the relative concern for a number of issues and the percentage of those concerned with each item. Although there is not a one-to-one correspondence between the two surveys, they are sufficiently similar to permit some useful comparison. First, and most significant, the relative concern for nuclear issues seems to have decreased between 1970 and 1975. Secondly, the concern for a number of issues which were of concern in 1970 appears to have dissipated in 1975. Of course, the conflict between regulation and development (which rated 5th in 1970) was eliminated from consideration by the Energy Reorganization Act, which created ERDA and NRC out of the AEC. Other earlier concerns, such as state vs federal government rights and antitrust considerations, are being resolved in conventional channels (i.e., the courts) in which the public has shown little interest. The question regarding nuclear insurance still exists as a problem in minds of many people and probably will persist until government participation in nuclear liability insurance is terminated — most probably in 1987.

Several of the concerns persist and may continue for some time for a variety of reasons. These concerns include waste disposal, activity release, explosive accidents, thermal pollution, sabotage, and safeguards.

In addition to the above, there are some more subtle and/or sophisticated contentions which are used by the critics in their arguments against nuclear power; e.g., nuclear power economics, nuclear plant reliability, the accident record of nuclear plants, and catastrophic nuclear accidents. Therefore, it is important that those of us concerned in any way with our national energy program fully understand each of these issues, so that the facts can be called upon whenever questions arise. In the remainder of my article, I would like to address a few of these issues.

Table 2. Relative Concern Toward Controversial Issues: 1970*

	Issue	Ratio of unfavorable to favorable articles	No. of articles 1969-1970
1	Safeguards		8
2	Antitrust and monopoly	13	19
3	Insurance	12	30
4	Legalistics	9	97
5	Regulatory conflict	4	49
6	Siting	2.2	183
7	Nuclear accidents	2.1	112
8	Waste disposal	2.1	311
9	Thermal pollution	1.4	229
10	Environment	1.1	206
11	Esthetics	0.6	22

*From *Nuclear Safety* 12(4), p. 287 (1971)

Table 3. Relative Concern Toward Controversial Issues: 1975*

	Issue	Ratio of favorable to unfavorable	Percentage of persons concerned[†]
1	Waste disposal	∿4.5	63
2	Gaseous radioactivity	∿2	49
3	Explosive accident	∿1.8	47
4	Thermal pollution	∿1.8	47
5	Sabotage	∿1.3	39
6	Air pollution	∿1.1	36
7	Safeguards	∿1	34

*From 1975 Louis Harris & Associates public opinion poll.

[†] Percentage of 1537 adults polled.

Operating Performance of Nuclear Power Plants. An issue which is frequently brought up is that of operating performance and reliability. It has been said that the 47 operating nuclear plants in the United States have been plagued by abnormal occurrences and that they are basically unreliable sources of power. The facts do not substantiate this claim. As opposed to accident analyses where judgments must be made on probability estimates, the operating histories for fossil-fired power plants and comparable nuclear units are a matter of record.

There are many bases for comparing nuclear vs fossil plants, but most seem to indicate little difference between the two. One measure of performance is the capacity factor, i.e., the percent of total electric power actually generated divided by the power which could have been produced had the plant operated continuously at full power. As determined from data published by the Edison Electric Institute,[11] the capacity factor for all fossil units, averaged over 1965–1974, was 67% and the corresponding figure for nuclear plants was 60%; but the output factor,

$$\text{Output factor} = \frac{\text{total generation (MWhr)} \times 100}{\text{service hours} \times \text{maximum design capacity}},$$

favored nuclear plants by 86% to 83%. Nevertheless, the nuclear figure is less than designers, manufacturers, and operators desire. However, part of the downtime in nuclear plants is directly attributable to the fact that regulations require nuclear plant operators to report and investigate all safety-related occurrences. Statistics show that there were over 800 such occurrences in 1973. Again, these must be placed in perspective.[12] Any drift in an instrument or malfunction of a valve, pump, etc., must be reported even if it occurs during a normal test sequence. Of the 800 safety-related occurrences, over 450 were assessed as insignificant and, of the balance, only 12 involved release of radioactivity off site. Of these 12 occurrences, 11 occurred at one plant and are reported as separate events. Although the release rates were above permissible limits, none of these events resulted in release of a total quantity of radioactivity in excess of the permitted value.

It is important to note that similar statistics are not available for fossil-fuel plants. However, it is hypothesized that if such statistics were available, they would show that fossil-fuel plants encounter at least as many, if not more, component failures, because their quality-assurance standards are not as rigid as those applied to nuclear plants.

Accident Risk. The nuclear industry has long lived under the shadow of WASH-740, a 1957 study of the theoretical maximum reactor accident.[13] The WASH-740 report is second only to reflections on the weapons origins of nuclear power, in arousing the unwarranted emotional apprehensions of many concerned with nuclear power. Let me set the record straight on both of these issues: (1) Under no circumstances can a nuclear power plant explode like a bomb; nuclear plants may conceivably have serious accidents, but the worst of these involve the release of radioactivity from fuel which is not cooled (2) Under no credible circumstances would it be possible for a nuclear power plant to release the amount of radioactivity as calculated in WASH-740. Both the credibility and the consequences of nuclear plant accidents have been reexamined in a monumental study,[14] which was completed in November 1975 in which the probability of an event is determined as a function of its consequences. This study analyzed the data to determine values of risk due to accidents in nuclear power plants.

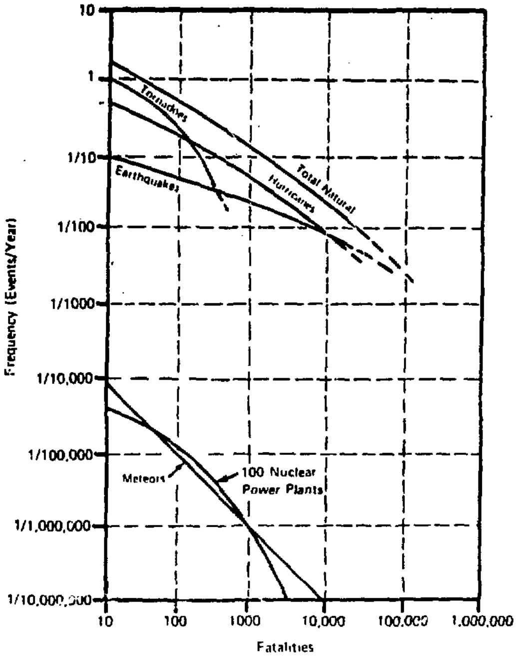
In addition to analyzing such accidents, the study also addressed the all-important question (one which is too infrequently asked), "How do the risks for other energy sources compare with the nuclear risks?" This question is not often asked because most people do not realize that there are measurable environmental and occupational health effects caused by the generation of electricity from any source.

In the study, which involved several hundred experts, the consequences of various types of accidents were evaluated by first developing event trees and then estimating the probability of various sequential failures. The basic conclusion of this study was that the risk to the public from potential accidents in nuclear power plants is very small; in fact, assuming 100 reactors of 1000 MW(e) each, the chance of a person living in the United States being killed as a consequence of a nuclear accident is 150 times less than the chance of being killed by lightning. It is important to note that the study did not conclude that there will be no accidents. In fact, it predicted that the so far unblemished safety record of the industry probably cannot continue indefinitely and that at some time there will be an incident that will have impact on the public. However, it predicted that the impact of such an event, when it occurs, will be of a limited and variable character and not the frightful catastrophe which some have depicted.

Figure 7 illustrates the conclusions of the study as to the frequency of fatalities which can be expected from nuclear accidents as compared to those caused by natural events. Note that if there are 100 nuclear power plants operating in 1980, we can expect an accident which will result in 100 fatalities once every 100,000 years. This compares with the estimate that one can expect to have a tornado which will cause 100 fatalities once every 5 years. Thus, in 100,000 years it is expected that there would be 20,000 tornadoes each of which would cause 100 deaths.Since we have little control over the natural elements, it may be more interesting to compare similar statistics for other man-caused events, as is done in Fig. 8 . You will note in Fig. 8 that again the nuclear fatality line falls well below the lines for other recognizable catastrophes. For example, let us look at dam failures. The study showed that one should expect to have a dam failure every 25 to 30 years which would result in approximately 100 fatalities. In the United States, there are over 100 major dams, and their failure history is fairly accurately recorded (see Table 4). Despite the fact that there have been failures, major population centers exist downstream of many of these dams.

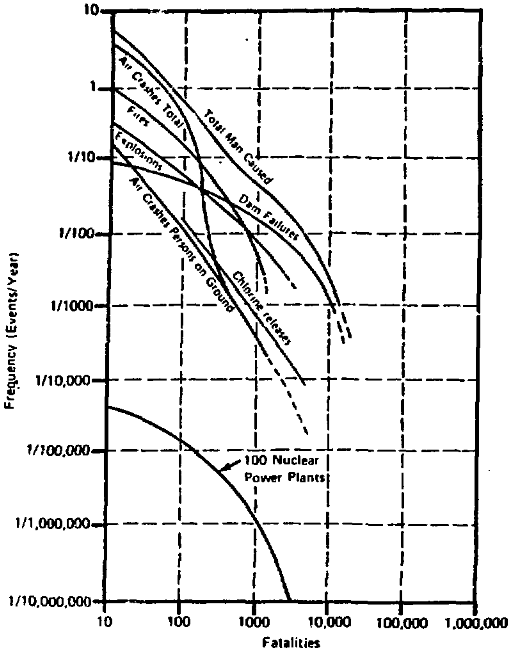
Public and Occupational Health Experience. Although the proponents of nuclear energy and those who are against nuclear energy rarely agree on any question relating to the safety of nuclear power plants, there is one fact that neither side disputes, and that is that no nuclear power plant to date has ever experienced an accident which resulted in measurable damage or injury to the public.[15] This is noteworthy, considering that as of 1975 there were approximately 47 nuclear

Figure 7



Frequency of Fatalities due to Natural Events

Figure 8



Frequency of Fatalities due to Man-Caused Events

Table 4. Dam and Levee Failures in the U.S. (1889–1972)

Year	Name and/or location	Type of structure	Lives lost
1889	Johnstown, Pa.	Dam	$\sim$2000
1890	Walnut Grove, Prescott, Ariz.	Dam	150
1894	Mill River, Mass.	Dam	143
1900	Austin, Pa.	Dam	8
1928	St. Francis, Calif.	Dam	$\sim$450
1955	Yuba City, Calif.	Levee	$\sim$38
1963	Baldwin Hills, Los Angeles, Calif.	Reservoir	5
1972	Buffalo Creek, W. Va.	Dam	125
1889–present		Total	2919

electrical generating plants on-line in the United States which have accumulated over 200 years of operating experience in commercial service. The same safety record is also applicable to our nuclear submarine fleet; the unblemished record of the fleet goes back to 1954 and encompasses over 100 submarines with over 1200 years of operating experience. Although there have been isolated charges of increased cancer deaths in the vicinity of nuclear plants, these have been refuted by all scientific groups who have investigated the matter, including the Environmental Protection Agency and the Health Physics Society, as well as the NRC and utility consultants.

More precise documentation is available on the question of occupational health, and there are correspondingly fewer questions. The most notable study[16] on this subject was that undertaken by the Council on Environmental Quality and published in August 1973. This study evaluated the health impacts in terms of death, injuries, and days lost from work in oil, coal, gas, and nuclear electrical generation and normalized the results to a 100-MW(e) plant. The results, summarized in Table 5, clearly substantiate the case for nuclear power.

Waste Disposal.[17,18] The matter of the disposal of high-level nuclear wastes must be understood both in terms of the volume of wastes and cost involved as well as the recent history of waste disposal technology in this country. The total volume of high-level solid waste generated in the operation of a 1000-MW(e) reactor for one year is of the order of 60 to 70 ft^3 and would be less than 1,000,000 ft^3 by the end of the century. The latter figure represents a space 25 ft high and 200 ft on each side; however, the waste would have to be distributed over several acres because of cooling requirements. The cost, when distributed among all the users, would be negligible.

Why then all the hassle over waste disposal? There are several contributing factors, including (1) the bad experience with some of the older waste storage facilities at federally owned and operated sites; and (2) ERDA's apparent vacillation in getting on with the job of developing a waste disposal facility and, in particular, their about-face on salt-mine disposal in Kansas.

While such experiences obviously color public opinion, neither relates to the actual merits of the proposed technology. Actually, the question of how and where such wastes will be disposed of still exists today, because ERDA (and previously AEC) in assessing its overall nuclear priorities, including the technology, need, and cost, knowingly gave the matter the low priority it technically deserves. Perhaps, if the ERDA and their predecessor (the AEC) could have predicted the undue concern over this matter by the public as well as the misrepresentation of this issue by the nuclear critics, the problem of waste disposal would have been resolved by now, as undoubtedly it can be. In any event, the most promising disposal scheme at the present time is underground disposal in a salt bed.

Safeguards. The possibility of the diversion of fissionable material by a terrorist or extremist group was belatedly recognized by the AEC and is still being assessed by the NRC.[18] In this regard, a quotation from the writings of Ralph Lapp,[19] in which I fully concur, is apropos.

> "The safeguarding of nuclear materials is a serious matter but it is not solved by throwing out both baby and bath. It is an international problem and if the United States were to opt out of the nuclear power business, the problem would still remain.

Table 5. Occupational Health Impacts from 1000-MW(e) Power Plants of Various Types*

	Deaths/ year	Injuries/ year	Days lost/ year
Coal, deep	4	112.3	15,280
Coal, surface	2.64	41.2	3,091
Oil, onshore	0.35	32.3	3,609
Oil, offshore	0.35	32.3	3,609
Oil, import	0.06	5.7	689
Gas	0.2	18.3	1,986
Nuclear (LWR)	0.153	5.37	270

*From "Energy and the Environment," Electrical Power, prepared by the Council on Environmental Quality, August 1973.

> "The United States has the responsibility of setting the highest standards of material accountability so that it sets a good example for the rest of the world.
>
> "The Nuclear Regulatory Commission is subjecting the safeguards issue to the most careful scrutiny. It is an integral part of its licensing of the fuel reprocessing facilities and is, of course, fundamental to plutonium recycle. NRC proceedings in this examination of materials accountability and safeguards is subject to public intervention."

The NRC has already significantly tightened its regulations in this respect and, as a consequence of studies still in progress, is expected to tighten them even further.

SUMMARY AND CONCLUSIONS

Any article concerned with the issues raised by nuclear power inherently tends to become somewhat defensive, as I expect this may be. While it is necessary to confront the issues with facts, these and other facts tell, in a very positive way, the benefits and advantages of nuclear energy. Without trying to be a nuclear evangelist, I hope I have conveyed to you with facts the basis behind my enthusiasm for nuclear power. Furthermore, there is reason to believe that this message is getting through to the general public. In particular, the same Louis Harris poll I referred to earlier included some other questions by which they determined not only the public attitude toward nuclear power but also what various groups expected the public attitude to be. As shown in Table 6, the public is more "enlightened" than was anticipated by any of the groups questioned. The response to another question concerning public confidence in various groups is shown in Table 7. I haven't attempted to interpret these results, but it seems that the utility people are holding their own with the newspapers. However, rather than running ads in newspapers they ought to seek university support. Furthermore, from the ratings given our public officials, it would appear that we have more politicians than statesmen.

I would like to conclude with some comments from a recent editorial I prepared for *Nuclear Safety*.[21]

> "In brief, it is this observer's opinion that (1) some of the criticism has been valid and has resulted in improving nuclear power technology; (2) much criticism has been proved to be outdated, overstated, and/or groundless; (3) neither ERDA nor NRC is omniscient, but they (as well as their common predecessor, the AEC) have adequately responded — sometimes under external pressure — to the valid technical concerns that have been raised; (4) the nuclear community is proceeding on a responsibly safe and desirable course in developing a vital energy option; (5) the technical criticism of nuclear power has peaked out and is now on the decline, although it will continue to be a real factor in nuclear decisions for many years; and (6) having unsuccessfully challenged nuclear power technology on technical issues, some unrelenting critics are resorting to the political arena.

Table 6. Various Concepts of Public Attitude Toward Nuclear Power*

Group	Favor	Opposed	Not sure
Political leaders	42	38	20
Business leaders	36	48	16
Regulators	45	40	15
Environmentalists	38	34	28
Public	63	19	38

*From 1975 Louis Harris & Associates public opinion poll.

Table 7. Public Confidence in Various Groups*

1.	Scientists	58	9.	Foundations	17
2.	NRC	38	10.	State governors	9
3.	ERDA	35	11.	Senators	8
4.	Environmentalists	26	12.	Representatives	7
5.	President Ford	24	13.	Ads by pro-nucs	7
6.	TV news	22	14.	Labor unions	7
7.	Newspapers	18	15.	Ads by anti-nucs	6
8.	Utility heads	18			

*From 1975 Louis Harris & Associates public opinion poll.

"In taking this position, I am not unaware of the 'loose' ends' that currently plague nuclear proponents (e.g., waste disposal, plutonium dispersal, diversion, reprocessing, etc.). I simply do not see in them any problems having solutions that would significantly compromise the safety and other virtues of nuclear power or override our national need to exploit same. On the other hand, I would not want all critics to fold up their tents and go away — some have played an important role in the safe development of nuclear power to date and can continue to serve a useful purpose. However, the present attempts of some critics to delay implementation of nuclear power through the political process reflect their inability to carry their arguments in the technical forum. Unfortunately, the political struggle may become more intensive and protracted than the technical one, unless the nuclear proponents can effectively educate the general public and their elected representatives. This education involves a psychological problem, namely the public's apprehensions associated with the use of a new and different technology. I have no doubts as to the ultimate outcome of this struggle since the facts will eventually out, but each year, month, or even day that it is protracted in the rearguard actions of a lost cause is that much more cost to all concerned."

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NUCLEAR SAFEGUARDS

Theodore B. Taylor

Princeton University

Princeton, New Jersey 08540

The main subject of my lecture is the safeguarding of nuclear facilities and nuclear materials against purposeful abuse for destructive purposes, whether by terrorists or other types of criminals, or by national governments. I am convinced that new actions by the nuclear industry, by various levels of government in the United States, and by multinational and international organizations could reduce such risks substantially below what they would be if the actions are not taken, and with a high sense of urgency. But I am also convinced that the risks of purposeful nuclear violence cannot be reduced absolutely to zero. To view these risks in perspective, therefore, it is necessary also to consider energy alternatives to nuclear fission, not only in terms of economics and technical practicality, but also in terms of environmental impact, risks of accidents, international political and military stability, and a number of other factors.

As has been clear from this series so far, all forms of energy technology, especially when used on a large scale, carry with them some risks. Mining of coal or uranium, or extraction of oil or natural gas can kill or disable people, and pollute the environment. Combustion of fossil fuels causes sickness and regional and possibly global changes in climate, changes that, conceivably, may lead to catastrophic expansion or melting of the arctic masses of ice. Nuclear power plants cores, though they cannot in any sense explode like an A-bomb, can accidentally melt and release dangerous quantities of radioactive materials. Nations can divert nuclear fuels from peaceful purposes to stockpiles of nuclear weapons that they may sometime use in war. They can also "divert" coal or petroleum products for making chemical explosives and ammunition. Terrorists or extortionists may someday use fission bombs made with stolen plutonium to serve their purposes. They now use bombs made from fossil fuels. Even solar energy, if collected on a large scale in areas that normally reflect much of the incident sunlight, may regionally change the heat balance in ways that make regional weather more unstable.

I contend that no group of people in this country or any other knows as much as should or could be known about the risks and possible benefits associated with any major present or prospective source of energy to be able to formulate an evidently sensible energy policy for either short range or long range implementation. When we consider coal, or petroleum, or natural gas, or fission, or fusion, or solar or geothermal or ocean thermal energy, we simply don't know what large scale further or new development of any of these will do to our environment, our economy, and our social structure, all within very wide limits of uncertainty. These uncertainties can never be reduced to zero, nor can the risks associated with any energy source. But I am convinced that we must do a great deal more than we are now doing or planning to do, to try to reduce these uncertainties, and then set forth our energy policies accordingly, or run high risks of doing irreversible economic, environmental, and social damage on a very big scale. The setting up of state, national, and international programs to assess the impact of large scale implimentations of each of several dozen different types of energy systems, from initial extractions through the ultimate disposal of waste heat, should be undertaken with an extremely high source of urgency. I have estimated that an allocation by the Energy Research and Development Administraction of a total of approximately $1 billion for the next five years, for this purpose, would be reasonable at the national level.

I shall now present a brief overview of some of the risks of purposeful abuse of nuclear materials and facilities for destructive purposes and of actions that could reduce these risks substantially. Various technical and non-technical aspects of this subject are covered in much greater detail in a number of recent publications.[1-9]

Given roughly ten kilograms (roughly twenty pounds) of reactor-grade plutonium oxide or about twenty kilograms of highly enriched uranium oxide, and using information that is widely published and materials and equipment available from commercial sources, it is quite conceivable that a criminal or terrorist group, or even one person working alone, could design and build a crude fission bomb that could be carried in a small automobile and that would be likely to explode with a yield equivalent to at least 100 tons of high explosive. Such an explosion in an especially densely populated area, such as lower Manhattan, could kill more than 100,000 people.

More efficient, reliable, higher yield, and compact nuclear explosives for military purposes could be designed and built by any country that has reactor-grade plutonium within its borders, using information and equipment that is generally obtainable worldwide. As long as five major nuclear weapons powers continue to behave as though they feel more secure with nuclear weapons than without them, I think we can expect other countries to follow suit. Technically, at least, just about any country that really wants nuclear weapons can have them, one way or another.

Plutonium, if dispersed in micron-size or smaller particles suspended in air, could also be used as means for causing large numbers of human casualties and considerable property damage in a densely populated enclosed area. As little as a few grams of plutonium more or less uniformly distributed in the air inside an office or residential building area of several thousand square feet for fifteen minutes could deliver an inhalation dose to the occupants that would be likely to cause death from cancer some 10 to 30 years later. Dispersal of plutonium in <u>outside air</u>, on the other hand, is likely to require considerably larger amounts of plutonium to lead to the same number of eventual fatalities as in an enclosed area. In either case, however, the potential threat of dispersal of plutonium in populated areas appears to be substantially less than potential threats of use of any of a large number of dispersed, poisonous chemical or biological agents or radioactive materials other than plutonium for blackmail or terrorist purposes.

Nuclear power plants, shipments of spent fuel discharged from power plants, nuclear fuel reprocessing plants, and high level radioactive waste storage facilities all have sufficiently large inventories of radioactive materials so that, if released and dispersed in populated areas by acts of sabotage, they could produce large numbers of human casualties and property damage. Studies of these types of risks have been underway for some time in the Energy Research and Development Administration (ERDA). Much of the substance of these studies is classified and is likely to remain so. I do not want to give the impression, however, that these studies are classified because the risks appear to be especially high, and difficult to reduce substantially. On the contrary, I find it difficult to conceive of ways of sabotaging nuclear facilities or shipments in ways that would cause as much damage as the release of relatively accessible chemical or biological poisons, or the sabotage of some types of non-nuclear facilities containing large quantities of chemical explosives or combustibles.

Of these types of risks associated with nuclear power systems, the ones I am most concerned about are the first two, that is, the use of stolen or diverted plutonium or highly enriched uranium in nuclear explosives for terrorist or other criminal purposes or by countries that want to join the nuclear weapons club. I shall therefore concentrate on these types of risk, and what can be done to reduce them, in the rest of my lecture.

Although the present rate of production of plutonium in U. S. power reactors is already very large--more than 10,000 kilograms per year--no commercial nuclear fuel reprocessing plants for separating this plutonium from fission products and uranium are operating in the U. S., nor are any expected to start operations for at least several years. Until this happens, the plutonium in the unprocessed fuel will not only be very dilute, and in a form not usable in fission explosives, but also will be impressively self-protecting because of the intense, highly penetrating radioactivity of the contained fission products. This situation will change markedly when fuel starts being reprocessed, and the separated plutonium is extracted and stored as plutonium nitrate solution. The chemistry for conversion of this solution to plutonium oxide, which could be used directly in a fission bomb, is straightforward and widely published. Since even minute quantities of plutonium are toxic, especially if inhaled, such an operation can be done safely only if people working with the material are protected from the plutonium by an air-tight barrier or by inhalation masks. But heavy shielding is not required.

The time at which any commercially extracted plutonium nitrate will be converted to plutonium oxide powder, for subsequent incorporation into fresh fuel for plutonium recycling, is uncertain. It depends to a large extent on the timing of decisions by the Nuclear Regulatory Commission (NRC) concerning additional safety and safeguards related regulations that may be imposed on recycled plutonium. The earliest possible time at which plutonium may be routinely recycled in the U. S. is about 1980, and this may well be delayed into the mid 1980's. In Western Europe and Japan, however, it is quite possible that routine recycle of plutonium may start sooner than in the United States.

Contrary to rather widespread belief, separation of plutonium from irradiated nuclear fuel, and its subsequent incorporation into nuclear weapons suitable for military purposes, is not potentially beyond the capability of most countries. A commercially competitive nuclear fuel reprocessing plant that produces separated plutonium and uranium that meets the stringent quality control specifications required by the nuclear industry is a highly complex, sophisticated, several hundred million dollar (at least) facility. But a reprocessing facility designed to extract plutonium for only nuclear weapons could be considerably smaller, simpler, and less expensive. It is possible to describe such a facility in a form that would require only a few months for construction, and an operating crew of less than a dozen appropriately skilled people, using information that is widely published, and materials and equipment that are commercially available worldwide.

Until very recently and, as far as I can determine, through the present time, U. S. safeguards applied to commercial plutonium and highly enriched uranium are not adequate to prevent theft by heavily armed groups with resources and motivation comparable to the Brinks gang and other groups of professional criminals that have carried out successful major robberies in the past.[10] Though not routinely recycled in power plants, plutonium for R&D purposes is now stored and transported in substantial quantities, annual shipments amounting to at least several hundred kilograms per year. Systematic studies are now being carried out by NRC, however, to determine the comparative costs and benefits of a wide variety of possible more stringent physical security and materials accounting measures. These studies are likely to provide much of the information required for further NRC decisions concerning regulations.

I have no evidence that physical security safeguards for fission product-free plutonium or highly enriched uranium are significantly more stringent in foreign countries than in the United States. Something like fifty countries either now have or have announced plans for building power reactors that produce several hundred kilograms or more of plutonium per year. Nuclear theft is therefore clearly an international risk. The International Atomic Energy Agency has responsibilities for international safeguards to detect diversion of nuclear materials from peaceful purposes to the illicit construction of nuclear weapons, but is not responsible for physical security measures to prevent theft. This is left to national governments to do. The IAEA has, however, made recommendations for such physical security measures.

A guiding principle, called the "principle of containment" has been proposed for the design and assessment of security systems for the protection of special nuclear materials.[11] According to this principle, all materials that could be used to make fission explosives and that are used, produced, or processed in the nuclear power industry would be contained in areas circumscribed by a well defined set of barriers. These barriers would exclude unauthorized persons. A minimum number of authorized channels for the flow of such materials through the barriers would be established. All other channels would be continuously monitored, by means of the best available technology, to detect any unauthorized flow of materials. In addition to the physical barriers, and other deterrents to theft, a network of alarms, communications, and security forces would be set up in such a way that no credible attempt to remove nuclear materials from authorized channels, whether by employees, outsiders, or a combination, would be successful.

Some of the specific security measures that might effectively be used in applying this principle and that are under study by NRC are the following:

* Use of specially designed motor vehicles and shipment vans to protect shipments of special nuclear materials from rather massive and sophisticated attempts to penetrate the van or commandeer the vehicle for sufficiently long times to allow large law enforcement, or even military forces to arrive at the scene of an attempted hijacking before it can be completed.
* As an alternative to the above measure, the use of rail transport of all special nuclear materials inside shipping containers similar to the roughly 100 ton containers contemplated for use in shipping irradiated fuel from reactors to reprocessing plants.
* Colocation of fuel reprocessing and fuel fabrication plants, to avoid shipment of concentrated, fission product-free special nuclear materials between the two.
* Dilution of separated plutonium by slightly enriched or natural uranium at the output stages of reprocessing plants, to produce the mixed oxide fuel materials <u>before</u> transfer to a fuel fabrication plant. In equilibrium, the concentration of plutonium in mixed oxide fuel would be about 0.6% to 1% if all refabricated fuel for a light water reactor power system consisted of mixed oxides.[12] This would not only lead to a requirement for chemical separation of the plutonium from stolen fuel material before it could be used for making fission explosives, but also, and perhaps more importantly, increase by about a factor of 100 the total weight of fuel material that would have to be stolen to provide a given weight of contained plutonium. These advantages, from

a physical security point of view, must be weighed against the likely additional costs of fabricating mixed oxide fuels, compared to the current plan for using much higher concentrations of plutonium (from 3% to 7%) in a much smaller fraction of the fuel rods contained in a reactor fuel assembly. The high toxicity of plutonium generally requires the use of air-tight process enclosures, which adds substantially to the cost of fabricating fuel rods that contain plutonium.

* Recycling of fuel with as high a concentration of plutonium as possible through a small fraction of the power plants that produce plutonium--essentially the opposite of the preceding possibility. The purpose in doing this would be to reduce to a minimum the number of power plants that receive fuel that contains plutonium, as well as the total number of shipments of plutonium. Under such conditions, all plutonium could be recycled, but less than half, and perhaps as few as about one fifth of all power plants would use recycled plutonium. The value of plutonium produced in reactors that did not receive fuel with recycled plutonium could be exchanged for money or for discounts on fresh uranium fuel.

* The establishment of a Federal protective service for the explicit purpose of safeguarding nuclear materials in transit and also at fixed sites. This possibility has been assessed by the Nuclear Regulatory Commission and, for reasons I find unconvincing, has been at least temporarily discarded.

A common reaction to these and other proposed major new safeguards measures is that, taken together, their costs are likely to make nuclear power economically uncompetitive with alternative sources of energy. Preliminary studies of the capital and operating costs of considerable more effective safeguards than those called for by present regulations, however, strongly suggest that this is not the case. One such set of estimates, for example, leads to the conclusion that the operating costs of a rather massive security system applied to light water reactor fuel cycles, with routine recycle of plutonium, would correspond to less than 1% of the cost of nuclear electric power produced by the system.[13] The total number of physical security personnel employed for the safeguarding of an 80,000 MW(e) light water reactor fuel cycle, with 20 separately sited power plants, was taken to be about 800, of whom approximately 150 would be on duty at any particular time.

Thus, from technical and economic standpoints, it appears to be possible to design physical security systems that would require skills and resources greater than those used for major thefts of valuables in the past for successful theft of potentially dangerous quantities of special nuclear materials. Whether or not the institutional and political obstacles confronting efforts to implement such effective safeguards against theft, by criminals or terrorists worldwide can be overcome within the next few years, however, remains to be seen.

As for preventing nations that do not now have nuclear weapons from getting them, I am much less sanguine, even from a strictly technical and economic point of view. I'm afraid it is becoming a fact of life that just about any country that really wants nuclear weapons will be able to have them, one way or another, whatever forms international nuclear power take, and whatever is done to try to prevent further national nuclear weapon proliferation. Nuclear power plants can be used to produce plutonium for nuclear weapons if the plants are not safeguarded effectively, or if a nation is willing to break agreements under what it believes to be high pressures to maintain or increase its national security. This option will persist even if all plutonium is extracted and refabricated in internationally operated regional centers. If a country has no nuclear reactors, it will have at least three options for acquiring nuclear materials for weapons: First, construct a plutonium production reactor using natural uranium and either heavy water or pure graphite, using information that is widely published and skills that can be developed or bought. Second, build a facility for enriching indigenous uranium. This is now very difficult and costly, but likely to become much less so as time goes by. Third, the country could arrange to steal high enriched uranium or plutonium from some other country.

Nevertheless, it is clear that actions could be taken to make national nuclear weapon proliferation more immediately detectable, and more difficult and costly than without taking new actions internationally. Among such possibilities are the following:

- IAEA technical safeguards to detect transfers of nuclear weapon materials from where they are authorized to where they are not, in very short times after such diversion, are technically possible, at very low costs compared to the costs of nuclear power.
- By international agreement, the separation of any plutonium from spent reactor fuel could be postponed for a number of years, to give the

world time to determine, in a concerted way, how best to deal with plutonium in the long run. This would not prevent national proliferation, but would require a national decision to build a reprocessing facility to use plutonium made in its power plants. This will take some time, though not long, and is likely to be a visible act, if only through national intelligence systems. Until plutonium breeder power plants exist in substantial numbers, the economic penalty for not recycling this plutonium would appear to be a few percent of the cost of nuclear power, at most. Another major benefit of not separating plutonium from spent fuel is that it would avoid the presence of plutonium not protected by massive gamma radiation levels, at all points in the fuel cycle (as it is now), greatly reducing the risks of theft of the plutonium by criminals.

* An alternative to recycling plutonium in low enrichment reactors and, later, in plutonium fast breeders, is to shift gradually to the ^{233}U-thorium cycle. From a proliferation standpoint, this would offer the opportunity for "denaturing" the ^{235}U or ^{233}U - that is, mixing it with enough ^{238}U to keep the enrichment below about 20%, rendering it useless for any practical nuclear explosions, unless it is further enriched. The possibility is excluded for plutonium, since no "denaturing" isotope of plutonium will exist in significant quantities. If the concentration of fissile material (^{235}U or ^{233}U) with respect to thorium is of the order of 5% or so, such a fuel would produce substantially more ^{233}U than plutonium. The ^{233}U could be separated at effectively safeguarded regional centers, and recycled in fresh fuel for national power plants. The relatively small amount of plutonium could be consumed in reactors at the regional center, and not nationally recycled. Such a system would allow recycling of produced nuclear fuels, but not as weapons - grade material, and the relatively small amount of produced plutonium would be highly self-protecting, in spent fuel, against theft by criminals.

If such a cycle were eventually to be attractive from a fuel reserves point of view, a method for achieving a self-sustaining cycle with respect to thorium would be required. The presence of ^{238}U in this cycle, for denaturing purposes, will probably not allow the converted light water or heavy water reactors to be true breeders. Highly preliminary estimates suggest that the overall conversion ratio of the thorium cycle in thermal neutron breeders or conversion reactors would be reduced by about 0.1 by including the ^{238}U in the fuel mix. There are several possibilities for producing enough "makeup" U^{233} from some additional source, however, to make the overall cycle self sustaining. One is to use plutonium fast breeders of the regional centers to convert plutonium in the cores to ^{233}U in thorium blankets. Another, more speculative possibility is to use neutrons from fusion reactors to make ^{233}U in a thorium blanket. This may conceivably become economically attractive before fusion for direct power production does.

* Still another possibility would be an orderly phase out of nuclear power, relying on alternative energy sources. From a long range point of view, coal and solar energy are probably the only practical non-nuclear alternatives. The former is fraught with very troublesome environmental issues, as well as being very non-uniformly distributed. The latter has yet to be proven out commercially for widely distributed heating and cooling applications, and is even more in doubt for process heat and electric power production. One can expect major technological advances on both fronts within the next decade, however.

In short, whatever may now be the risks of nuclear weapon proliferation, by countries or by non-national groups, they will not go to zero whatever is done to control them. But I have a strong conviction that we can and should delay firm commitments to a long range plutonium economy until the possible alternatives are thoroughly examined.

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Issues in Plutonium Toxicity*

Bernard L. Cohen
University of Pittsburgh

Toxicity of Plutonium from ICRP-BEIR Data

The calculation of the cancer risk due to exposure to plutonium alpha emitting isotopes consists of

(1) determination of the dose in rem to each exposed body organ using ICRP data
(2) use of BEIR estimates of cancer risk per rem vs age
(3) average over ages

We now explain these factors in turn.

(1) The dose in rem is defined as

$$\text{rem} = \frac{\text{energy deposited } (\div 100 \text{ ergs})}{\text{mass of body organ (gm)}} \times \text{RBE}$$

where RBE, the relative biological effectiveness, is obtained from ICRP as 50 in bone and 10 in other organs

masses of body organs are given by ICRP for standard man (ICRP Publication No. 23)

energy deposit = energy of alphas x alphas emitted per day x number of days Pu remains in organ

The fraction of Pu intake spending various times in various organs is available from ICRP (Publication No. 19). For example, if PuO_2 particulate of 1 micron diameter is inhaled, 25% deposits in the lung; 40% of this is eliminated with a one day half life to the gastro-intestinal (G-I) tract, another 40% is transferred with a 500 day half life into the lymph nodes from which it goes with a 1000 day half-life into the blood stream, and 5% passes directly into the blood stream with a 500 day half life. Of the material getting into the G-I tract, 3×10^{-5} penetrates the intestine walls into the blood stream and the rest is excreted. Of that in the blood stream, 45% ends up in the bone and 45% goes to the liver. It is eliminated from bone with a 70 year half life and from the liver with a 35 year half life.

From this it is clear that the lung is exposed to 0.25 x (0.4+0.15+0.05) = 15% of the inhaled plutonium for an average of $500/\ln 2$ days. The bone collects 0.25 x (0.15+0.05) x 0.45 = 2.3% of the inhaled Pu and keeps it for

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*Paper presented at Annual Meeting of American Nuclear Society, July 1976. It is based on a more detailed paper to be published in Health Physics. References are given therein.

essentially the remainder of life; etc. Thus the dose to lung, bone, etc are calculable in rem per microcurie inhaled.

(2) The BEIR Report recommends a model in which there is a 15 year latent period following exposure during which there are no effects, followed by a 30 year "plateau" period during which there is a constant risk, r. It gives $r = 1.3 \times 10^{-6}$ per yr-rem for lung cancer, 0.2×10^{-6} per yr-rem for bone cancer, etc. For children less than 10 years old, these are divided by 5. For an older person, there is a calculable probability that death will result from other causes before the cancer develops. From these one can calculate the cancer risk per rem as a function of age at intake.

(3) Combining (1) and (2) and averaging over age gives the average cancer risk per microcurie of Pu inhaled.

The results are given in Table I for Pu^{239} (16.3 gm per curie) and for the mixture of isotopes in typical reactor-Pu (2.5 gm/curie). The inverse of the risk per microgram inhaled is called the "cancer-causing" dose; for Pu^{239} it is 1300 μg. In view of the linearity hypothesis in the dose-effect relationship, one expects one cancer for every 1300 μgm inhaled by people in a large population.

Table I: Cancer-causing Doses (microgram)*

Entrance Mode	Pu^{239}	Reactor-Pu
inhalation (particulate in air)	1300	200
injection in blood stream	280	44
ingestion with food or water	6.5×10^6	1×10^6

*defined as the inverse of the risk per microgram. See discussion in text.

Slightly different procedures were used by the British Medical Research Council in its report "The Toxicity of Plutonium" and by C. W. Mays (one of the principals in the experiments with Pu in dogs) in IAEA-SM-202/806. They obtain cancer-causing Pu^{239} doses of 820 and 1250 μg respectively, but they do not include age dependences, calculating for the most unfavorable age (young adults). The value used here is thus in reasonable agreement with those.

If Pu is injected directly into the blood stream, the bone and liver receive 45% of it rather than the 2.3% following inhalation, so bone and liver cancers are much more frequent; but in this case there are no lung cancers which are the dominant effect from inhalation. The calculated results are given in Table I.

If Pu is ingested with food or water, the danger is greatly reduced by the fact that Pu does not easily pass through the intestine walls, so only 30 parts per million gets into the blood stream. The bone and liver cancer risks are thus reduced relative to that from injection by that factor. There is, in addition, a risk of similar magnitude of cancer of the G-I tract (colon, stomach). These results are also shown in Table I.

Genetic effects, due to concentration of Pu in the gonads, are roughly 1/5 of the number of cancers. These are expected to occur over the following

5-10 generations.

All of these estimates are based on data from radiation effects on humans as analyzed in the BEIR Report. These include the Japanese A-bomb survivors, miners exposed to radon gas, people treated with radium or with x-rays, etc. None of these effects were from Pu. However, there is a considerable amount of data from animal studies with Pu, and this is summarized for lung cancer in Figure 1 where the line shows the estimate from our calculation. In general the agreement is not unreasonable. There has been a great deal of publicity about the high point for dogs at an abscissa value of about 1.2×10^3, but we see that our curve passes within the error bars given by the authors. One aspect of that experiment that is frequently overlooked is that the latent period for development of the cancers increased with decreasing dose, and in fact the dogs contributing to the point under discussion developed cancer very late in life. If this effect is extrapolated to lower doses, the latent period for most doses usually considered would greatly exceed life expectancy, so the effects derived from the linearity hypothesis would be greatly reduced.

Criticisms of Standard Procedures

Critics of nuclear power have objected to treatments like the one we have given. The best known of these objections is the "hot-particle" theory, which gives greatly increased effects (by a factor $\sim 10^5$) due to the fact that the Pu is not evenly distributed over the lung but is concentrated in particles which give much higher than average doses to a few cells. This theory has been studied and rejected by the following groups:

(1) NCRP in its Publication No. 46.
(2) British Medical Research Council in its publication "The Toxicity of Plutonium".
(3) United Kingdom National Radiological Protection Board in its Report R-29 and Bulletin No. 8 (1974).
(4) U.S. AEC in the most elaborate study, WASH-1320.
(5) U.S. NRC in Federal Register, Vol. 41, No. 76.
(6) Several publications by individuals.

There is also a National Academy of Sciences study expected to report soon. One easily understood aspect of these criticisms is that there were about 25 workers at Los Alamos who inhaled varying amounts of Pu about 30 years ago, and according to the "hot particle" theory each should have experienced an average of over 100 lung cancers, whereas there have been no lung cancers among them.

After these criticisms of the "hot particle" theory appeared, John Gofman came out with a new theory giving enhanced effects. His basic premise is that cigarette smoking destroys cilia and thereby greatly retards bronchial clearance, making Pu much more dangerous to humans than to animals since the latter do not smoke. He manages to explain the lack of lung cancers among the 25 Los Alamos workers by a combination of four improbable hypotheses, the failure of any one of which would destroy his theory.

There have been at least seven individual critiques of the Gofman theory. One criticism is that direct measurements of bronchial clearance rates (by inhalation of radioactively labeled dust followed by measurements of radiation emitted) show little difference between smokers and non-smokers. Apparently smokers do more coughing and have more mucus flow to compensate for loss of cilia. Another criticism is that if bronchial clearance were as slow

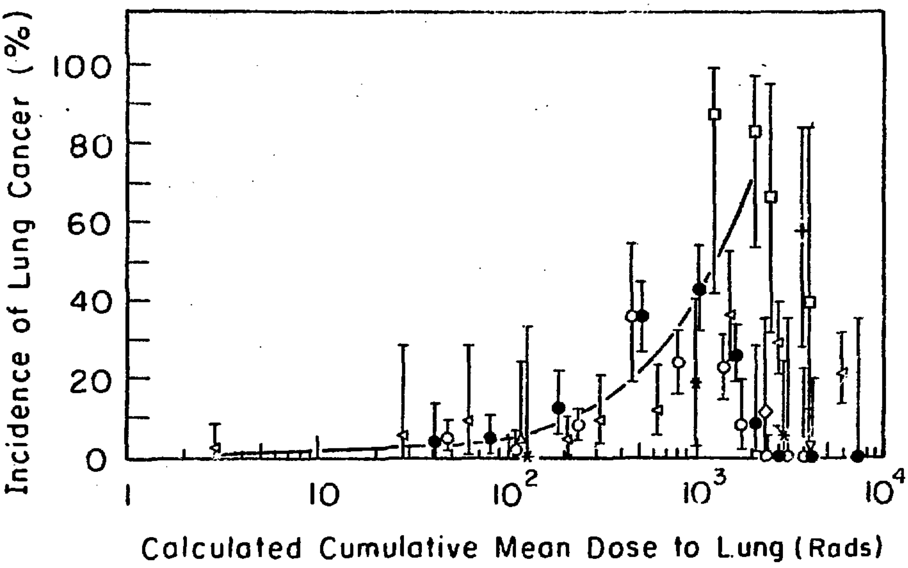

Figure 1

□ PuO_2, dogs, J. F. Park, private communication to R. C. Thompson quoted in BNWL-SA-4911

▽ PuO_2, mice, L. A. Temple et al., Nature 183, 498 (1959).

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◁ Pu nitrate, rats, R. A. Erokhin et al., translation in AEC-tr-7337 (1971), p. 344.

\+ Pu nitrate, rabbits, N. A. Koshurnikova, translation in AEC-tr-7387 (1971), p. 334.

* Pu pentacarbonate, rabbits, N. A. Koshurnikova, translation in AEC-tr-7387 (1971), p.334.

as Gofman hypothesizes, smokers would die of suffocation from ordinary dust. Gofman has suggested that the great increase in lung cancer in recent years may be due to Pu, but this increase has been steady since the 1930s whereas Pu-induced cancers should not have occured until 1960. Moreover, the lung cancer increases have been in areas with chemical industry and high air pollution, and there has been no increase in areas down-wind from the Nevada test site where Pu would have its maximum effect.

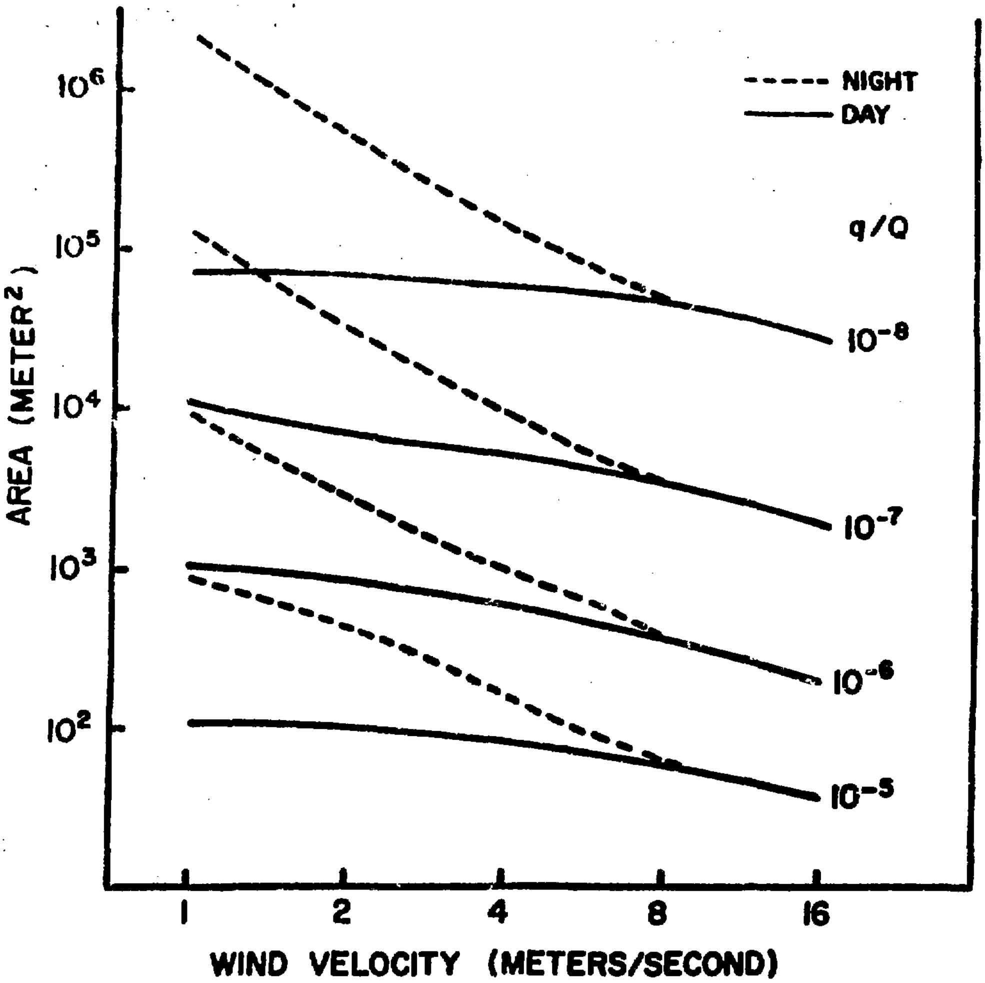
A relatively less publicized attack on the conventional approach to evaluating plutonium toxicity is the "warm particle" theory of Edward Martell. He hypothesizes that natural radiation is one of the principal causes of cancer, but this idea is rejected by the cancer research community.

K. Z. Morgan has proposed that the RBE in bone might be 250 times larger than the usual value of 50. C. W. Mays, on whose experiments much of Morgan's hypothesis is based, reanalyzed Morgan's work and concluded that if his approach is correct, the increase should be only by a factor of 10. There is experimental information on this from the supposedly "terminally-ill" patients injected with Pu in 1945-46 to study Pu metabolism. Four of these are still alive and one who was injected with a rather large quantity lived until 1968. If the RBE of Pu were 10 times the present value, there is a good chance that one of these five would have gotten bone cancer but none did. Since our calculated inhalation effects are dominated by lung cancer, a factor of 10 increase in bone cancer risk would only double the total inhalation risk.

In evaluating all of the criticisms outlined above, it is important to realize that they are actively considered every year by a committee of ICRP and they have repeatedly been rejected. Likewise EPA, which has jurisdiction in the U.S, studied the matter and decided not to modify its standards. No standard-setting or official study group in any country has given credence to any of these criticisms of standard procedures.

Consequences of Plutonium Dispersal

It is clear from Table I that Pu is dangerous principally as an inhalant, so we now consider the consequences of a dispersal of PuO_2 powder in a populated area. The calculations are done with the Gaussian Plume Model, in which the dust cloud moves with the wind dispersing as a gaussian distribution in the downwind, cross-wind and vertical directions. Meteorologists have determined the widths of these gaussian distributions as a function of wind velocity and atmospheric stability. Figure 2 shows the results of calculations assigning the atmospheric stability most characteristic of each wind velocity. This is different between day and night, so separate curves are given for each. These curves give the area within which various fractions, q/Q, of the dispersed Pu are inhaled. For example, we see from Fig. 2 that for a typical 8 m/sec wind velocity, only in an area of 500 m^2 is as much as 10^{-6} of the dispersed Pu inhaled. A typical city population is 10^{-2} people per m^2, so there would typically be about 5 people in this area. Similarly, about 50 people would inhale 10^{-7}, 500 people would inhale 10^{-8}, etc of the dispersed Pu. Since we know the cancer risk per microgram of Pu inhaled, it is straightforward to calculate the total number of cancers expected per gram of Pu dispersed. When corrections are applied for the fraction of typical PuO_2 powders that are in particulate of respirable size, the efficiency in dispersal, and the protection afforded by being inside buildings, the result is that we may expect about one eventual cancer for every 15 grams of Pu dispersed, or about 30 fatalities per pound. If there is a warning, as in a blackmail scenario, people can be instructed to breathe through a folded handkerchief or



Area over which the ratio of inhaled to dispersed Pu has values shown for q/Q, vs wind velocity under typical day and night atmospheric conditions.

a thick article of clothing, with a resulting ten-fold decrease in fatalities to 3 per pound dispersed.

Eventually the Pu settles to the ground and may be resuspended by being blown up by winds. Within the first few months, this causes about 0.014 fatalities per gram dispersed, about 5 times less than inhalation from the initial cloud. Beyond this time period, resuspension is of much less and continually decreasing importance as the Pu becomes part of the soil like any other part.

Of course, Pu^{239} lasts for tens of thousands of years, so let us consider its effects over this time period. We know the amount of uranium in soil and we know how much there is in the air, so we can estimate how much is inhaled per year -- about $1.3x10^{-11}$ of that in the top 20 cm of soil. If this factor is applied to the Pu after it becomes part of the soil, we find that over the 25,000 year half-life there will eventually be about one fatality per 2500 gm of Pu dispersed.

A summary of all these effects of Pu dispersal is given in Table II. It also includes plant uptake into food which is a small effect due to the slow rate at which Pu penetrates membranes.

Table II: Summary on fatalities per gram of reactor-Pu dispersed

Source	Fatalities/gram dispersed
Inhalation from cloud	0.067 (1/15)
Resuspension	0.014
Long term	0.0004 (1/2500)
Plant uptake into food	0.00004
Total	0.081

Perspectives on Dangers of Pu Dispersal

The fear is sometimes expressed that the world may become "contaminated" with Pu^{239}. To evaluate this potentiality, we calculate that if all of the world's electric power were produced by fast breeder reactors in an equilibrium situation where Pu is consumed as fast as it is produced, the total amount of Pu^{239} in the world would be $2x10^8$ curie. By comparison, the radium (Ra^{226}) in each meter of depth of the earth's crust is $1.2x10^9$ curie, so there is as much Ra in each 17 cm of depth as there would be Pu^{239} in the whole world. For ingestion, Ra is 40 times more toxic than Pu as it passes through the intestine walls much more easily. For direct inhalation, Ra is less hazardous than Pu, but it serves as a source of radon gas which is a very serious inhalation hazard so as materials on the ground,Ra is a 40 times greater inhalation hazard than Ra. Thus, as a long term hazard either for ingestion or inhalation, Ra is 40 times worse than Pu and the total Pu in existence from an all-breeder power system would be as dangerous as the Ra in each 4 mm of our soil.

Of course nearly all of this Pu would be in reactors or in other parts of the nuclear industry, well isolated from the environment. In fact if we used breeder reactors for a hundred thousand years (so Pu^{239} decay is in equilibrium with its sources), the total Pu accumulated in the environment would be only 0.4% of that in the nuclear industry.

The total Pu releases from the U.S. nuclear industry with present technology is estimated to be about 1 gram per year. This does not include releases in reactor accidents; if the Rasmussen probabilities are assumed to apply to LMFBRs, average annual releases would be about 40 grams per year, so this source is dominant over routine releases. It would cause about one fatality every 2-3 years.

The same estimate of Pu toxicity predicts about 200 U.S. fatalities to date from Pu releases in bomb tests, and 4000 in the world. It also predicts about 200 fatalities world-wide from the re-entry burn-up of an earth satellite carrying a SNAP reactor heat source using Pu^{238}.

It is important to keep in mind that all of these estimates are theoretical, based on the linear-no threshold hypothesis of dose-effect relationship. There is no evidence for Pu toxicity having caused serious injury to any human being, anywhere, ever.

One often hears that in large scale production of plutonium we will be creating unprecedented quantities of poisonous material. Since Pu is dangerous principally as an inhalant, we compare it in Table III with quantities of other poisonous inhalants produced in the U.S.

Table III: Lethal inhalation doses produced annually in U.S. (trillions)

Chlorine	400
Phosgene	18
Ammonia	6
Hydrogen cyanide	6
Pu if all U.S. power were from fast breeder reactors	1

It should be noted that Pu is not easily dispersed whereas the others are gases and hence readily dispersible. Of course Pu released to the environment will last far longer than these gases which would be decomposed chemically, but it should be recalled from our earlier discussion that nearly all of the damage done in Pu dispersal is by the initial cloud of dust; all of the later resuspension and the thousands of years spent in the soil do far less damage. It is thus not unfair to compare Pu with the poison gases, and we see from Table III that it is far less of a hazard.

Terrorist Use of Pu Toxicity

One often hears that terrorists might disperse Pu, making use of its toxicity. To do so in open air and thereby cause 30 cancers per pound dispersed would hardly suit their purpose. It would only be thinkable if dispersed into the ventilation system of a large building. However, chemical poisons (e.g. those listed in Table III) would be equally effective and would take effect immediately whereas Pu would have no effect until 15 to 45 years later. Another problem from the terrorist viewpoint is that Pu dispersal could not be used as a threat in a blackmail scenario, as the problem can be eliminated by simply switching off the blowers in the ventilation system.

The use of Pu for its toxicity in a city water supply would be most ineffectual, causing about 2 eventual (15 to 45 years later) cancers per pound. Even this requires that the plutonium be in a chemical form that stays in solution. Normally it precipitates out above about pH 3, whereas water supplies are typically pH 7.

Pu Leakage from Low-level Waste Burial Grounds

There was recently substantial publicity given to an EPA Report citing evidence for leakage of Pu from a burial ground for low level waste at Maxey Flats, Kentucky. Actually, the evidence presented was far from conclusive; there are other simpler explanations for the observations reported based on above-ground transport.

However, even if the leakage mechanism proposed is found to be correct, it would not apply to deep burial like that planned for high level waste and future transuranic waste. Moreover, the level of danger is truly minimal. The plutonium in the most contaminated water found in the area is 10 times less dangerous than the radium found in average city tap water. In fact, if all of the Pu^{239} buried in Maxey Flats were to leak out and find its way into rivers, there is only about a 10% chance that it would cause a single fatality.

THE ASSESSMENT OF IMPACTS AND THE PREPARATION OF ENVIRONMENTAL IMPACT STATEMENTS FOR THE LICENSING OF NUCLEAR POWER PLANTS

by

E. G. Struxness
Environmental Sciences Division
Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830

ABSTRACT

The National Environmental Policy Act of 1969 (NEPA) established the nation's policy of protecting the environment. The Atomic Energy Commission (AEC) then, and the Energy Research and Development Administration (ERDA) and the Nuclear Regulatory Commission (NRC) now, have enlisted the aid of three national laboratories, including Oak Ridge National Laboratory (ORNL), to assist in the preparation of Environmental Impact Statements required by NEPA in connection with the licensing of nuclear power plants. This lecture describes the ORNL approach to the assessment of potential environmental impacts and the preparation of Environmental Impact Statements (EIS) for the NRC and the manner in which the EIS is used in NRC's licensing procedure.

INTRODUCTION

Under NEPA[1] and the regulations for implementing it, Environmental Impact Statements (EIS) must be prepared for all projects directly undertaken or sponsored by federal agencies; supported in whole or in part through federal agencies, contracts, grants subsidies, loans, or other forms of funding assistance; or requiring a federal lease, permit, license, or certificate. This broad inclusion covers most major developments contemplated today. Those not covered under federal law are or may soon be covered under state or local laws.

The intent is to insure the fullest practicable provision of timely public information and understanding of plans and programs with environmental impact, in order to obtain the views of interested parties.

Environmental Impact Statements[2] must include:

1. A description of the proposed action including information and technical data adequate to permit a careful assessment of the environmental impact by reviewing agencies.

2. A consideration of the probable impact of the proposed action on man and the environment, including the impact on ecological systems or sub-systems.

3. A description of any probable adverse environmental effects which cannot be avoided. Guidelines of the Council on Environmental Quality[3] say that an adverse effect is one which degrades the quality of the environment, curtails the range of beneficial uses of the environment, and allows long-term environmental goals to be sacrificed to short-term goals.

4. An analysis of appropriate alternatives to the recommended or proposed course of action. The analysis must accompany the Statement through the review process in order not to foreclose options which might have less detrimental effects.

5. A concern for the relationship between local, short-term uses of man's environment and the maintenance and enhancement of long-term beneficial uses of the environment, on the grounds that each generation is a trustee of the environment for succeeding generations.

6. The use of a systematic, interdisciplinary approach to the assessment which will insure the integrated use of the natural and social sciences and the environmental design arts in the planning and decision-making process.

The aim of this lecture is to show how the U. S. Nuclear Regulatory Commission prepares and uses environmental impact statements in the licensing and regulation of nuclear power plants.

EVALUATING ENVIRONMENTAL IMPACTS AND PREPARING IMPACT STATEMENTS FOR NUCLEAR POWER PLANTS

Basically, the evaluation of nuclear plant impacts consists of characterizing the existing environment at the site and its surroundings, and then determining how and to what extent the proposed plant may alter that environment. Estimates are made of resources that would be consumed and effluents that would be discharged by alternative plant configurations, and, concurrently, the dynamic characteristics of the receiving water and the airshed are analyzed. The estimated thermal, chemical, radioactive and sanitary discharges then are projected onto existing conditions to define, as quantitatively as possible, potential alterations to the environment and potential impacts (radiological, social, economic) on people in the environs. Biota other than man likely to be affected by the plant are inventoried, and the potential impact on these natural populations is predicted. The evaluation is extended to include estimates of potential impacts that result from accidents, transmission lines, traffic and transportation, as well as economic and societal impacts. Table 1 lists the impacts considered in the evaluation and the things that may be affected.

Impact on Air Quality

One objective of the assessment is to evaluate the effect the plant could have on air quality, particularly with respect to radionuclides in gaseous and particulate form that are routinely discharged from the plant's radioactive waste system. In assessing this potential impact, several factors have to be considered:

1. Meteorological data

TABLE 1

ANALYSIS FOR ENVIRONMENTAL IMPACT

We examine each proposed nuclear power plant for effects on:

- People
- Land use
- Air quality
- Water use
- Historic and esthetic things
- Animals and plants

We consider

- Radiolological impacts
- Thermal impacts
- Chemical wastes impacts
- Sewage impacts
- Noise impacts
- Transportation impacts
- Accident impacts
- Social impacts
- Economic impacts
- Transmission lines impacts

We look at

- Need for power
- Alternatives
- Expended resources

2. Effluents released to the atmosphere

3. Emission orifice (stack or vent)

4. Dispersion modeling

5. Radiation dose estimation

The meteorological data, along with expected annual average rates of radionuclide emissions, are used in empirical Gaussian plume dispersion models to predict point-by-point airborne concentrations at ground level. The model predictions are estimates of average values over specified time periods. With this information and by the use of standard dose models, estimates are made of whole body (external) and inhalation (internal) radiation doses to the individual and the population (man-rems) and compared with background doses and ICRP (International Commission on Radiological Protection) recommended standards.[4]

Cooling Tower Impact

If the power company proposes to dissipate waste heat via cooling towers (forced draft, natural draft, etc.), it is necessary to assess their potential impacts. Using plant operating data and tower design criteria, estimates are made of tower intake and discharge temperatures, evaporation rates, blowdown rates, drift, fogging and icing, noise, and ground deposition of chemicals from the towers (due to treatment of the circulating cooling water with biofouling agents and corrosion inhibitors). These chemicals can affect vegetation and man-made surfaces.

Impact on Water Bodies

Rivers, lakes, estuaries and oceans play key roles in the life cycles of many fish species. Unless polluted, they are usually productive bodies of water, supporting dense populations of phyto- and zooplankton, upon which the larval stages of forage, rough, and game fish feed (See Fig. 1, "Trophic Structure of the Food Chain in an Estuary"). Consequently, special care must be taken in understanding and predicting the potential local and regional effects a power plant could have on aquatic ecosystems.

Thermal Effects

Temperature is a critical factor in aquatic ecosystems. Seasonal changes in temperature initiate and control the rate of gonad maturation, and the onset of spawning activities; embryological development, hatching, and larval growth also are all highly temperature dependent. Slight elevations in temperature can initiate spawning prematurely. Persistent higher-than-normal temperatures can severely retard larval development, and extreme elevations can kill larval fish, especially during summer months, when many aquatic organisms already are living near their upper temperature limits. Data on the temperature preferences of fish indicate that they will be attracted to thermal discharges in the winter. This attraction to warmer temperatures can increase their vulnerability to being victims of cold shock, "cold kill", if the plant is shut down and the heated water discharge is discontinued. Therefore, to assess these potential thermal effects, it will be necessary to have detailed inventories of plankton, benthic invertebrates, and resident and transient fish populations. With these data and with an understanding of productivity and behavioral patterns (spawning habits, migratory habits, etc.), it should

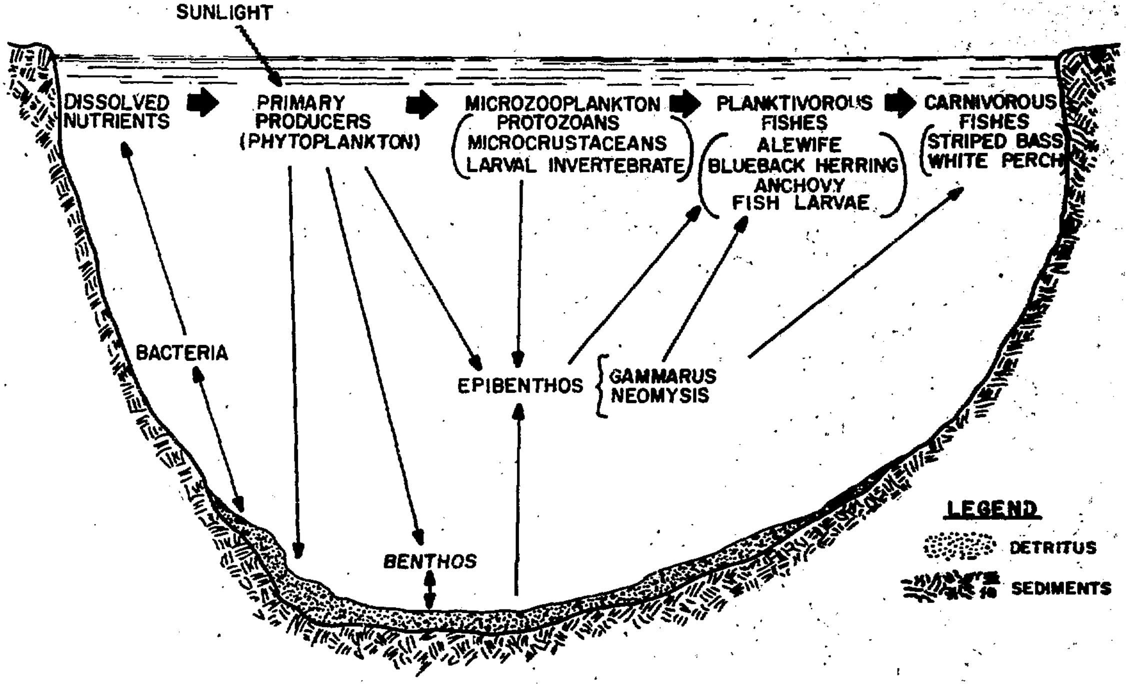


Fig. 1. Trophic Structure of the Food Chain in an Estuary.

then be possible to predict the thermal effects, at least qualitatively, and to suggest ways of minimizing the thermal impact.

Entrainment

Another common concern with steam-electric generating plants using once-through cooling is the problem of entrainment. Entrainment is the capture of organisms in the water used for cooling the condensers in the plant. Thus, the plant withdraws a portion of the planktonic, or passively drifting, biota with the cooling water (See Fig. 2, "Schematic Representation of the Sources of Potential Biological Damages from Condenser Cooling System of a Power Generating Station"). This water with its content of organisms is pumped through the plant and is subsequently discharged back into the receiving body of water. Thus, a large proportion of the organisms can be killed or injured during the passage through the plant (due to the effect of changes in pressure, temperature, and chemicals). Figure 2 indicates where thermal, mechanical and chemical changes may occur in the condenser cooling system of a typical power plant.

Impingement

Many organisms in the water initially drawn to the power plant are too large to pass through screening systems used to protect the condensers from debris. Under certain conditions (e.g., intake velocities above 1 cfs, winter temperatures when fish are "sluggish" and unable to respond quickly and swim away, etc.), these organisms are unable to resist the intake flow and are killed by impingement upon the screens. The magnitude of this problem varies a great deal from one plant to another but, in some cases, can be a significant impact.

Chemical Effects

Heavy biofouling and corrosion can occur in condenser cooling systems, requiring control by the use of biocides and corrosion inhibitors. Chlorine is commonly used as the biocide. If the receiving body of water has a heavy organic content, it would create a high chlorine demand, with ammonia and other nitrogenous materials combining with free chlorine to form chloramines. Long exposure to very small doses of these compounds can have harmful effects on aquatic organisms. Until more information is available on the amounts produced and persistence of such chlorine derivatives, the acceptable level of free chlorine in the power plant's waste water releases is limited to 0.01 ppm or less.

Impact on Land Use

Construction of the plant and transmission facilities may disturb the existing terrain and remove wildlife habitats. Different land-use types (residential, agricultural, industrial or recreational) may be crossed by the transmission lines, and access roads and maintenance roads may be constructed on or near the right-of-way. Construction activities usually require permanent clearing of trees and vegetation, changes in topography, and removal of homes and other man-made structures. Areas valued for either their historic, scenic, cultural or natural significance may be affected. The extent to which location of the plant and transmission facilities will modify land-use patterns are described, as are planned improvements (wildlife refuges, camping areas, parks, etc.) and plans for mitigating impacts on land use.

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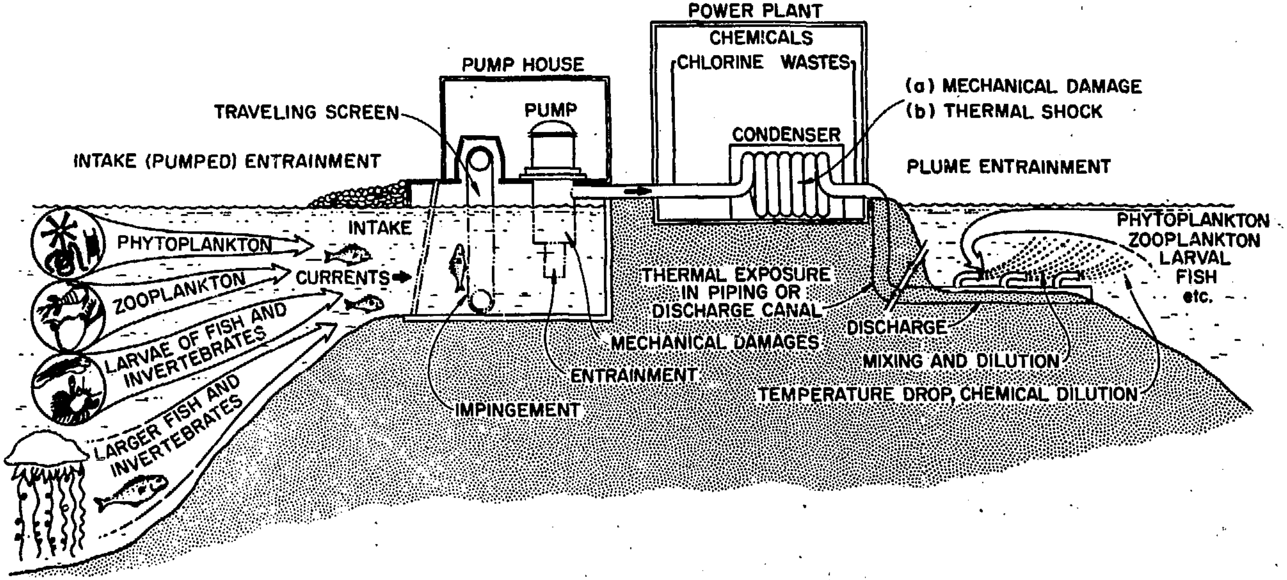

Fig. 2. Schematic Representation of the Sources of Potential Biological Damages from Condenser Cooling System of a Power Generating Station.

Impacts on Terrestrial Biota

The major terrestrial features of the plant site and its environs are characterized in terms of geology, hydrology, meteorology and ecology. Ecological characterization of the site includes identification of local flora and fauna and descriptions of their distribution and habitats. Vegetation is described in terms of community type (forest, grassland, cropland, marsh, etc.) and maps showing the size and location of plant communities are included. In considering impacts on animal life, special attention is given to endangered species and breeding populations. The major terrestrial impact of plant construction is associated with land use. Primary impacts on terrestrial ecosystems resulting from normal plant operations are fogging, icing and spray drift from cooling towers or cooling ponds.

Radiological Impacts

Of primary concern, though not necessarily of primary significance, are the radiological impacts on man of plant operation and the transportation of radioactive materials (reactor fuel and radioactive waste) to and from the plant. Nuclear power plants routinely discharge small quantities of radioactivity to the atmosphere (as gaseous effluents) (Table 2) and to nearby water bodies (as liquid effluents in the form of contaminated waste water or chemical effluents or both) (Table 3). This radioactivity is dispersed and diluted (or reconcentrated) in the environs, resulting in direct or indirect exposures of people living in the area. Thus, the annual discharges of such radioactive releases must be evaluated and predictions must be made of potential individual radiation doses (Table 4) and the man-rem population dose (Tables 5 and 6) from all potential exposure pathways (Fig. 3). These dose estimates are then compared with pertinent standards and judgments are made as to the radiological safety of the plant's releases. If dose estimates exceed accepted standards, the applicant is required to alter his equipment or his operating procedures to stay within the prescribed limits. As a corollary to the radiological impact assessment, consideration is given and recommendations are made to an environmental monitoring program that focuses on critical radionuclides, exposure pathways and exposed population groups.

Societal and Secondary Impacts

In the joining of "benefit/cost" to "environmental impact", the primary problem is getting straight who is paying what cost, in return for what benefits (to whom). This is a thorny problem that requires stress upon social impacts on the human environment. For example, people living near the plant may experience all or most of the adverse impacts (or "environmental costs") while the people in some distant metropolis receive all or most of the benefits. On the other hand, local residents who receive the direct economic benefits from the plant's tax assessment might be regarded as having been compensated for bearing the brunt of the plant's adverse effects. Other factors must be considered, including the need for power, the effect that electric power has on the environmental future, pricing of electric power, safety from nuclear hazards, the direct radiological impact, the long-run and eventual dismantling of the plant and the need for regional models, models which need to take into account the regional boundary conditions such as connections to other power pools. These issues are seldom if ever resolved in the NEPA review of a given nuclear power plant. Most often when a major project of any kind is launched we literally do not know what we are doing, in the sense that the important consequences of social action are almost always unanticipated. This situation can be acknowledged even if nothing is done about it at the beginning of such a project. What is needed is a definiteness about questions (though not a

TABLE 2

Principal Radionuclides Released in Gaseous Wastes of Current Light-Water Power Reactors

^{83m}Kr	^{131m}Xe	^{131}I	^{3}H
^{85m}Kr	^{133m}Xe	^{133}I	
^{85}Kr	^{133}Xe		
^{87}Kr	^{135m}Xe		
^{88}Kr	^{135}Xe		
^{89}Kr	^{138}Xe		

TABLE 3

List of Radionuclides and Decay Chains That Should Be Assessed in the Liquid Effluent of Current Light-Water Power Reactors

$^{3}\mathrm{H}$
$^{14}\mathrm{C}$
$^{22}\mathrm{Na}$
$^{24}\mathrm{Na}$
$^{32}\mathrm{P}$
$^{35}\mathrm{S}$
$^{46}\mathrm{Sc}$
$^{51}\mathrm{Cr}$
$^{54}\mathrm{Mn}$
$^{55}\mathrm{Fe}$
$^{59}\mathrm{Fe}$
$^{57}\mathrm{Co}$
$^{58}\mathrm{Co}$
$^{60}\mathrm{Co}$
$^{63}\mathrm{Ni}$
$^{64}\mathrm{Cu}$
$^{65}\mathrm{Zn}$
$^{69m}\mathrm{Zn}$-$^{69}\mathrm{Zn}$
$^{86}\mathrm{Rb}$
$^{89}\mathrm{Sr}$
$^{90}\mathrm{Sr}$-$^{90}\mathrm{Y}$

$^{90}\mathrm{Y}$
$^{91}\mathrm{Sr}$-$^{91m}\mathrm{Y}$-$^{91}\mathrm{Y}$
$^{91}\mathrm{Y}$
$^{93}\mathrm{Y}$
$^{95}\mathrm{Zr}$-$^{95}\mathrm{Nb}$
$^{95}\mathrm{Nb}$
$^{97}\mathrm{Zr}$-$^{97m}\mathrm{Nb}$-$^{97}\mathrm{Nb}$
$^{99}\mathrm{Mo}$-$^{99m}\mathrm{Tc}$
$^{103}\mathrm{Ru}$-$^{103m}\mathrm{Rh}$
$^{105}\mathrm{Rh}$
$^{106}\mathrm{Ru}$-$^{106}\mathrm{Rh}$
$^{110m}\mathrm{Ag}$-$^{110}\mathrm{Ag}$
$^{122}\mathrm{Sb}$
$^{124}\mathrm{Sb}$
$^{125}\mathrm{Sn}$-$^{125}\mathrm{Sb}$-$^{125m}\mathrm{Te}$
$^{125}\mathrm{Sb}$-$^{125m}\mathrm{Te}$
$^{125m}\mathrm{Te}$
$^{127}\mathrm{Sb}$-$^{127m}\mathrm{Te}$-$^{127}\mathrm{Te}$
$^{127m}\mathrm{Te}$-$^{127}\mathrm{Te}$
$^{127}\mathrm{Te}$
$^{129m}\mathrm{Te}$-$^{129}\mathrm{Te}$

$^{130}\mathrm{I}$
$^{131m}\mathrm{Te}$-$^{131}\mathrm{Te}$-$^{131}\mathrm{I}$
$^{131}\mathrm{I}$
$^{132}\mathrm{Te}$-$^{132}\mathrm{I}$
$^{133}\mathrm{I}$
$^{134}\mathrm{Cs}$
$^{135}\mathrm{I}$
$^{136}\mathrm{Cs}$
$^{137}\mathrm{Cs}$-$^{137m}\mathrm{Ba}$
$^{140}\mathrm{Ba}$-$^{140}\mathrm{La}$
$^{140}\mathrm{La}$
$^{141}\mathrm{Ce}$
$^{143}\mathrm{Ce}$-$^{143}\mathrm{Pr}$
$^{143}\mathrm{Pr}$
$^{144}\mathrm{Ce}$-$^{144}\mathrm{Pr}$
$^{147}\mathrm{Nd}$-$^{147}\mathrm{Pm}$
$^{147}\mathrm{Pm}$
$^{182}\mathrm{Ta}$
$^{185}\mathrm{W}$
$^{187}\mathrm{W}$
$^{239}\mathrm{Np}$

TABLE 4

Summary of the Estimated Doses to Individuals per Year of Release at Points of Maximum Esposure to Gaseous and Liquid Effluents from Arkansas Nuclear One Unit 2[a]

Pathway	Location	Dose in millirem	
		Total body	Thyroid
	Gaseous effluents		
1. Immersion	Site boundary, W, 0.65 mile	0.32	0.32
2. Direct radiation from ground	Site boundary, W, 0.65 mile	0.08	0.08
3. Inhalation of contaminated air	Site boundary, W, 0.65 mile	< 0.01	1.5
4. Terrestrial food chains	NNW, approx. 2 miles	0.01	2.9
	Liquid effluents		
1. Drinking water	Main body of reservoir	< 0.01	0.01
2. Aquatic food chains	Discharge embayment	1.8	2.0
3. Swimming	Main body of reservoir	< 0.01	< 0.01

[a] The information in this table appears in the final environmental impact statement related to Arkansas Nuclear One Unit 2, published as Docket No. 50-368, U. S. Atomic Energy Commission, September 1972.

TABLE 5

Summary of Dose Estimates to the Population from Immersion in the Gaseous Effluents Released by Arkansas Nuclear One Unit 2[a]

Radial distance from plant (miles)	1970 Cumulative population	Cumulative population dose (man-rem/yr)	Average individual dose (rem/yr)
0-1	101	0.007	0.000072
0-2	709	0.024	0.000034
0-3	1,411	0.030	0.000021
0-4	2,260	0.035	0.000015
0-5	3,920	0.042	0.000011
0-10	23,610	0.094	0.0000040
0-20	48,310	0.13	0.0000026
0-30	73,680	0.15	0.0000020
0-40	99,600	0.16	0.0000017
0-50	150,000	0.18	0.0000012

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[a] The information in this table appears in the final environmental impact statement related to Arkansas Nuclear One Unit 2, published as Docket No. 50-368, U. S. Atomic Energy Commission, September 1972.

TABLE 6

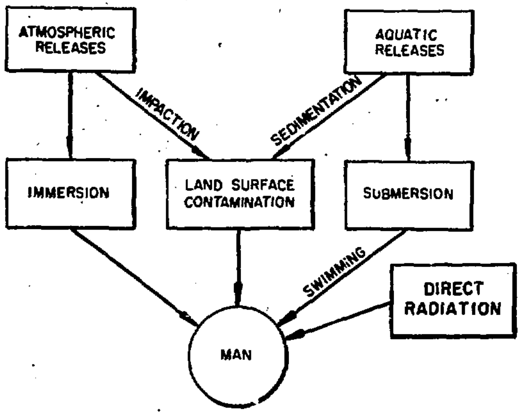
Summary of Estimated Population Doses per Year of Release of Gaseous and Liquid Effluents from Arkansas Nuclear One Unit 2[a]

Pathway	Population Dose (man-rem)[b]	
	1970	2010
Gaseous effluents		
1. Immersion	0.2	0.3
2. Contaminated ground surface	0.02	0.03
3. Inhalation of contaminated air	0.0008	0.001
4. Terrestrial food chains	0.02	0.05
Liquid effluents		
1. Drinking water	c	c
2. Aquatic food chains	0.6	1.0
3. Swimming	0.00004	0.00006
Total population dose	0.84	1.4

[a] The information in this table appears in the final environmental impact statement related to Arkansas Nuclear One Unit 2, published as Docket No. 50-368, U. S. Atomic Energy Commission, September 1972.

[b] Based on a population within a 50-mile radius of 150,000 for 1970 and 238,000 for 2010.

[c] Dardanelle Reservoir and the Arkansas River downstream are not currently used for drinking water. If the population within 50 miles obtained its drinking water from the reservoir, the annual dose would remain below 1 man-rem through year 2010.



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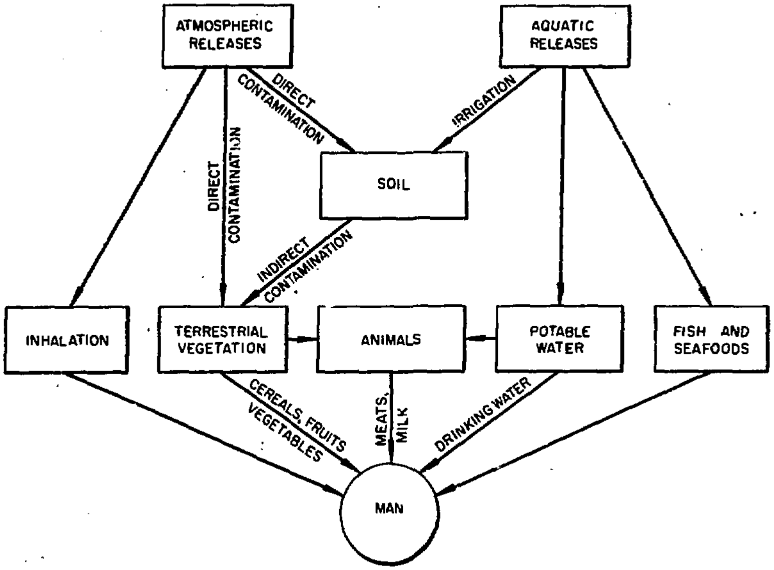

INTERNAL

Fig. 3. Pathways for Radiation Exposure of Man

completeness) which seems worth asking even when they cannot be answered. In many cases the answers will emerge as the project evolves.

Alternative Energy Sources and Sites

The applicant describes in his environmental report (ER) the range of practical alternatives among the sites and energy sources available. The aim is to demonstrate that none of these alternatives is preferable to the proposed site-plant combination. Generally speaking, two categories of alternatives are considered: those which can meet the power demand without new generating capacity and those which require the construction of new generating capacity. The former may include purchased energy, reactivation or upgrading an older plant, or base load operation of an existing peaking power plant; the latter may include both site and energy source options (nuclear, fossil-fueled, hydroelectric, geothermal). A cost-effectiveness analysis of these practical alternatives is then made in terms of both economic and environmental costs to show why the proposed site-plant combination is preferred over all other candidate alternatives for meeting the power demand.

Plant Design Alternatives

Most of the environmental effects of a nuclear power plant are associated with the operation of certain plant subsystems (heat, dissipation, waste collection and treatment). The proposed plant incorporates a combination of these identifiable systems, each of which has been selected through a cost-effectiveness analysis of economic and other factors. The analysis usually includes the cooling system, intake system, discharge system, chemical waste treatment, water treatment, radwaste system, and transmission facilities. Each alternative plant system is described, estimates are made of its environmental impact, and these estimates are then compared with that of the proposed system.

Benefit-Cost Analysis

The environmental impact statement concludes with a benefit-cost analysis of the proposed plant to show how the aggregate benefits outweigh the aggregate costs. The approach to this analysis cannot be in a purely economic context. This is because the benefits and costs cannot all be monetized. The nature of the benefits and costs makes it virtually impossible to provide a concise assessment of benefits vs. costs in quantitative terms. However, although a numerical weighing of benefits against costs is not feasible, efforts are made to identify the costs and the benefits of the proposed plant and the practical alternatives, and these are then summarized and tabulated so that the reader can understand how, in the judgment of the USNRC staff, the benefits outweigh the costs.

Technical Specifications

Issuance of the Environmental Impact Statement does not complete a NEPA review. The statement identifies potential effects which may become adverse if control of plant operation is not exercised. Accordingly, operating limits derived from consideration of potential impacts must be specified. In the case of thermal effluents, for example, consideration must be given to the aquatic organisms which might be affected by the heated water discharge, and from this a temperature limit must be derived which will prevent unacceptable effects. In accordance with NEPA, this limit is derived independently of established water quality standards.

The legal basis of such limits is of some interest. They must be necessary and they must be solidly based on considerations of potential environmental impact. Only then can they be imposed as technical specifications and appended as a condition to the construction permit or the operating license.

ORNL'S ENVIRONMENTAL IMPACT STATEMENT ORGANIZATION

Approximately 50 scientists and engineers are drawn together into several Task Groups. Each nuclear power plant being considered for a license and assigned to ORNL is assigned to one of these Task Groups. As shown in Table 7, each Task Group is made up of specialists in areas such as reactor engineering, aquatic ecology, terrestrial ecology, social science, economics and cost/benefit analysis. Thus the make-up of a Task Group is in response to NEPA's recommendation to follow an interdisciplinary approach to the analysis of environmental impacts and the consideration of costs and benefits.[5] From all of the Task Groups, specialists in a given area, e.g., aquatic and terrestrial ecologists, are affiliated together under the leadership of a Program Manager to develop capabilities in the problem area and to strive for consistency in all assessments and statements. The specialists in each Task Group are led by a Task Group Leader who manages all activities involved in preparing the statements assigned to his Task Group. Thus the Task Group Leader's essential responsibility is to complete the assessment and to prepare the impact statement on schedule, while the Program Manager's essential responsibility is to strive for consistency and high quality in those sections of the statement that fall within his specialty area. The original Task Groups required seven (7) specialists, as Table 7 indicates; currently, however, four (4) specialists constitute the core of a Task Group: aquatic ecologist, terrestrial ecologist, heat transfer expert, and a cost/benefit analyst.

From the beginning, attempts have been made to cultivate an attitude of concern for the environment. There are plenty of pro-nuclear protagonists as well as environmentally concerned people at ORNL and each Task Group is staffed with a good "mix" of both types so that the ORNL statements reflect a reasoned balance of both views. This work is looked upon as an opportunity to help realize the promise of nuclear power while, at the same time, taking a hard look at the adequacy of environmental protection in nuclear power plants and searching for alternatives to minimize the impacts.

When the Task Group has completed its assessment and prepared a preliminary draft statement, it is reviewed by Program Managers and various ORNL experts who have had nothing to do with its preparation. The NRC Project Manager also participates in this internal review.

Following the internal review the NRC Project Manager (EPM) and the Laboratory's Task Group prepare the Preliminary Draft Environmental Statement (PDES), taking account of comments by the reviewers and incorporating generic statements on reactor accidents and on transportation prepared by the EPM and other "boiler plate". The PDES is then reviewed at the Laboratory by representatives of the NRC's Directorate of Licensing and Office of the General Counsel (OGC), after which it is corrected and shipped to Washington to be printed as the NRC's Draft Environmental Statement (DES), the date of which publication is announced in the Federal Register.

The Nuclear Regulatory Commission distributes the DES for comment to federal, state and local agencies, as well as to intervenor groups and interested individuals. Forty-five to 60 days are allowed for commenting agencies and individuals to review the DES and offer comments. The NRC Project Manager and the Laboratory Task Group then consider the comments and revise the

TABLE 7

Environmental Impact Organization

Reactor Task Groups	Problem Areas						
	Reactor Cooling Systems	Gaseous Effluents	Liquid Effluents	Site & Environs	Radiological Impacts	Biological & Environ. Impacts	Cost-Benefit Analysis
Palisades	Mr. "A"	Mr. "B"	...				
Oconee 1	Mr. "M"	...					
Indian Point 2	Mr. "N"						
Vermont Yankee	...						
Hatch							Mr. "X"
Arkansas and 10 others						Mr. "Y"	Mr. "Z"

DES as necessary. The revised statement is then printed as the NRC's Final Environmental Statement (FES).

It is essential that enough time be spent for a thorough assessment of potential impacts to be completed, and for adequate safeguards to be devised to protect the environment; but it is also important that this process not be allowed to "drag" on indefinitely. Efforts are made to avoid unnecessary delay in licensing a nuclear power plant that is needed to prevent brownouts or blackouts next summer or winter. Another important consequence of delays is the cost of an idle plant, costs which would be passed on to the utility's customers. Interest charges alone on monies borrowed to build the nuclear plant can mount up to tens of millions of dollars a year or tens of thousands of dollars a day. As a result, the Task Groups are under tremendous pressure to produce high quality impact statements on ever-decreasing schedules.

THE ROLE OF THE EIS IN NRC'S LICENSING PROCEDURE

Table 8 shows the average schedule and the steps involved in gaining an NRC construction permit. The subscript values are working days. As can be seen, approximately 140 working days are required for the publication of the DES. Approximately 215 working days or 9 months are required for publication of the FES. Following approximately 4 weeks for the Acceptance Review, Day Zero is set for the project by the NRC. Thirty working days is the target for completing the review of the Applicant's Preliminary Safety Analysis Report (PSAR) and his Environmental Report (ER), and for preparing questions of the applicant and the agenda for the Site Visit. One week is taken up by the Site Visit, once it is scheduled, following which each member of the Task Group begins his assessment of impacts and the writing of his sections of the statement. If everything goes smoothly, the Task Group will have produced and reviewed a complete rough draft of the statement (PDES) by the 110th working day. The next 30 working days are allowed for reviewing, revising and printing the NRC's Draft Environmental Statement (DES).

Average times for the FES are as follows: (1) 45 working days for agency comment; and (2) 30 working days for the applicant and the NRC to answer agency comments to publish the FES. Thus the average time from Day Zero to publication of the FES is about 9 months. What follows publication of the FES is a 30-day review by the Council on Environmental Quality and an indeterminate time for Atomic Safety and Licensing Board (ASLB) Hearings and the eventual granting of a license. The Nuclear Regulatory Commission hopes to reduce the total time from date of application to date of fuel loading to about 6 months. That hope is still very far from actual realization.

Role of EIS in ASLB Hearings

The NRC's FES represents, in effect, its preliminary assessment of potential impacts and its judgment of the merits of the proposed action. Thus its conclusions are of great interest and significance to the deliberations of the Atomic Safety and Licensing Board, which must make the final recommendations to the NRC. Therefore, the FES is an important resource that needs to be discussed in ASLB Hearings. The ASLB's aim is to put on the record of its proceedings all of the important environmental impact findings detailed in the FES, as well as the matters relating to nuclear safety that are discussed in NRC's safety evaluation report. As a result, members of the Task Group who prepared the FES participate as expert witnesses in the Hearings, presenting their parts of the assessment and defending them before the ASLB. Since the ASLB Hearings are an adversary proceeding and provide an opportunity for all parties to the proposed action (the NRC, the applicant, intervenors, etc.) to participate in the

TABLE 8

Average Schedule for Processing Environmental Impact Assessments Associated with NRC's Grant of a Construction Permit for a Nuclear Power Plant[*]

T_{0}........T_{30}	Acceptance Review of Utility's Environmental Report
T_{30}.......T_{60}	Site Visit by NRC's Interdisciplinary Team
T_{60}.......T_{67}	Scoping the Assessment
T_{67}.......T_{110}	Preliminary Draft Environmental Statement (PDES)
T_{110}......T_{140}	Publication of NRC's Draft Environmental Statement (DES)
T_{140}......T_{185}	Review of DES by Agencies, Intervenors, etc.
T_{185}......T_{215}	Publication of NRC's Final Environmental Statement (FES)
T_{215}......T_{245}	Review of FES by Council on Environmental Quality (CEQ)
T_{245}......T_{275}	ASLB Preconference Hearing (Atomic Safety Licensing Board)
T_{275}......T_{310}	ASLB Public Hearings
T_{310}......T_{340}	ASLB Findings of Fact
T_{340}......T_{370}	ASLB Recommendations to NRC
T_{370}......T_{380}	NRC Grants Construction Permit (CP)

[*] This process is repeated several years later when the utility applies for an operating license. The above schedule represents a "guesstimate" of the average time required to process the environmental impact assessment considerations (DES and FES) associated with NRC's licensing and regulation of nuclear power plants. The NRC's "target" schedule for the process is 6 months but it is seldom met. In difficult cases (e.g., Indian Point), the process can continue for several years. The "tail end" of the process is especially difficult to predict because the hearings for a given plant have to be scheduled to fit the schedule of the ASLB which may be dealing with several plants at a given point in time. It should be noted that another assessment process (i.e., nuclear safety assessments) parallels this one and the results of the two eventually form the major part of the agenda of the ASLB hearings.

deliberations, this is where the differences are aired and the "bottom lines" on impacts, alternatives, and technical specifications are reached. Thus the proceedings of the ASLB Hearings and the Findings of Fact are the foundations of its final recommendations to the Nuclear Regulatory Commission: whether or not to grant a construction permit or an operating license, and what conditions should be attached to the applicant's request.

ACKNOWLEDGMENT

This research sponsored by the U. S. Energy Research and Development Administration under contract with the Union Carbide Corporation.

Publication No. 939, Environmental Sciences Division, Oak Ridge National Laboratory.

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GENETIC EFFECTS OF RADIATION

Paul B. Selby

Biology Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830

Introduction

Many of the most important findings concerning the genetic effects of radiation have been obtained in the Biology Division of Oak Ridge National Laboratory. Rather than try to cover, in comprehensive fashion, the whole field of radiation genetics, this paper will focus on some of the major discoveries made in the Biology Division and on a new method of research that assesses damage to the skeletons of mice whose fathers were irradiated. The results to be discussed have considerable influence upon estimates of genetic risk in humans from radiation, and an attempt will be made to put the estimated amount of genetic damage caused by projected nuclear power development into its proper perspective.

Development of Specific-locus Method in Mice

H. J. Muller first demonstrated that X-rays were mutagenic in 1927 in an experiment using the fruit fly, Drosophila melanogaster. After Muller's discovery, much follow-up work on the genetic effects of radiation in the fruit fly and in lower organisms led to what was considered by some an adequate understanding of the genetic effects of radiation. There were some scientists, however, who considered it essential to examine the genetic effects of radiation in an animal more closely related to man. The mouse was the animal of choice, as it is a small mammal that breeds rapidly and it was, even at that time, used extensively in genetics research. The small size and rapid reproduction were crucial because of the large number of progeny which would need to be examined.

W. L. Russell proposed using the specific-locus method for testing the effects of radiation in mice. He developed this method in the mouse, and it proved so successful that it has given rise to most of the results described in this paper. For this reason, it seems worthwhile to describe this method in some detail.

The specific-locus method is so named because it permits the identification of recessive mutations at specific genetic loci. The animal that is irradiated has the normal type of gene for both of its genes at each of seven specific loci. The irradiated animal is mated with a test-stock mouse containing a recessive for both of its genes at each of the same loci. Unless a mutation occurs at one of these loci in the germ cells of the irradiated animal, all of the progeny of this mating will contain a normal gene from the irradiated parent and a recessive gene from the unirradiated parent for each of these seven loci. In this event, the normal genes mask the effects of the recessives, and all progeny are normal in appearance. Only if a mutation occurs, in which case a given offspring has a new recessive mutant gene from the irradiated parent and the recessive gene from the unirradiated parent, does any unusual appearing offspring occur among the first-generation progeny. Mutations at six of the specific loci cause characteristic alterations in the coat color, and a mutation at the remaining locus causes the external ear to be much smaller. Owing to the ease of noticing mutants at the seven specific loci, the large samples of progeny required can be examined in reasonable periods of time.

Discoveries Made by W. L. Russell

Higher mutation rate in mouse than in fruit fly

A_s spermatogonia, the stem cells in the testis, are known to be of overwhelming importance in assessing genetic hazard in the male. As has been shown by E. F. Oakberg[6] in the Biology Division, the other male germ cells, which are differentiating, persist only relatively short times. Whereas mutations induced in the differentiating germ cells are eliminated from the ejaculate within a few weeks following irradiation, mutations induced in A_s spermatogonia can be in the ejaculate at any time from a few weeks after irradiation until the mouse dies. For this reason, all discussion of genetic effects of radiation in the male will be restricted to results for A_s spermatogonia.

The first test of the genetic effect of radiation in the mouse yielded a surprising result: the mutation rate in the mouse is 15 times higher than that in the fruit fly[7]! Following this discovery there was a three-fold reduction in the permissible exposure level for the human population. A fifteen-fold reduction was not necessary because the ratio of 15 is for the comparison of spermatogonia in the two species. The earlier permissible exposure level had been based incorrectly upon the mutation rate in fruit fly sperm, which have a much higher mutation rate (about 5 times) than fruit fly spermatogonia. The mutation rate in the mouse following exposure to 600 R of acute X-radiation was 22×10^{-8} per R per locus[7]. The finding that the mouse was quite different in mutational response from the fruit fly showed the importance of not basing estimates of hazard strictly on the results in the fruit fly and other lower organisms. This finding generated much interest in learning more about genetic effects of radiation in mice. In the experimentation that followed, a number of principles of radiation genetics accepted prior to this work have fallen by the wayside as the result of findings in the mouse.

Shape of dose-response curve in male

For the purpose of estimating genetic hazard in humans[12], the assumption was made that there is a linear dose-response relationship between the mutation rate found in the unirradiated controls and at 600 R. The experiment at 600 R was followed by an experiment at 1000 R, with the expectation that a higher mutation rate would be obtained at this higher dose. Unexpectedly, the mutation frequency dropped at 1000 R[13]. This then raised concern about the true shape of the dose-response curve. On the one hand, the earlier assumption of a linear relationship between 0 and 600 R might be correct, but, on the other hand, the possibility existed that there was a humped dose-response curve and the data point at 600 R might be far below the maximum mutation frequency per R found at some lower exposure level. To check this out, a large experiment was performed with an exposure of 300 R acute X-radiation. The mutation rate obtained, 8.72×10^{-5} mutations per locus, lies close to the straight line between 0 (mutation rate = 0.75×10^{-5} mutations per locus) and 600 R (mutation rate = 13.29 x 10^{-5} mutations per locus) without differing significantly from the expected value if the linear relationship holds[10].

This result supported the assumption that there is a linear dose-response relationship between 0 and 600 R. (Later studies on dose-rate effects suggested that the dose-response curve would fall below linearity at small doses[14]. This was later confirmed.) Irradiation at high doses is known to cause extensive cell killing of spermatogonia. The reason for the drop in the dose-response curve that occurs between 600 and 1000 R is thought to be a positive correlation between cell killing and mutational sensitivity in the spermatogonia. Thus, at the very high doses, only spermatogonia with a lower mutational sensitivity survive[13].

Dose-rate effect in male

The exposure of the human population consists almost entirely of low total doses, most of which are received as small doses given at acute dose rates (as in medical exposure) or as protracted doses. For this reason, in estimating human hazard it is useful to have data at as low dose rates and total doses as is practical for experimentation.

A series of experiments were performed in which male mice were exposed to gamma radiation delivered at 0.8, 0.009 or 0.001 R/min[8]. Figure 1 shows the results of the experiments at 0.009 and 0.001 R/min.

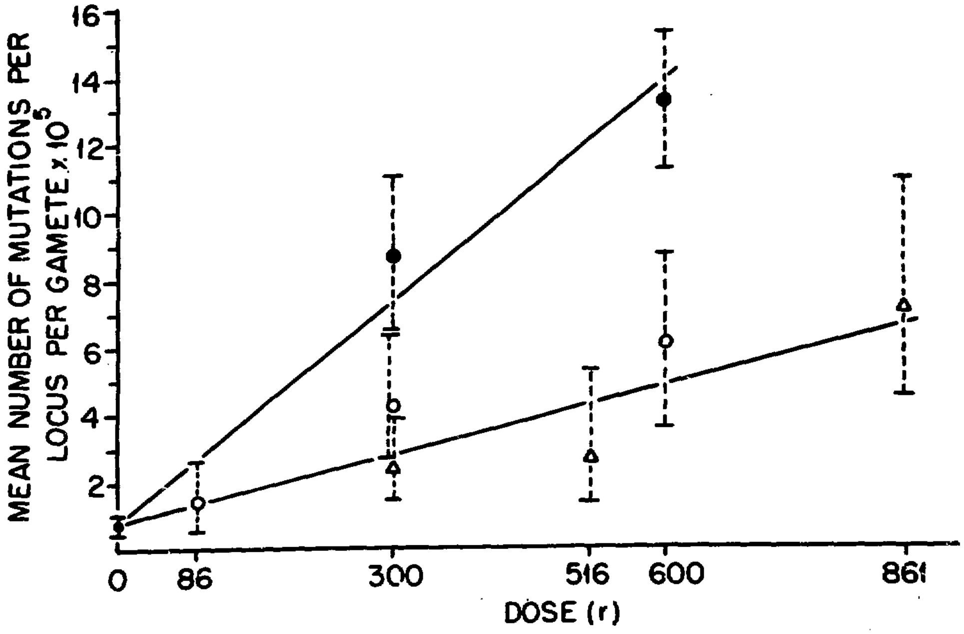

FIGURE 1. Specific-locus mutation rates, with 90 percent confidence intervals, for various doses and dose rates, in spermatogonia of mice. The lower straight line is fitted to the combined 0.001 R/min (open circles) and 0.009 R/min (open triangles) dose-rate data. The upper line is fitted to the 90 R/min (solid circles) points. (Taken from Russell, reference 8, page 206)

The upper regression line shows the linear dose-response relationship, described above, found with 90 R/min (acute) X-irradiation. The lower regression line is that found at the two low dose rates, there being no significant difference between the frequencies at the two low dose rates. The mutation rate at 0.8 R/min lies almost exactly on the regression line for the two lower dose rates, and it is also significantly lower than the mutation rate at the 90 R/min dose rate. With an intermediate dose rate of 9 R/min X-radiation, an intermediate mutation rate was obtained, the 90% confidence intervals of which did not overlap either of the regression lines shown in Figure 1. The lower regression line in Figure 1 can thus be taken to represent the dose-response relationship for the following dose rates: 0.8, 0.009, and 0.001 R/min. The slope of the low-dose-rate regression line is 30% of that found with acute irradiation[12].

The initial dose-rate effect was determined using X rays for acute and gamma rays for chronic irradiation, but additional experiments showed that the difference in response was not due to radiation quality because a dose-rate effect could be found using X rays alone or gamma rays alone[14,15,8].

Russell[14] advanced his repair hypothesis to explain the dose-rate effect. He suggested that there is a repair system present in the cell which is saturated or damaged when large doses of radiation are administered at high dose rates. This system, in the male, can apparently repair about 70% of the mutations induced if large doses are administered at low dose rates. Various alternative explanations to explain the dose-rate effect have been ruled out by Russell by means of other experiments. See reference 8 for a further discussion of this.

Dose-rate effect in female

Unlike the male, there are no stem cells present in the gonads of female mice and humans after birth. All oocytes that will ever be produced are present at birth. Many of these remain in various stages of prophase of meiosis for a significant fraction of the lifetime of a female before they enter the final stages of maturation in the few weeks before ovulation. Thus the majority of oocytes present at one time are immature oocytes in some stage of prophase[5], and these oocytes are probably the oocytes most relevant to a hazard evaluation for the human female. The results discussed below will be for oocytes in various stages of maturity present in adult female mice. In the female it is not possible to get as clean a separation of the germ cells most relevant to a hazard evaluation as in the male.

The mutation rate has been determined for female mice exposed to 400 R of X-radiation delivered at 90, 0.8, or 0.009 R/min[8]. A dose of 258 R was also given at the lowest dose rate. Figure 2 shows these results, with the same two regression lines described earlier for the male as a standard for comparison. The point estimates of the mutation frequencies are given together with their 90% confidence intervals. As is shown, the mutation frequency is much higher in maturing oocytes of female mice exposed to 400 R of acute (90 R/min) X-radiation than would be expected in spermatogonia of males receiving this exposure. An additional contrast to the male is that the mutation rate continues to drop as the dose rate decreases all the way to 0.009 R/min, which is the lowest dose-rate used. At this low dose rate, the mutation rates for 258 and 400 R are not significantly greater than the spontaneous mutation rate in spermatogonia! Thus, the repair system in females apparently can repair essentially all mutations induced by large doses if they are administered at low enough dose rates.

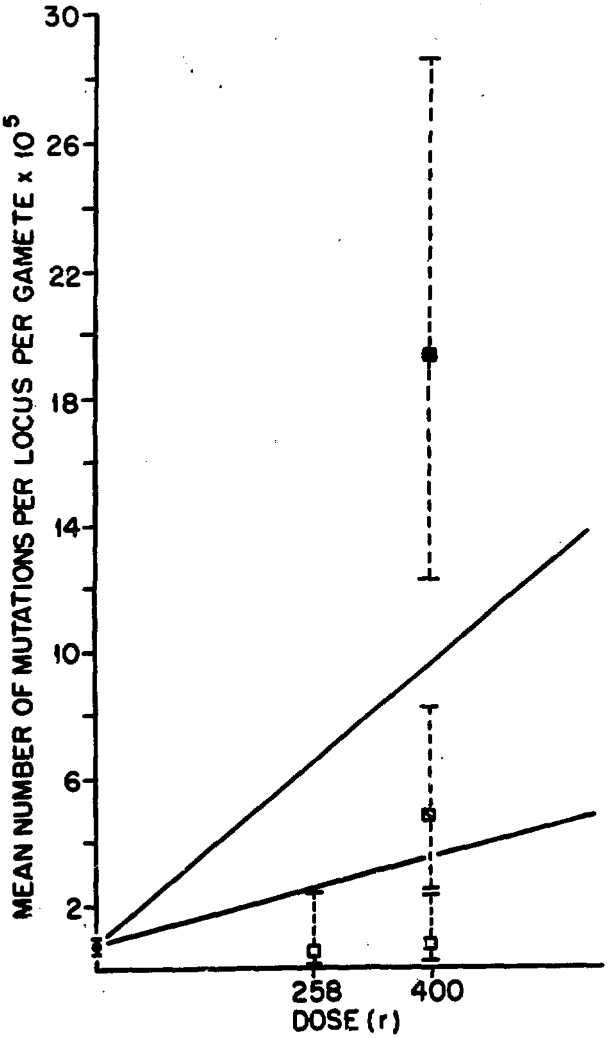

FIGURE 2. Specific-locus mutation rates, with 90 percent confidence intervals, for various dose rates, in oocytes of mice. Dose rates are: open squares, 0.009 R/min; barred square, 0.8 R/min; and solid square, 90 R/min. The control point and the straight lines, all taken from FIGURE 1, are spermatogonia results shown for comparison. (Taken from Russell, reference 8, page 210)

Low dose effect in female

One might expect that just as a large dose given at a low dose rate does not saturate or damage the repair system, a small dose given at a high dose rate might not affect it. To test this, Russell gave female mice a total of 50 R of acute X-radiation. Repair was apparently functioning under these conditions because the mutation frequency obtained was less than 1/3 that expected on the basis of a linear dose-response relationship between 0 and 400 R, this difference being highly significant[11].

Effect of interval after irradiation

In adult female mice a pronounced drop in the mutation rate occurs at about 7 weeks after irradiation. This is illustrated in Table I. This phenomenon was first discovered in an experiment using neutron irradiation, and since that time it has been shown to hold true for X-irradiation[12].

Mutation Frequencies at Two Intervals after Irradiation of Female Mice

			Interval between Irradiation and Conception			
			Up to 7 Weeks		More than 7 Weeks	
Rad.	Dose (rad)	Dose rate (rad/min)	No. of offspring	No. of mutations at 7 loci	No. of offspring	No. of mutations at 7 loci
N	60	0.15	46,301	22	80,395	1
N	60	75	43,000	37	40,096	0
X	50 R	80-84 R	180,472	13	78,191	0

TABLE I. Data from Russell, reference 12

This pronounced effect is thought to result from a change in mutational response at some time during the development of the oocytes, so that all of those ovulated more than 7 weeks after irradiation have a lower induced frequency of mutations. This change in response could result from an increase in efficiency of the repair system, from an intrinsic difference in mutational sensitivity, or, perhaps, from something else[11]. It is important to realize that the dose-rate effects and the low-dose effect in females are not artifacts caused by this interval effect operating in the presence of different periods of fertility following different irradiation treatments. The effects hold up if only data from the first 7 weeks are compared. The results given demonstrating the low-dose effects were, in fact, based only upon conceptions in the first 7 weeks[11].

Use of Specific-locus Data in Determining Present Maximum Permissible Level of Radiation for the Human Population

The specific-locus method provides most of our information about mutation frequencies for gene mutations and small deficiencies. These types of mutations account for the great majority of genetic diseases in humans, and for this reason no attempt has been made in this paper to discuss the influences of radiation upon the incidence of gross chromosomal aberrations. Such aberrations, however, are certainly of importance in assessing genetic risk, as they would account for an important fraction of induced diseases in at least the first few generations following elevated exposure levels.

The present maximum permissible level of radiation for the population, which is 5 rem per generation of 30 years, was formulated in 1956[12]. The specific-locus data available at that time were used in making the estimate of genetic hazard, but many of the discoveries described in this paper had not yet been made. As the data on induced mutation rates in the female were inadequate at that time, the assumption was made that the induced rate in the female was the same as that in the male determined for 600 R acute X-radiation and that in both sexes the dose-response relationship was linear between 0 and 600 R[12,20].

It appears that the assumption that the mutational response is the same in both sexes greatly overestimated genetic hazard. The reasons for saying this are shown in Figure 3, which shows the linear dose-response relationship used in 1956 and the point estimates and confidence limits of the mutation frequencies found in female mice for all exposures at low dose rates or to a small dose at a high dose rate. None of the data points shown for the female differs significantly from the spontaneous mutation rate in the male.

Another indication that the risk is lower than was thought in 1956 is that the dose-rate effect in the male had not been discovered at that time. Thus, if one figures that the male is only about 1/3 as likely to have a mutation as was thought and that the female is likely to have almost no mutations under usual exposure conditions for the human population, it appears that the maximum exposure limit of 5 rem per generation is about 6 times as safe as was thought in 1956, as regards genetic effects[12]. I am not suggesting that the maximum exposure level be raised by a factor of 6; however, it is reassuring that at least some previous assumptions appear to be well on the safe side.

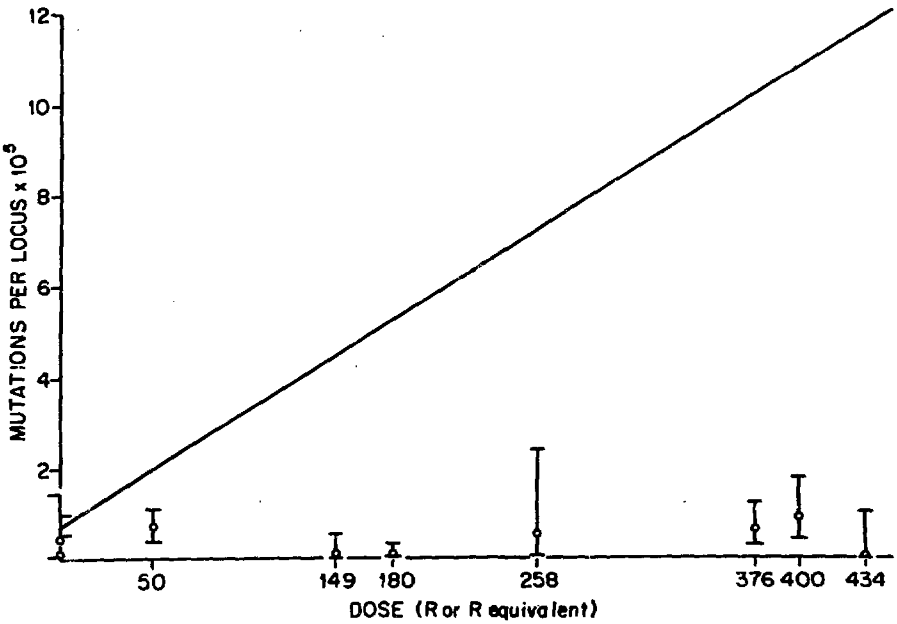

FIGURE 3. Comparison of various mutation frequencies in female mice with the straight-line estimate used in setting the present permissible levels of radiation. 90 percent confidence intervals shown. See text for brief explanation and reference[12] for detailed explanation. (Taken from Russell, reference 12, page 497)

Lower Mutational Response in Newborn Male

One reason for caution before greatly decreasing the estimate of hazard is that the assessments of hazard are so complex and continue to be supported by many assumptions. Such assumptions are necessary in order to reach an answer at a given time even though some pertinent information may take years to obtain or even be beyond the reach of present technology. At least most of the assumptions presently made appear to be, if anything, on the safe side. As recently as the early 1970's, however, there was at least one major assumption that was purely a guess. A description of this assumption and the experiments that tested its validity gives a good example of how an assumption has been replaced by knowledge.

Until the early 1970's it had been assumed that for the entire 30 years per generation the mutational response of the male is the same as that found for spermatogonia. This was in spite of the fact that for somewhat more than the first third of this period the human testis is immature and numerous spermatogonia do not appear until about age 10[2]. The mutational response of the gonocytes, which precede the spermatogonia, had only been examined slightly in the mouse, and there was no knowledge as to whether there might be some germ-cell stage with a high mutational response present at some time before the testis was completely developed.

In order to examine this possibility, a large specific-locus experiment was performed on newborn male mice[17], the germ cells of which are mostly or entirely gonocytes, and smaller experiments were performed on males 2, 4, 6, 8, 10, 14, 21, 28, and 35 days of age[18]. At 35 days the testis looks like an adult testis histologically. All mice were given a dose of 300 R of acute X-radiation. It was found that the mutational response in the newborn male is only 1/2 as high as that in the similarly irradiated adult male, the difference being statistically significant. Furthermore, there was no indication that the testis passes through any period with a greatly increased mutational response. The data suggested that the transition between the lower mutational response found in the newborn male and the higher response in the adult occurs at about one week of age[18]. The cell types present in the newborn male probably correspond to those present during at least the first ten years in human males. The assumption that for all 30 years the response is like that in spermatogonia, which had been nothing more than a guess, thus turned out to be on the safe side.

Ways of Estimating Genetic Hazard to Humans

As mentioned, calculations of genetic risk are complex. The mutation rates found in specific-locus experiments have been used for this purpose, even though Russell[12] has stressed that such a usage is of questionable validity, the real usefulness of the specific-locus data being instead to reveal the relative frequencies of gene mutations and small deficiencies under a great number of different conditions. If the specific-locus mutation rates are used directly in estimating hazard, it is necessary to assume that the average mutation rate for the seven loci is representative of the average mutation rate per gene for the whole genome. This is open to question, especially since there are large differences in mutational response among these few loci. In this way of estimating risk it is also essential to estimate (1) the number of genes in the genome, and (2) the fraction of the total mutations that cause abnormalities in those individuals containing one normal gene and one mutant gene at a given locus (i.e., the fraction with dominant effects). The final estimate of genetic hazard obtained is then applied to humans.

Another way of estimating risk is to see what amount of radiation doubles the mutation rate in the mouse. Specific-locus data, plus data measuring other endpoints, are used in calculating a doubling dose. This value is then used, together with knowledge about the current incidence of genetic disease in man and certain assumptions, to calculate what the incidence of disease would be at genetic equilibrium following an increase in the radiation exposure of the population. In humans, genetic equilibrium for the genetic diseases considered most important would not occur until well in excess of 500 years after the change in exposure occurred. From the estimated incidence of induced diseases at equilibrium, further assumptions are made in order to estimate how many induced genetic diseases would occur in the first one or two generations. Although this indirect method has certain advantages, it is handicapped by considerable uncertainty as to the fraction of the irregularly inherited diseases which would increase if the mutation rate increases. This is no small problem because the irregularly inherited diseases, those diseases that are not simply inherited according to expected Mendelian ratios, constitute the bulk of human genetic disease.

A third approach that has been used to estimate genetic hazard is an empirical estimate of damage to the skeletal system of the mouse caused by irradiation of the prior generation. The method is only now being developed, but already shows considerable promise. At present it is necessary to guess what fraction of total dominant mutations affecting all body systems would be found by studying only the skeletal system. Furthermore, it is not known with certainty what fraction of the total mutations would seriously handicap a human getting such a mutation. It is likely, however, that there is no more uncertainty about these two fractions than exists in the assumptions used in other methods of estimating risk. This method has the obvious advantage of being based on effects easy to relate to genetic disease in man (in particular, many birth defects), and it is hoped that further development of this approach will improve estimates of genetic risk. As this is a new approach for estimating risk with which I am closely associated, I shall describe it in more detail.

Skeletal Mutation Method in Mice

Background

The skeletal mutation method was initiated by U. H. Ehling in a series of experiments performed in the early 1960's[3]. His experiments consisted of examining the skeletons of four-week-old mice that had either an irradiated sire or an unirradiated sire. Various irradiation treatments were administered. He found that certain classes of malformations were statistically significantly more frequent among the progeny of irradiated males, and he termed mice with malformations of these types "presumed dominant mutations." These are termed dominant mutations because their effects are seen in the first generation even though the irradiated parent is mated to a genetically normal mouse. Ehling's experiments provided strong evidence that many dominant mutations affecting the skeleton were induced, but there is no way to be completely certain that skeletal malformations are caused by dominant mutations without actually breeding the affected mice to see if their malformations are transmitted. Ehling performed no large-scale transmission experiment to test this. When he finished the experiments mentioned, he switched from this field of research to the rapidly growing field of chemical mutagenesis, in which he used other techniques.

Procedure

My wife and I picked up the skeletal mutation method where Ehling left it when I entered his laboratory to do postdoctoral research. Our experiment[19] consisted of treating spermatogonia with a dose of 100 + 500 R of 60 R/min gamma radiation with an interval of 24 hours between doses. We used this exposure regimen because Russell[9], using his specific-locus method, had discovered that such a fractionated treatment causes an elevated mutation rate, and our goal was to obtain as many mutations as possible to test for transmission. The irradiated male mice were mated with unrelated females, and the first-generation sons were collected. These were mated with unrelated females in order to obtain second-generation offspring. After mating, the first-generation sons were killed and their skeletons prepared for study. If such a son were found to contain a malformation, the skeletons of some of his progeny could be prepared to see if the malformation was transmitted, thus providing a means of proving that a dominant mutation was the cause of the malformation. Other second-generation progeny could be used to set up mutant lines of the mutations found in order to permit more detailed study of mutations of this type. No control experiment was performed because the main objective was to get as many mutations as possible, and Ehling's experiments indicated that the spontaneous mutation frequency for this type of mutation is low.

Results

In a sample of 2,646 F_1 sons, 31 were proved to have a dominant skeletal mutation by breeding tests and 6, having no offspring, were concluded to be mutants based on criteria developed for finding mutants in the absence of breeding tests. This is a mutation rate of 1.4% per gamete[19].

Almost all regions of the skeleton were affected by one or more of the 37 mutations found. Many skeletal mutations cause a large number of effects in widely separated parts of the skeleton. Malformations are usually of the following types: (1) too many bones, (2) too few bones, (3) extreme shape defect caused by the presence or absence of bone, or (4) fusion of bones. Many mutations cause more than one of these types of malformations. No attempt was made to detect mutations causing only subtle shape changes.

Many of the skeletal effects found are similar to those seen in some birth defect syndromes in man. One mutation caused a number of effects similar to those present in a genetic disease in man known as cleidocranial dysostosis. Mice with this mutation have incomplete formation of their clavicles and holes in their skulls, besides other characteristic effects.

In addition to the estimate of the mutation rate, another important finding was that dominant mutations typically exhibit low penetrance for some or all of their effects. This means that all mice with a given mutation do not have all of the effects caused by that mutation. Certain of the malformations thus skip generations even though they are caused by dominant mutations. Malformations that do this are by definition irregularly inherited, and thus mutations of this type provide good models of irregularly inherited conditions in man.

Implications

As mentioned earlier, the mutation rate obtained permits a direct estimate of genetic hazard in the mouse which could probably be applied to man with reasonable confidence. In addition, the new information about the nature of dominant mutations is important because it indicates that irradiation does increase the frequency of irregularly inherited diseases. The argument has been advanced recently that our society is spending too much money on safety by overestimating genetic hazard, perhaps by a factor of 30 times[4]. The key point in this argument was the assumption that an increase in the mutation rate would not cause an increase in the frequency of irregularly inherited diseases. The results from our experiment show this assumption to be incorrect, and thereby support indirect estimates made under the assumption that if the mutation rate increases, there will be an increase in the incidence of at least an important fraction of the irregularly inherited diseases.

The induction of dominant skeletal mutations is of great interest because they are dominant mutations and therefore capable of expressing their serious effects in the early generations after induction. An increase in the frequency of this type of mutation should lead to a much more rapid increase in the incidence of genetic disease than would occur following an increase in the frequency of induction of recessive mutations. Even though dominant mutations are of the greatest concern in assessing genetic hazard, most of our information about the induction of mutations is based on the study of recessive mutations. The main reason for this is simply that the specific-locus method has for many years provided the most efficient way known for learning about the induction of gene mutations and small deficiencies in mammals. Even though the skeletal mutations are dominant mutations, they appear to be mostly gene mutations or small deficiencies, and it thus seems reasonable to assume that the knowledge about the influences upon the mutation frequency of different irradiation conditions and germ-cell stages that has been found in specific-locus experiments will hold true for dominant skeletal mutations. This is an assumption that can and will be tested.

Relationship of Background Radiation and Spontaneous Mutation Rate

It is, perhaps, important to note that radiation is not the only cause of mutations. Radiation increases the frequency of mutations, but it is not the major cause of spontaneous mutations. Some people seem to think that the spontaneous rate is dependent upon the background radiation level. That this is not so is clearly illustrated by data from a few of Russell's experiments: In his 300 R acute experiment on spermatogonia he found 40 mutations/65,548 offspring, a mutation rate of 2.04×10^{-6} mutations per R per gamete[10]. In his control experiment on spermatogonia he found 28 mutations/531,500 offspring[10]. It is instructive to calculate the expected number of mutations in the control experiment from the 300 R data under the (false) assumption that all mutations are radiation induced. The expected value is (2.04×10^{-6} mutations per R per gamete) (5.315×10^{5} gametes)(1 year, for assumed average time male was exposed to background radiation before siring young) (.1 R per year background radiation level[1]) (0.30 to correct for expected dose-rate effect) = 0.03 mutation compared to the observed value of 28. This finding that the observed spontaneous mutation frequency is about 900 times as high as would be expected based on the mutation frequency following irradiation shows clearly that background radiation can account for only a small fraction of the spontaneous mutation frequency.

Estimates of Genetic Hazard

Present risk estimates are founded upon much of the data described in this paper. According to a recent large epidemiological study encompassing 756,304 live births in British Columbia, 9.44% of all liveborn humans will be seriously handicapped by a genetic disease at some time in their lifetime[21]. Risk estimates vary, but, according to two currently used estimates, the increase in serious genetic diseases at genetic equilibrium will be (1) 0.5 to 12.5%[1] or (2) 0.3 to 3%[16] of the current incidence levels if humans are continuously exposed to the maximum permissible level of 5 rem per generation.

Radiation Exposure Levels

To give some perspective on the hazards of radiation from energy production, it is useful to know the amount of radiation the population is exposed to from other sources. Natural radiation causes a whole-body exposure of 102 mrem per year, of which the genetically significant exposure is 90 mrem per year. By far the biggest man-made source is medical and dental radiation, which causes a whole-body exposure of 73 mrem per year, of which the genetically significant dose is 30—60 mrem per year. In contrast, whole-body exposure from fallout is 4 mrem per year, from nuclear power production in 1970 was 0.003 mrem per year, and from nuclear power production in 2000 is projected to be less than 1 mrem per year[1].

* * * * *

Oak Ridge National Laboratory is operated by the Union Carbide Corporation for the U.S. Energy Research and Development Administration.

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Terminal Storage of Radioactive Wastes in Geologic Formations

by

T. F. Lomenick

Office of Waste Isolation,
Union Carbide Corporation - Nuclear Division
Oak Ridge, Tennessee 37830

ABSTRACT

The principal aim of the National Waste Terminal Storage (NWTS) program is to develop pilot plants and, ultimately, repositories in several different rock formations in various parts of the country. Rocks such as salt, shale, limestone, granite, schists, and serpentinite may all qualify as host media for the disposition of radioactive wastes in the proper environments. In general, the only requirement for any rock formation or storage site is that it contain any emplaced wastes for so long as it takes for the radioactive materials to decay to innocuous levels. This requirement, though, is a formidable one as some of the wastes will remain active for periods of hundreds of thousands of years and the physical and chemical properties of rocks that govern circulating groundwater and hence containment, are difficult to determine and define. Nevertheless, there are many rock types and a host of areas throughout the country where conditions are promising for the development of waste repositories. Some of these are discussed below.

I. INTRODUCTION

Figure 1 is a generalized tectonic map of a portion of North America that depicts the U.S. as having a large central stable region that is flanked on the west and east by mountain systems. To the north lies the old and complex system of crystalline rocks of the Canadian Shield and to the south lies the Gulf Coast Geosyncline. Indeed, the almost flat-lying and undisturbed sedimentary rocks of the central stable region could possibly contain many attractive sites for repositories; however, some of the crystalline rocks of the Appalachian and Rocky mountain orogenic belts and the Canadian Shield may also be suited for waste storage as are certain segments of the sedimentary sequence in the Gulf Coast region.

ORNL-DWG 73-3139

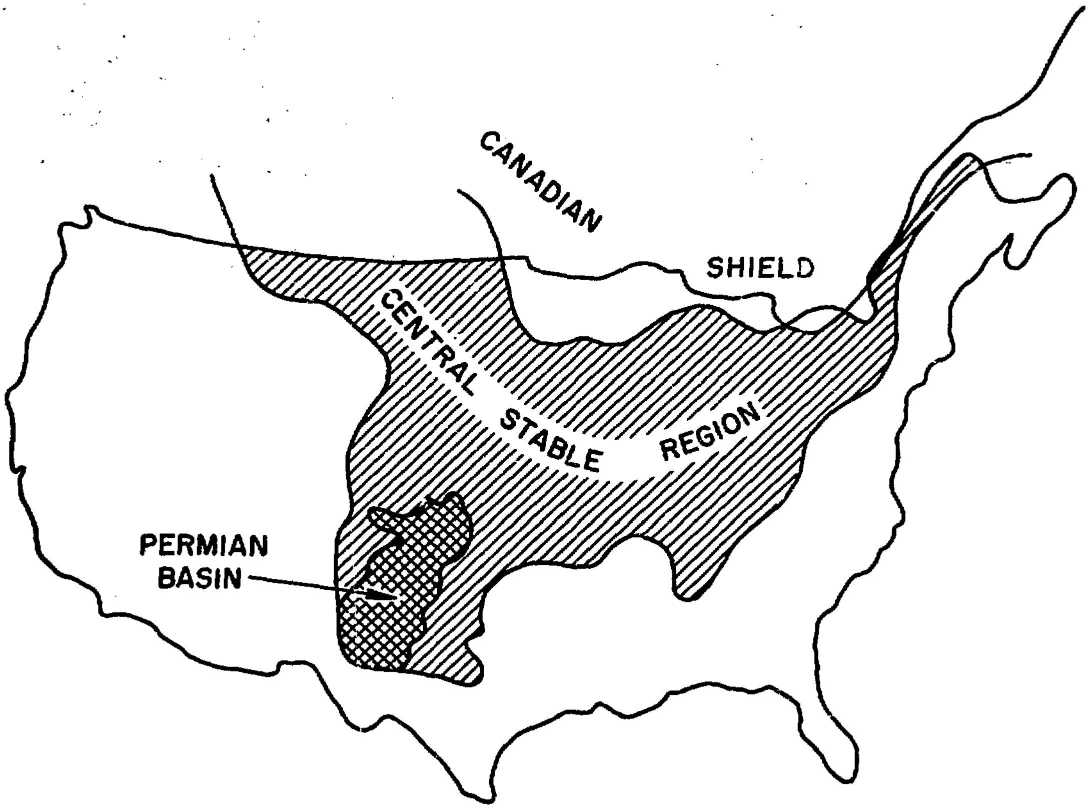

FIGURE 1. LOCATION OF PERMIAN BASIN AND CENTRAL STABLE REGION.

II. ROCK SALT

Rock salt has long been regarded as the most favored geologic medium for the containment of radioactive wastes in the United States. This stems largely from the plastic behavior of salt which promotes self-healing and otherwise makes it impermeable to circulating groundwater (Committee on Waste Disposal, 1957). Other important advantages of salt include its wide distribution, ease of mining, and favorable heat dissipation characteristics. Figure 2 is a map of the conterminous United States that shows the occurrence and distribution of rock salt deposits. Although some of the smaller deposits in the western U.S. could possibly contain wastes, most of our attention has been directed toward the larger deposits, namely the Paradox and Permian basins, and those of the northeastern U.S. and the Gulf Coast region.

Salt deposits are present throughout the Permian Basin, which stretches from central Kansas through the Oklahoma Panhandle and into western Texas and eastern New Mexico, covering an area of about 120,000 sq miles. In general, salt deposits within the basin become progressively younger, thicker, and deeper toward the southwest; however, in most areas the salt body is found at depths of less than 2,000 ft. In Figure 3, which shows the aggregate thicknesses of the principal salt-bearing formations in the Permian basin, it is seen that extremely thick beds of salt occur in the Salado Formation in southeastern New Mexico. This formation dips gently eastward along with the overlying Rustler Formation and the underlying Castile Formation, which locally contain appreciable quantities of salt. Together they comprise the Ochoa Series of evaporites of Late Permian age. The Salado Formation is characterized by thick salt beds with thin intervals of anhydrite, shale, and polyhalite. Locally, near Carlsbad, New Mexico, the formation is also rich in potash minerals. In Kansas, the thickest and most widespread salt deposit is the Hutchinson Salt Member of the Wellington Formation, a part of the Sumner Group of westward-dipping Upper Permian rocks. Salt deposits have also been found in the younger Nippewalla Group of Permian rocks toward the southwest, but their distribution and thickness are not precisely known. The Hutchinson salt, as shown in Figure 3, underlies central and south-central Kansas and extends southward into Oklahoma. The eastern edge of the salt body lies approximately 400 ft. below the land surface, but near its western edge in Kansas it is found at a depth of more than 1,500 ft. Thicknesses of the unit in the state range up to 700 ft. In general, the Hutchinson consists of a complex mixture of salt, anhydrite, and shale, with salt as the predominant fraction throughout most of its extent in Kansas. Figure 3 shows the salt to be thickest in the south-central part of the state.

The Permian salt basin is located within the stable Mid-Continent area of North America, which is characterized by low topographic relief and flat-lying beds of sedimentary rocks (see Figure 1). Even though the Permian salt basin and the stable interior of the country have not been subjected to diastrophic movements since Precambrian time, some areas have been structurally positive (rising) in the geologic past, and others have been structurally negative (subsiding). These ancient structural features, although largely masked by surface rocks today, are extremely important in the subsurface as they were instrumental in controlling the deposition of the salt rocks. Principal events in the geologic history of the region include, during the early Paleozoic, submergence and subsequent deposition of marine sediments on an irregular and long-eroded surface of Precambrian igneous and metamorphic rocks. During Mississippian and Pennsylvanian time, the region was alternately submerged and elevated before a period of aridity during the Late Permian which is evidenced by the extensive evaporite deposits of that age. Another major period of emergence and erosion occurred throughout most of the region during the Mesozoic Era before

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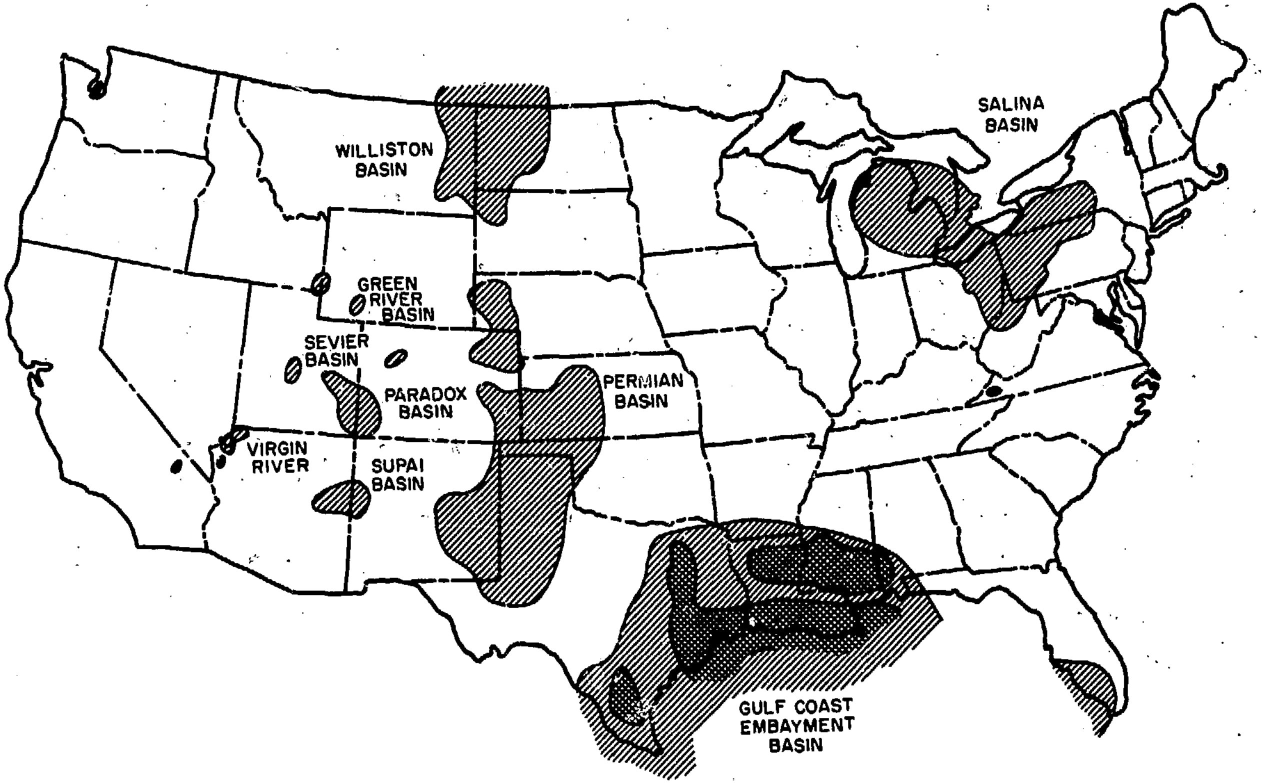

FIGURE 2. MAP OF CONTERMINOUS UNITED STATES SHOWING AREAS UNDERLAIN BY ROCK SALT--DOUBLE CROSS-HATCHED PORTION OF GULF COAST EMBAYMENT REPRESENT SALT DOME AREAS

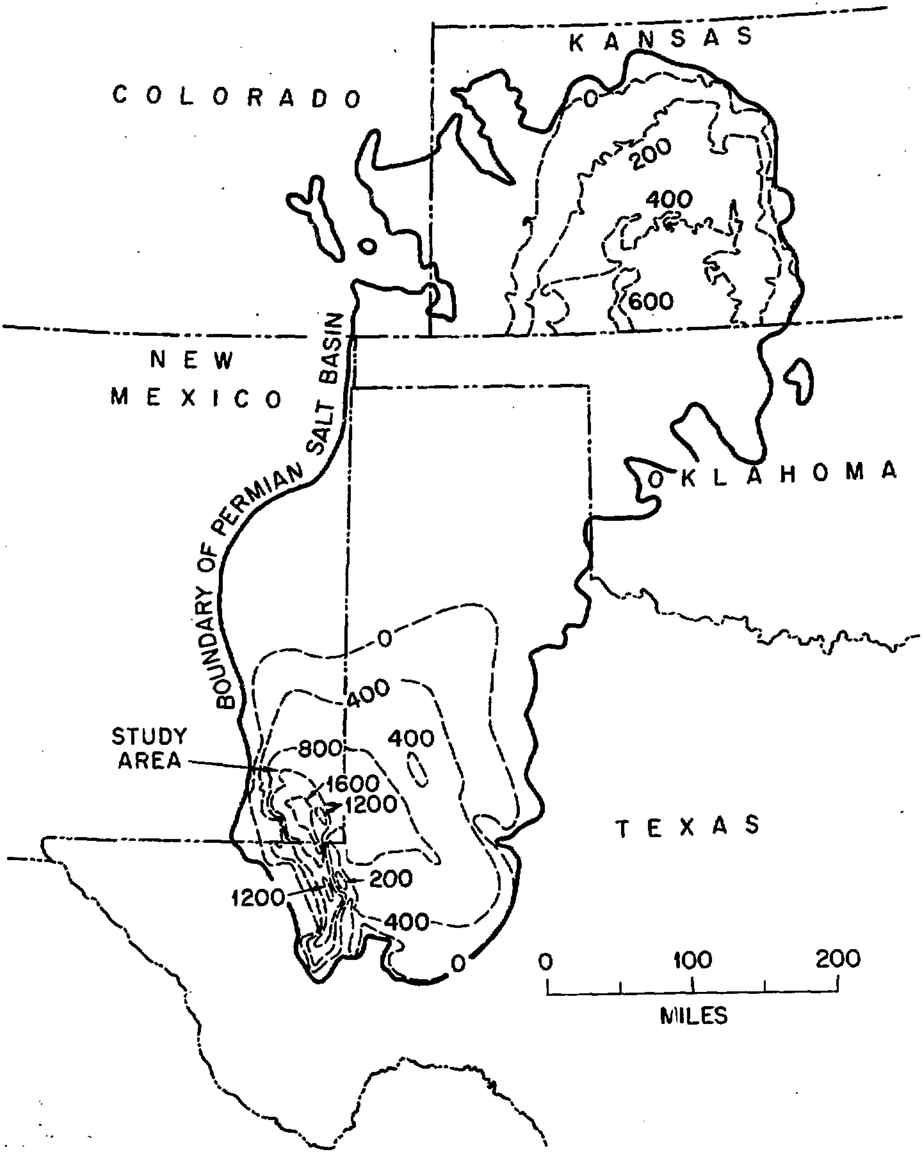

FIGURE 3. OUTLINE OF PERMIAN SALT BASIN SHOWING AGGREGATE THICKNESSES OF SALT IN SALADO AND WELLINGTON FORMATIONS. AFTER HAYES (1958) AND KULSTAD (1959).

the deposition of marine and continental sediments mostly of Cretaceous age. Erosion was prominent during the early Tertiary, but later eastward and southeastward-flowing streams left thick accumulations of gravel, sand, and silt over the area. Some slight tilting and warping along with wind and water erosion have since formed the present plains landscape of the region.

In addition to the long geologic history of tectonic stability of the Permian basin, as revealed by the generally flat-lying nature of the rocks and by the dearth of deep-seated faults and igneous intrusion, the seismicity of the region also suggests quiescence and stable tectonics.

All rocks that lie relatively near the land surface undergo some leaching by circulating groundwater. However, rock salt is unique in that generally only the uppermost surface is vulnerable to the leaching action of water as its self-healing properties preclude the development of open fractures, fissures, faults, etc., that provide the avenues for deeper and intraformational circulation in all other rock types. In the Permian salt basin, dissolution of rock salt at shallow depths by circulating groundwater is a common phenomenon. In central Kansas at least a part of the eastern edge of the salt basin has been dissolved in the subsurface by groundwater, as has the western edge of the salt in southeastern New Mexico. Active solution of shallow salt beds in other parts of the basin is also occurring as evidenced by the high salinities of rivers, such as the Arkansas, Red, Canadian, Brazos, and Pecos, that drain the region. Figure 4 is a generalized cross section of a part of central Kansas that shows the prominent stratigraphic and structural features of the Hutchinson Salt Member. It is observed that the gently westward-dipping salt body does not extend to the land surface but is dissolved along its eastern edge to a depth of several hundred feet. The abrupt end of the deposit coupled with an overlying series of subsidence ponds and saltwater springs strongly suggests that the original limits of the salt extended somewhat farther eastward. Channel fillings of Pleistocene and older sediments near the edge of the salt show a distinct westward progression of younger sediments that are presumed to have been laid down as the underlying salt was removed in that direction. Precise dating of these sediments indicates that during the last few million years the edge of the salt body has retreated westward at the rate of a few miles per million years. Therefore, only the first few miles of the salt body along its eastern edge would be vulnerable to dissolution by this phenomenon for the lifetime of the wastes or for the next few hundreds of thousands of years.

In southeastern New Mexico, the western boundary of the Permian salt basin is believed to have migrated eastward at the rate of a few miles per million years during the recent geologic past. On Figure 5, which depicts the present state of the salt and overlying beds in the region near Carlsbad and the study area, it is apparent that the uppermost beds of salt once extended farther west but were subsequently eroded with the development of the Pecos River Valley east of the Guadalupe Mountains. Indeed, Bachman and Johnson (1973) have suggested that at the close of "Ogallala" time (4 million years ago) the Salado salt may have extended as far westward as the base of the Guadalupe Mountains, or another 25-35 miles. With this premise they concluded that the rate of retreat averaged about 6-8 mi/m.y. during this span of time. Furthermore, Bachman has found that the quantitites of salt presently being removed from watersheds within the Permian salt basin range up to about 0.5 ft/1,000 years. With these rates of vertical and horizontal removal of salt, it is seen that the study area, which is some 20-30 miles from the western edge of salt and is more than 1,000 feet deep into the salt beds, would not be affected by dissolution for the next few hundreds of thousands of years or for the duration of the wastes' radioactivity.

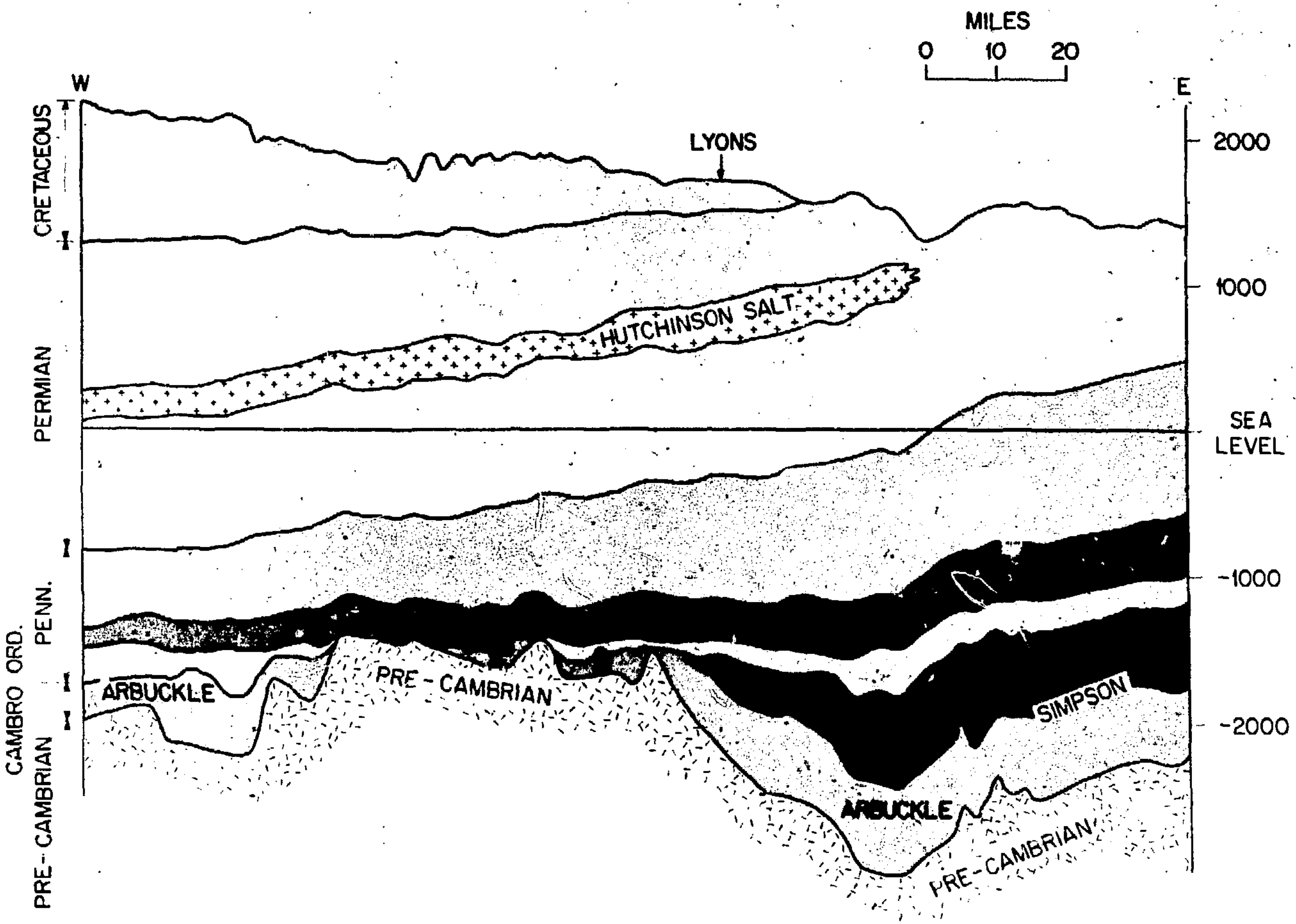

FIGURE 4. GEOLOGIC CROSS SECTION OF A PORTION OF CENTRAL KANSAS.

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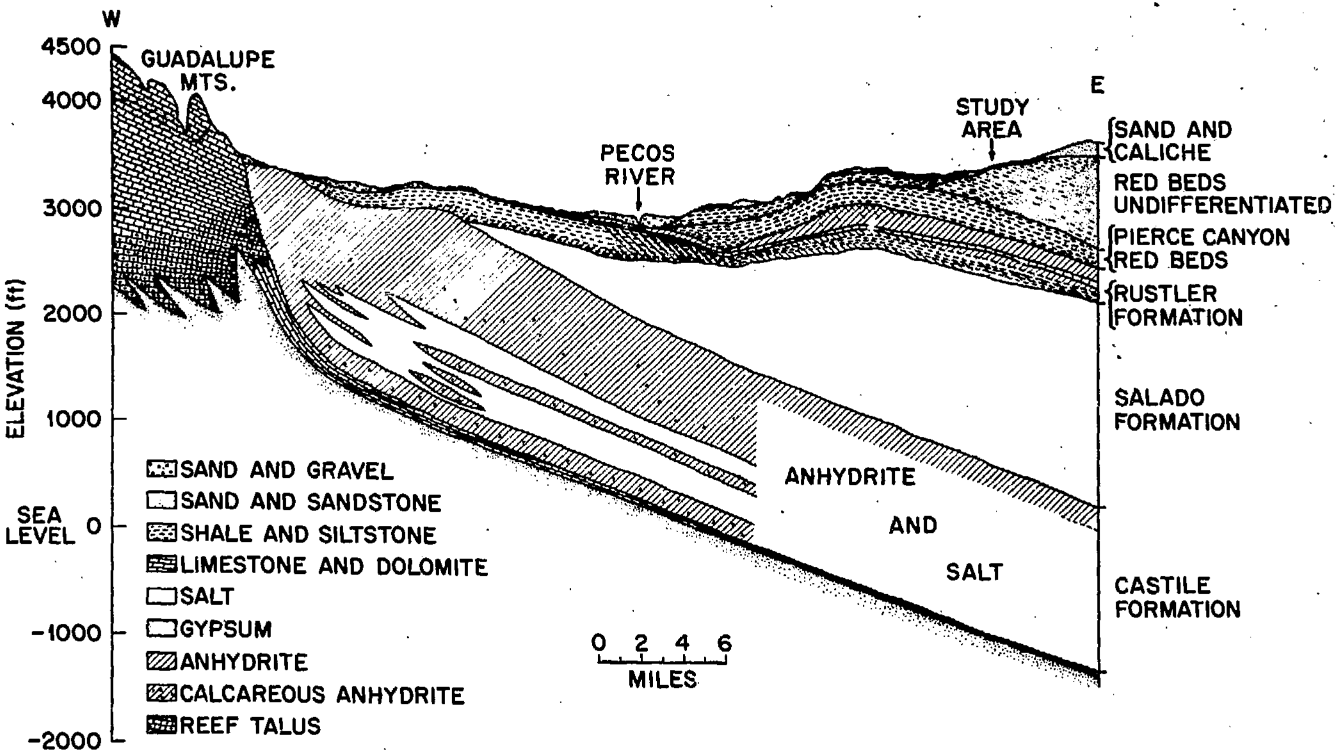

FIGURE 5. GENERALIZED CROSS SECTION OF PART OF ROCKS IN SOUTHEAST NEW MEXICO. ADAPTED FROM COOPER (1960).

Significant quantities of potash ore and extensive deposits of oil and gas occur in selected localities of southeast New Mexico. To preclude conflicts of interest in the economic development of the region, the rocks underlying the study area preferably should have a low potential for oil or gas development and should not contain extensive high-grade ores. Potash mines in the southeast New Mexico region produce more than 80 percent of all the potassium minerals mined in the U.S. However, most of the higher grade commercial ore within the area is nearing depletion.

Major oil and gas fields have not been discovered in the vicinity of the study area in southeast New Mexico, although some localized accumulations of oil and gas occur along trends to the north and south. Exploration for gas has itensified recently in the deeper rocks of southeastern New Mexico and will undoubtedly lead to a renewed interest in the deeper rocks in the vicinity of the study area.

Because circulating groundwater is perhaps the only mechanism for dispersing and transporting radioactive wastes placed in rock salt, it is essential to determine the hydrologic characteristics of the rocks that lie in close proximity to the salt. In the Permian salt basin fresh water is generally confined to the first few hundred feet of surface rocks, and the rocks below the salt beds commonly contain saline water. The hydraulic characteristics of water-bearing rock formations can best be identified by testing in open boreholes. In southeast New Mexico, tests showed that the rocks immediately above the salt beds were extremely tight and incapable of transporting significant quantities of groundwater.

In extreme cases the natural geologic processes of erosion and denudation have the potential, over long periods of geologic time, for stripping away significant quantities of overburden and subjecting wastes that are buried at shallow depths to circulating groundwater and surface water. On the basis of general knowledge of the Great Plains landscape and on the sediment loads of streams that drain the province, it appears that the rates of denudation and stream incision within the Permian salt basin range up to only a few hundreds of feet per million years. This general conclusion is substantiated in part by the recent work on erosion and denudation in the Lyons, Kansas, area (Stewart, 1973). On the basis of the precept that glacial and interglacial episodes similar to those of the Pleistocene will continue throughout the next 1 million years, Stewart concludes that the probability that stream erosion will breach the salt formation in the Lyons area is so small that it is inconsequential. By extrapolating and adjusting present-day rates of denudation in central Kansas to accommodate glacial as well as interglacial conditions, Stewart also finds that, for all practical purposes, the probability that denudation will exceed 25 feet during the next 1 million years in the Lyons area is zero. Should continental glaciers advance into central Kansas, Stewart judges that the flow patterns of the major streams will not change appreciably, nor will the rise and fall of sea level accompanying glaciations and interglaciations affect stream entrenchment and valley alluviation in the Mid-Continent. The effects of new ice sheets on the underlying rocks in central Kansas have also been evaluated and it is concluded that deep scouring is unlikely and only minor fracturing and flexuring would be expected in the near-surface rocks due to glacial loading and unloading.

In order to establish the stratigraphic levels for waste storage and to provide sample specimens for mineralogic determinations and rock-property testing, a series of coreholes were drilled at the study areas. In central Kansas, mineralogic studies of cores indicate that hydrated minerals and water-bearing rocks are present throughout the evaporite section, with a general decrease in water content with depth (Kopp and Fallis, 1973). Upon heating sample specimens to 100°C it was found that gypsum is the major mineral constituent for rocks that lose more than 10 percent water. Similarly, for rocks that lose from 2 to 10 percent water upon heating, shales are dominant or the rocks have high clay content. The relatively pure halite rocks were found to lose less than 2 percent water upon heating. Thus, to avoid extensive dewatering, the containers of heat-generating waste should be placed only within the relatively pure halite beds of the evaporite sequences. The cores also provide samples for establishing thermal and mechanical properties including conductivity, specific heat, density, elastic moduli, Poisson's ration, etc., for the several rock types at the study areas for use in thermal-analysis calculations and the rock-deformation analyses.

In summary, a series of coreholes have been drilled to provide the critical data for selecting appropriate disposal levels and for assessing the hydraulic characteristics of the overlying and underlying formations on a tract of federally owned land in southeastern New Mexico and in parts of Kansas. Selective parts of the cores have been analyzed to determine the quantities and characteristics of various minerals in the evaporite section and, in particular, of any hydrated minerals and rocks that could dehydrate upon heating due to radioactive decay of the wastes. Measurements of the physical properties of these rocks also have been made to calculate their deformational behavior. Because of the need for long-term confinement, several unique studies have been initiated. The long geologic history of relative quiescence coupled with data on historic earthquakes strongly suggests that the Permian basin will continue to be tectonically stable for the next few hundreds of thousands of years or for the effective lifetime of the wastes. In addition, studies of subsurface salt dissolution show that the rate of basinward migration of the relatively shallow edges of the salt has, during Quaternary time, averaged only a few miles per million years. Also, present rates of denudation in central Kansas have been found to average less than 1 foot per 1,000 years and stream incisions in the same area during Quaternary time have not exceeded several hundred feet. Finally, investigations have revealed that the buried wastes would not be adversely affected by the advance of a new continental ice sheet. Similar investigations are underway or are planned for the other salt deposits and rock types discussed herewithin.

A general survey of the salt deposits of the Paradox basin has revealed that the best prospects for further study lie at the north end of the Salt Valley anticline and the adjoining area to the northwest (Hite et al., 1973) (see Figure 6). A map of the local surficial features has been constructed and detailed studies of existing well logs and geophysical surveys that traverse those areas have been made. With these data a drilling and hydraulic testing program coupled with a vertical seismic profiling procedure has been outlined to determine and define such things as the exact depth of the salt, the stratigraphy and structure of the deposits, the nature and extent of potash mineralization and hydrocarbon bearing interbeds of shale, and the occurrences and characteristics of overlying groundwaters.

The salt deposits that underlie the northeastern states are strategically located in regard to the nuclear power industry, as there are already numerous power reactors operating within the region and a small fuel reprocessing facility has operated in western New York state. Figure 7 shows the outline of salt beds in this region and also depicts those areas where the deposits are at least 200 feet in aggregate thickness and lie at depths of less than 3,000 feet below the land surface. Preliminary reconnaissance surveys of these areas in Michigan, northeastern Ohio, and western New York have been made and several

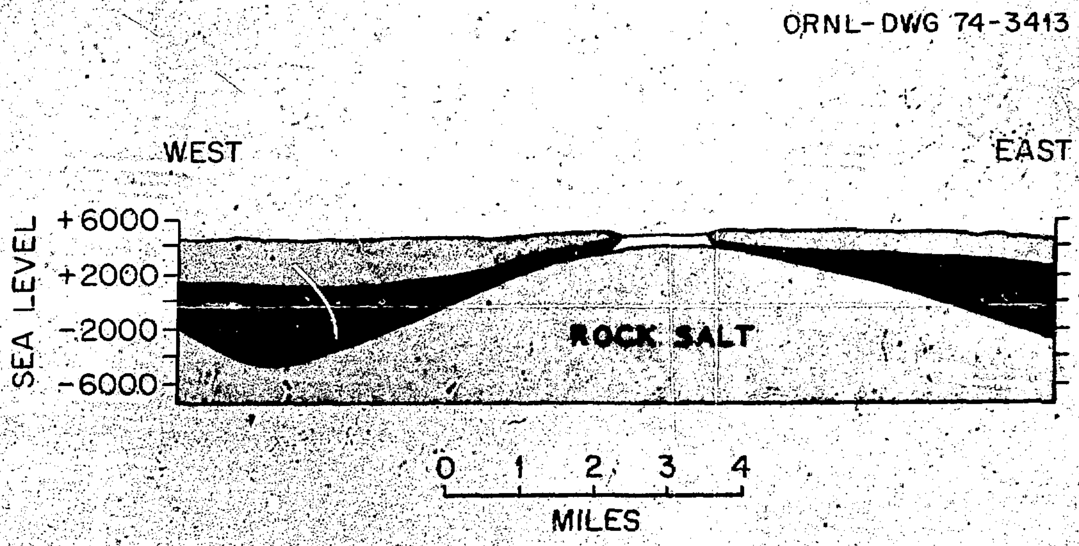

FIGURE 6. GEOLOGIC CROSS SECTION THROUGH A PORTION OF THE SALT VALLEY ANTICLINE, GRAND COUNTY, UTAH.

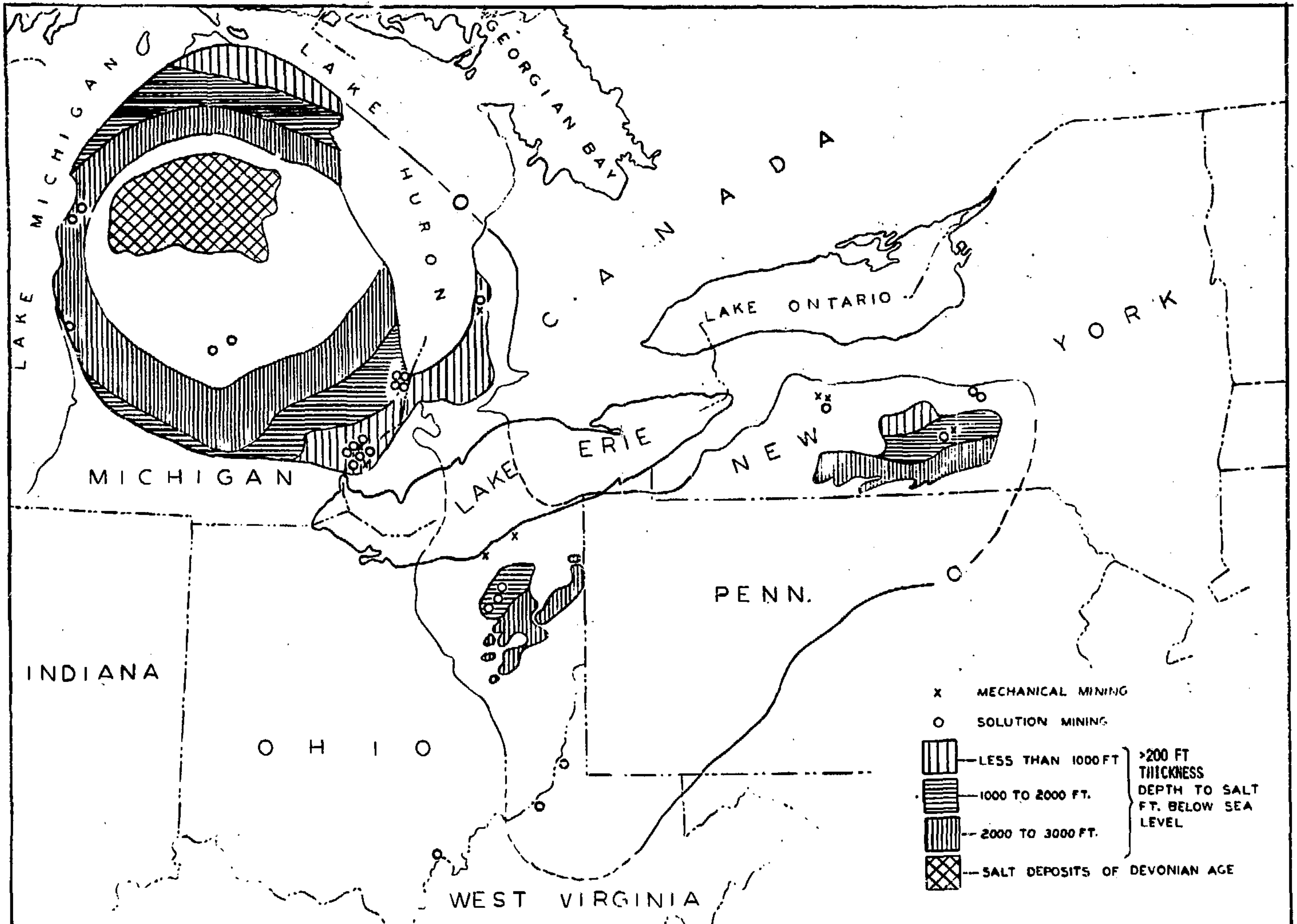

FIGURE 7. EXTENT AND DEPTH OF CERTAIN ROCK SALT DEPOSITS IN MICHIGAN, NEW YORK, AND OHIO.

general areas have been chosen for further study. The next stage of work will include the drilling of one or more test holes at each study area, hydrologic testing of water bearing formations in close proximity to the salt, aerial surveys, and studies of the possible future oil and gas development of the rocks above and below the salt deposits.

Salt domes, provided that they are tectonically and hydrologically stable, are excellent structures for radioactive waste repositories as the salt is generally homogenous and persists to extremely great depths in the vertical dimension. More than 300 salt domes are known to exist in the Gulf Coast Embayment; however, less than 50 of them are considered to be good candidates for further study as the large majority are either located off-shore, are too deep, have active production of petroleum, or have existing mining operations (Anderson et al., 1973). To date, our detailed investigations have been confined to the interior salt dome basins of northern Louisiana, northeastern Texas, and Mississippi (see Figure 8). Specifically, these studies have been designed to determine the tectonic and hydrologic stability of the domes and to define more exactly the sizes and shapes of selected "target" domes. Kinematic studies of northern Louisiana salt have centered on the basin-wide determination of stratigraphic thicknesses of sediments to develop growth indexes for the domes (Martinez, et al., 1975). In general, this work shows decreasing salt activity with time. Initially, during Jurassic time, the salt flowed to form large pillow-like structures. This was probably followed by piercement during lower Cretaceous time which could have resulted in some salt flowage to the surface. At the end of Upper Cretaceous time, activity was greatly reduced, and by Tertiary time, the inward movement of salt from the remnants of the old pillows had virtually stopped. As Tertiary sediments are locally domed over the salt structures it is concluded that either some upward movement of the salt continued or surrounding sediments were compacted. Work is currently underway to obtain evidence of kinematic stability or instability from studies of Quaternary terrace deposits overlying and adjacent to selected salt domes. To monitor any current movements, an instrumentation system utilizing tiltmeters, extensometers, and geophones coupled with first-order leveling is being installed at selected domes.

The hydrologic stability of salt domes in the Gulf Coast region is being evaluated by utilizing a method for determining groundwater salinity from electric logs coupled with selective drilling and sampling of formation waters. Furthermore, for domes identified as undergoing active dissolutioning, the patterns and rates of dissolutioning at the tops and flanks of the domes can be estimated through numerical modeling of saline water plumes.

III. ARGILLACEOUS ROCKS

Several thick sequences of shale and clay in the U.S. are favorable for further study as candidates for terminal storage facilities. In general, these deposits possess extremely low permeability, relatively high plasticity, high ion-exchange capacity, and are persistent, both vertically and laterally. Powerful evidence that dry and stable openings can be excavated in these types of rocks has been presented in recent studies of cavities mined for the storage of petroleum products (Cobbs, 1975). The successful excavation and operation of dry and stable openings to depths of more than 1800 feet in several shale formations appears to be demonstrable proof of the extreme tightness of such rocks. The most notable deposits of argillaceous rocks that are being studied include: (1) Late Ordovician shale in Ohio and New York, (2) Devonian-Mississippian shales in Ohio and Michigan, (3) Paleocene clays in Mississippi, Louisiana, and Arkansas, and (4) the Pierre shale and its equivalents in the upper Great Plains. In addition, Triassic basins along the Atlantic Coastal Plain and the Eleana shale at the

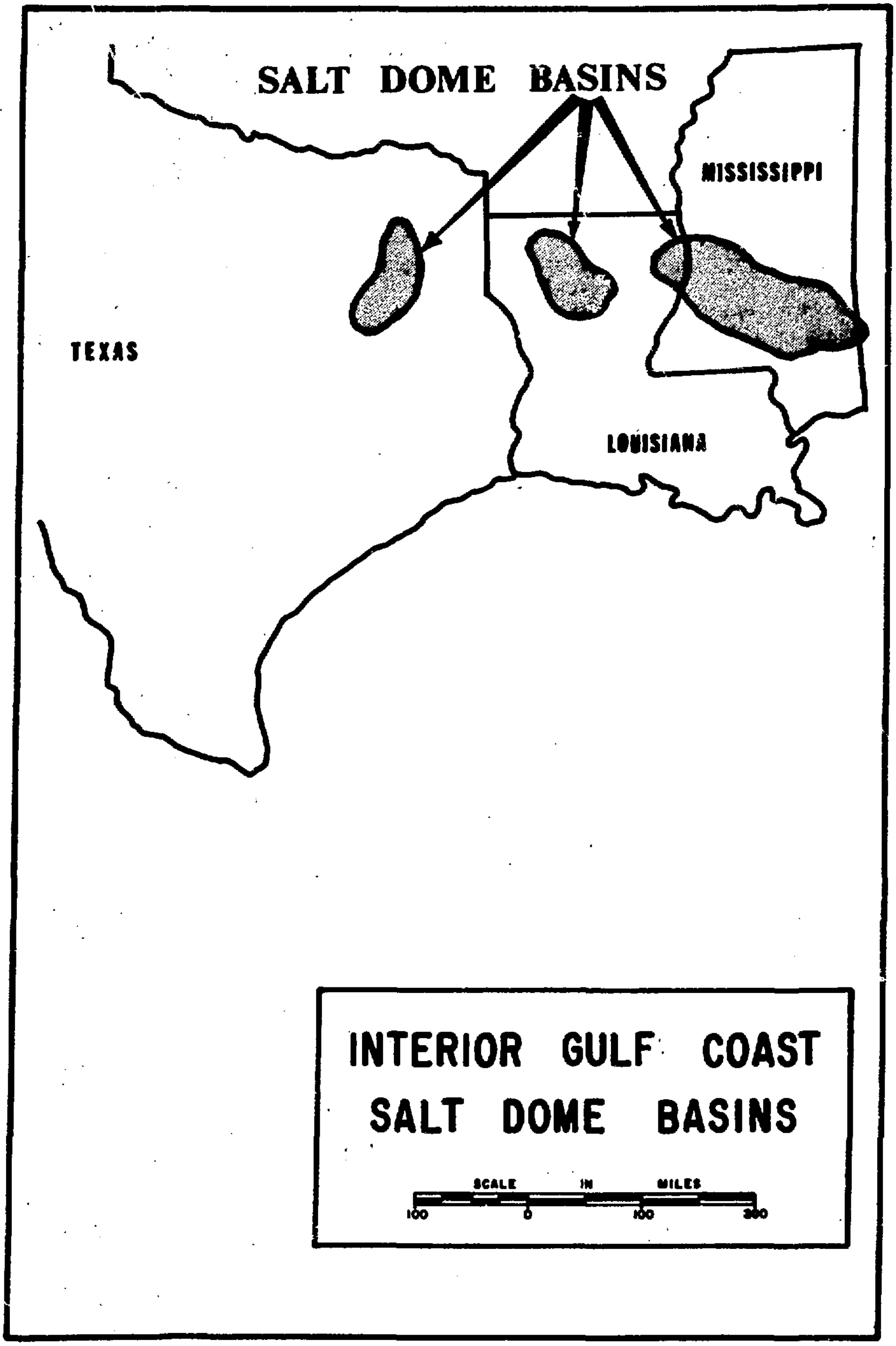
SALT DOME BASINS
MISSISSIPPI
TEXAS
LOUISIANA
INTERIOR GULF COAST
SALT DOME BASINS
SCALE IN MILES
100
0
100
200

FIGURE 8.

Nevada Test site are being evaluated (see Figure 9). At this time all available and pertinent geologic and hydrologic data are being assembled on these deposits to select areas for detailed study for each formation. Ensuing investigations will consist of such things as drilling and coring and in-hole hydrologic tests. Also, various types of aerial surveys, seismic studies, and mineral resource investigations will be required as will special tests in tunnels excavated in the rocks to establish their utility for waste storage.

IV. CALCAREOUS ROCKS

Although calcareous rocks like limestone and dolomite are brittle and thus susceptible to extensive fracturing as well as to dissolutioning by circulating groundwater, these rocks may also be regarded as potential candidates for storage facilities in certain unique environments. One such environment is in northeastern Ohio where a deep dry mine has been developed in the Columbus limestone of Devonian age (see Figure 10). Here mining has continued for more than 30 years and has resulted in excavations covering between 600 and 700 acres. The dryness of these workings is believed to be due mainly to the thick sequence (1,700 feet) of dense impermeable shale that overlies the limestone and to the relatively undisturbed nature of the rock column (see Figure 11). Dry openings in calcareous rocks have also been excavated for petroleum storage in the stable interior portion of the country where the limestone is "protected" by shale and the depositional sequence is continuous. Excavations in chalk deposits in the Gulf Coastal Plain have also proven to be extremely effective containers for the storage of petroleum products and these must be considered to have some potential for storage of radioactive wastes. After specific study areas in limestone and chalk are selected, special geologic and hydrologic examinations of these rocks, including in-situ experiments and tests, will be initiated.

V. CRYSTALLINE AND VOLCANIC ROCKS

Figure 12 is a map of the United States showing those areas underlain by crystalline and volcanic rocks. Note that significant accumulations of crystalline rocks occur in the Canadian Shield as well as in the Appalachian and Rocky Mountain orogenic belts. Based on investigations in a number of mines in the Canadian Shield and in the Maritime provinces' extension of the Appalachian belt, it appears that these rocks are tight and free of circulating groundwater below depths of about 3,000 feet. The geologic and/or hydrologic factors that promote the impermeability of these rocks at depth are not clear; however, rock pressure and perhaps even some form of self-healing over long periods of geologic time are probably important elements. Study areas for detailed investigations in these types of rocks are also being selected.

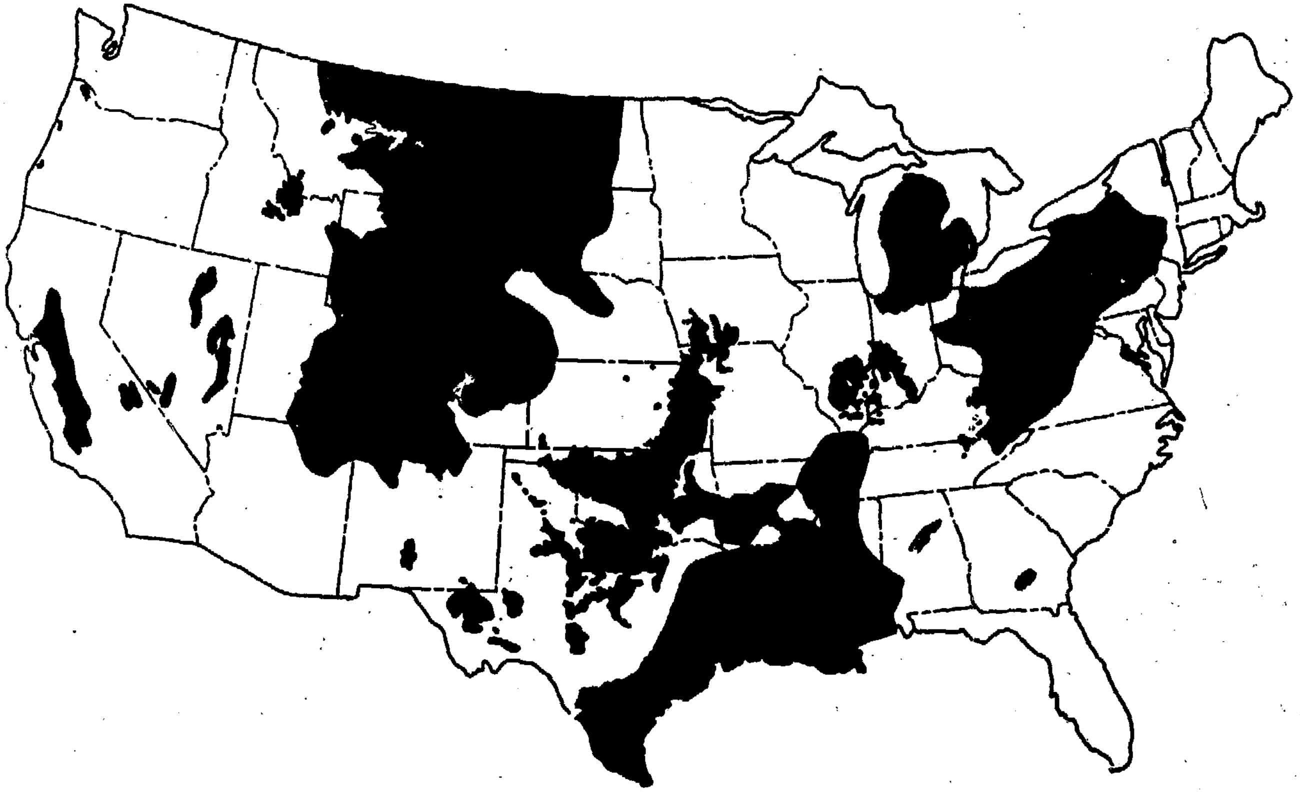

FIGURE 9. THICK BODIES OF SHALE, MUDSTONE, AND CLAYSTONE IN THE U.S.

FIGURE 10. PHOTOGRAPH TAKEN IN THE 2200 FT DEEP LIMESTONE MINE AT BARBERTON, OHIO. NOTE GAS ESCAPE HOLES IN ROOF.

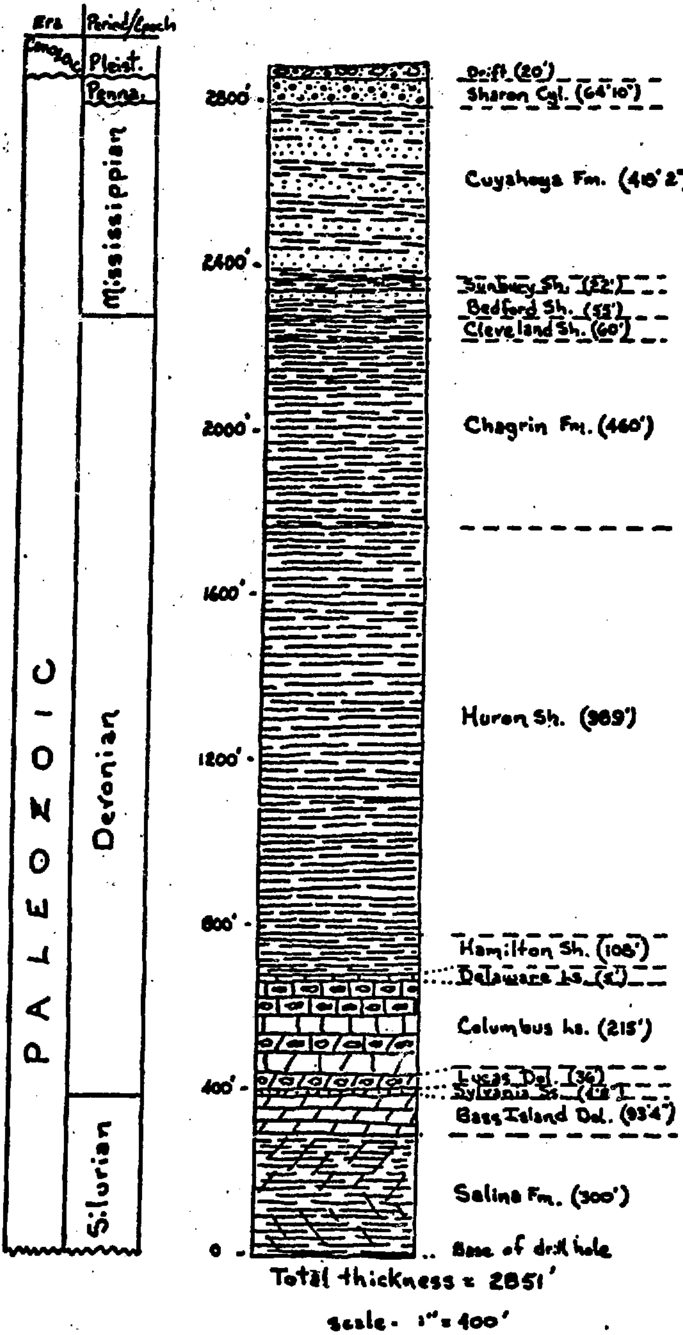

FIGURE 11. GENERALIZED STRATIGRAPHIC SECTION, BARBERTON MINE, OHIO. (AFTER C. R. STAUFFER, 1944).

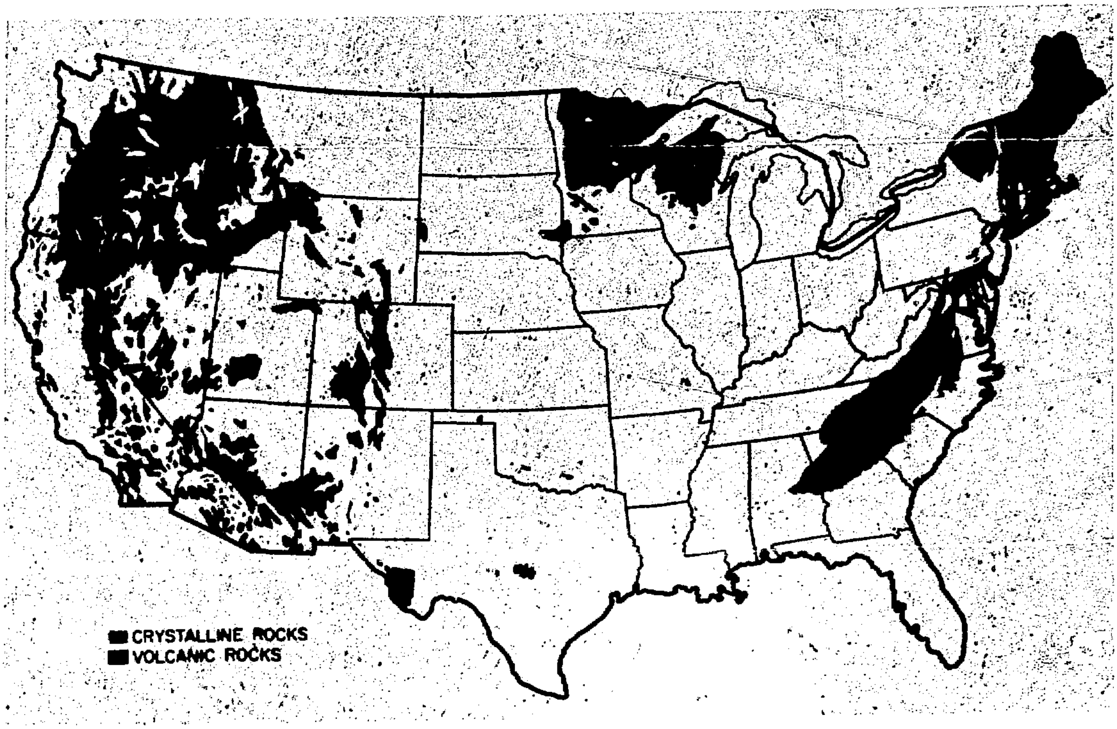

FIGURE 12. CRYSTALLINE AND VOLCANIC ROCKS IN THE U.S.

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