ENVIRONMENTAL IMPACTS OF NUCLEAR POWER PLANTS

CHIHIRO KIKUCHI

INFORMAÇÃO IEA N.º 31

Setembro — 1974

INSTITUTO DE ENERGIA ATÔMICA
Caixa Postal 11049 (Pinheiros)
CIDADE UNIVERSITARIA "ARMANDO DE SALLES OLIVEIRA"
SAO PAULO — BRASIL

ENVIRONMENTAL IMPACTS OF NUCLEAR POWER PLANTS

Chihiro Kikuchi

Coordenadoria de Engenharia Nuclear
Instituto de Energia Atômica
São Paulo - Brasil

Informação IEA Nº 31
Setembro - 1974

INDEX

ENVIRONMENTAL IMPACTS OF NUCLEAR POWER PLANTS

Chihiro Kikuchi

INTRODUCTORY REMARK

This publication contains the class notes of a series of Seminars on Environmental Impacts of Nuclear Power Plants given at IEA by Prof. Chihiro Kikuchi, Prof. of Nuclear Engineering of the University of Michigan, Ann Arbor, Michigan.

These Seminars were given in August directed mainly for the Researches of the Department of Nuclear Engineering of IEA.

INTRODUCTION

The following notes are based on an introductory course in Nuclear Engineering given at the University of Michigan. The purpose of the course is to help students respond to the bombardment of anti-nuclear comments in newspapers, magazines, and others and to prepare them for questions raised by their friends, dormitory mates, and others. What we find is that the traditional technically logical presentation of the subject matter does not adequately prepare them for the social situations they meet. They have the basic technical information, but the information, is structured inappropriately and so are not able to regroup their technical information quickly enough to respond decisively to issues being raised. By presenting the subject matter from a different perspective, as suggested by the notes, our hope is that the students will begin to see a little more clearly the relevance of their chosen profession and technical information to the society in which they live.

The notes therefore are oriented towards American students, and even more specifically to students in Michigan colleges and universities. The reason for doing this is that the issues being raised by the opponents of nuclear power are very imprecise and they often confuse the issues by raising points that are not directly applicable to Michigan. The problems of the state of Michigan are quite different from those of California, of Arizona, and of Montana. Michigan is located in the central northern part of the United States, has no coal, very litlle oil and gas, and has been geologically stable for the last few hundred million years. California, another state, is on the west coast, has geothermal energy, and for while was one of the richest oil producing states of the United States; as a consequence a large fraction of the electric power stations are run on oil, and today the state of California depends on foreign sources for the oil it needs. Arizona is in the southern part of the United States, is known for its sunshine, and at the same time it has its deserts. Consequently many of the suggestions for the use of solar energy come from laboratories in Arizona universities. Montana is in the north-west part of the United States. It is the part of the North American continent that was the last to rise from the sea. The dinosaur fossils are found out there, the extensive deposits of shale oil have been known for years, and there is an abundant supply of coal. For these reasons, the economic viability of energy sources for the generation of electric power are quite different for different regions of the United States.

Another source of confusion, we find, is the time scale needed to develop a technology. We find that the public has been misled into thinking that the energy technologies, such as nuclear fusion, solar energy, and others, can be developed more or less instantaneously. We find that we need to keep repeating the importance of **"lead time"**, that a lead time of 10 years or more is needed, even if the technology exists today.

Admittedly the problems here in Brasil are different. For one, the national per capita energy consumption for Brasil is about 10 million Btu/year compared to about 180 million Btu/year/person for the United States. But the concerns about nuclear power, whether expressed yet or not, are the same. I think it will pay to think about them. And I think it might pay to think through the problems that the USAEC faces today. For many years, the USAEC carried on a program to educate the American public about the facts of nuclear power; the USAEC **thought** that the public was beginning to accept nuclear power. But somewhere, something went wrong. The point is to see what needs to be done to avoid the mistakes of the USAEC.

And as I see it, the problems that we face in the United States are deep rooted, coming from the basic philosophy of education. The American educational system is oriented towards creating political awareness of the citizens, but leaves almost completely untouched the problem of creating technological awareness. The average American knows almost nothing about how electric power is generated; and yet the question of what to use for generation of electric power can be made into a political issue.

I'm hoping therefore that the comments in the notes to follow will help in identifying the problems that might arise here in Brasil, and also help in making plans that are more nearly ideal.

The advantage that you have here in Brasil over us in the United States is that the per capita energy consumption is still quite low. Therefore now is the time to start planning.

CHAPTER I

Nuclear Power: A Model for Developing New Technologies

> "In our highly technological society, where we face many problems as a result of excessive and poorly planned uses of science and technology, it is understandable that nuclear power should be under attack as part of the public's disillusionment with science and technology. These issues-including the effect of nuclear energy on the environment-should be vigorously debated. In the case of nuclear power, I believe that when all sides are heard and all the facts presented, the public will agree that the advantages outweigh any problems. In fact, the development of nuclear power may prove to be a turning point in the way we plan and develop most of our future technologies".
>
> Glenn T. Seaborg, in
> The Controversial Atomic Energy
> Commission, Newsweek, Jan. 4, 1971.

1. Prophets of Doom

The report "The Limits to Growth" for the Club of Rome's Project on the Predicament of Mankind, now available in paperback, may very well turn out to be one of the more authoritative accounts of the fate facing our modern technological society. The study program that led to the dire predictions was started in April 1968, when an international group of experts from a variety of disciplines met in the Accademic dei Lincei in Rome-and hence the name Club of Rome-to discuss some of the compelling global problems. For the first phase, they chose the Project on the Predicament of Mankind and focussed on five major global trends, namely accelerating industrialization, rapid population growth, wide-spread malnutrition, depletion of non-renewable resources, and deterioration of the environment. The club of Rome prediction is that for a while the world population and the needed food supply will continue to increase, but during this period-between now and the end of this century-the non-renewable resources will decrease at an accelerating rate, which will have a catastrophic effect upon our food supply and hence upon the world population. Some critics no doubt will quarrel with some of the details of the predictions, but qualitatively the predictions are not too surprising.

This report and others like it will no doubt trigger a flood of hardbacks and paperbacks, magazine articles and newspaper editorials, etc., predicting the coming of doomsday. One of the most recent ones is **The coming Dark Age: What Will Happen When Modern Technology Breaks Down?**, by Roberto Vacca, which was reviewed in the Ann Arbor News, Sunday, Dec. 23, 1973, by none other than the science editor, Larry Bush. According to this book, the prediction is that transportation, power, and other systems upon which we depend in our modern industrial society will start to break down between 1985 and 1994, beginning first in the United States and Japan, leading to world-wide catastrophic collapse. The point that Vacca makes is that our modern technological systems are hopelessly overloaded, poorly planned, and badly managed, and that the unthinking public is "like a prisoner in a croweded, locked freight car who complains about the uncomfortable ride and gives no thought to the extermination camp that awaits him".

Some of us, and even experts in the field, might disagree with these predictions. But this is not the point. Sooner or later, we'll begin to exhaust our non-renewable resources, but because of inflexibilities in our social, economic, political, and legal systems, our industrial organization and the population will continue to grow for a while-overshoot as systems engineers will say-and then suddenly collapse.

The recent so-called energy crisis has given us a mini-example of the catastrophic consequences of socio-economic growth whithout farsighted planning. The experts saw that the energy crisis was coming but were unable to avert it, because it was too late; to avert it, planning would have to have started 20 to 30 years ago. And keep in mind the suddenness with which the energy crisis struck the public; for just a few years earlier the general topic of conversation was the affluent society.

In contrast to the history of planless development of most of our technologies, the record of nuclear technology is marked with a number of very far-sighted decisions. Perhaps one of the earliest ones was the concern for the biological effects of plutonium. This element was discovered in 1940, but almost immediately research on the biological effects of this material was started as part of the Plutonium Project, under the auspices of the wartime Manhattan Project. The book on the **Histopathology of Ionization from External and Internal Sources** documents a part of the research activities carried out under the Plutomium Project between 1940 and 1948. In the much-publicized **Poisoned Powers** by Gofman and Tamplin (publication date 1971), there is a picture of a rat tumor; but what seems to be less well known is that picture was taken from another volume of the same series, namely the **Effects of External Beta Radiation**, edited by Zirkle, published in 1951. The critics of nuclear power, and hence of the USAEC, frequently use the word bioconcentration; yet record shows that the effect was first noticed by the AEC and the research on it was started in the early 1950's.

And possibly one of the most far-sighted actions taken by the AEC, shortly after its establishment in 1947, was to commission P. C.Putnam in 1949, to assess the U.S. and world energy resources for the 50 to 100 years to come. The results of this study are documented in the book entitled **Energy in the Future**, which was published in 1953. Even today, 20 years later, this book is frequently quoted.

We want then to see what goes into the planning of nuclear technology.

REFERENCES

1 - MEADOWS, D. H. et alii. *The limits to growth.* S. l., Signet, 1972.
2 - VACCA, R. *The coming dark age.* Garden City, N. Y., Doubleday, 1972.
3 - CHASE, S. The Club of Rome and its computer. *Sci. Public Affairs,* **29**:36, Mar. 1973.
4 - GOLDSMITH, M. Meadows unlimited or caveat computer. *Sci. Public* Affairs, **29**:16, May 1973.
5 - WATTS, R. G. Limits, misunderstood. Sci. Public Affairs, **29**:2, Nov. 1973.
6 - PUTNAM, P. C. *Energy in the future.* S. n. t.

CHAPTER II

National Environmental Policy

Act and the USAEC Regulatory Guide 4.2

> "We the people of the United States, in order to form a more perfect union, establish justice, insure domestic tranquility, provide for the common defense, promote the general welfare, and secure the blessings of liberty to ourselves and our posterity, do ordain and establish this Constitution for the United States of America".
>
> Preamble, Constitution of the United States

1. Declaration of Intent

All of us, no doubt, still remember Earth Day, April 22, 1970, when millions of Americans in more than 2000 colleges, 2000 community groups, and 22,000 schools joined in clean-up campaigns, mass meetings, and parades, to protest against environmental pollution and to shout ecology, eco-system, biota, quality of life, etc. Since then, however much of this emotional outburst of enthusiasm has abated, blunted possibly by the facts of life and time. The ecology centers, recycling centers and others sprouted out over night but closed down one after another. And many seem to have been turned off by the environmental movement.

Despite these seeming reversals in the environmental movement, we need to keep in mind that the impact of the National Environmental Policy Act of 1969 will continue to be felt. And possibly nuclear technology will turn to be the "testing ground for the new and noble experiment".

Every American should read and study the Act and in particular note the words appearing in the section on the Declaration of National Environmental Policy, which reads:

> "The Congress, recognizing the profound impact of man's activity on the interrelations of all components of the natural environment, particularly the profound influences of population growth, high-density urbanization, industrial expansion, resource exploitation, and new and expanding technological advances and recognizing further the critical importance of restoring and maintaining environmental quality to the overall welfare and development of man, declares that it is the continuing policy of the Federal Government, in cooperation with State and local governments, and other concerned public and private organizations to use all practicable means and measures, including financial and technical assistance, in a manner calculated to foster and promote the general welfare, to create and maintain conditions under which man and nature can exist in productive harmony, and fulfill the social, economic, and other requirements of present and future generations of Americans".

2. USAEC Regulatory Guide 4.2, Preparation of Environmental Reports for Nuclear Power Plants.

A copy of this document can be obtained by writing to the U.S. Atomic Energy Commission,, Washington, D. C. 20545, Attention: Director of Regulatory Standards. The first page is reproduced to get an appreciation for the intent and scope of the so-called environmental report. The point to note is that the word environment, as used by the Regulatory Guide, includes the social, cultural, economic, and political effects, in addition to the physical impacts.

The 10 chapters or so of the environmental report can be grouped into facility justification and site selection, the environmental impacts of plant construction and operation, the effects of accidents, the economic and social effects of plant construction and operation, and alternative energy sources.

For example in the chapter on the Detroit Edison Greenwood Energy Center the justification for the facility hinges on the fact that the electric energy load will double by 1983. They note that for 1963 the demand was 18 billion Kwhr and rose to 38 billion Kwhr for 1973. They estimate that the demand for 1983 will amount to 65 billion Kwhr. It is interesting to note the basis for their projections. They point out that the battery-operated car is not expected to make in-roads into our economy. The energy burdens of hydrogen-driven cars and of extensive mass transportation system are not considered.

The points to be brought out in chapter 2 are interesting. For example in Sec. 2.3, the applicant is asked to consult such sources as the National Register of Historic Places and the National Register of National Landmarks, for possible regional historic, scenic, and cultural national landmarks. Sec. 2.4 is on site geology, and the practice is to study the geological features and movements during the past 100,000 years or so. Michigan fortunately, has been exceptionally stable for the past 400M years or so. More comments about this will be made later. In Sec. 2.8, measurements on the background radiological characteristics need to be discussed.

Chapters 8, 9, and 10 are concerned with certain general aspects of nuclear power plant construction and operation. The title of Chapter 8 is Economic and Social Effects of Plant Construction and Operation. Sec. 8.2, Costs, makes interesting reading. For example the following statements appear under Examples of Temporary External Costs:

> Shortages of housing; inflationary rentals or prices; congestion of local streets and highways; noise and temporary aesthetic disturbances; overloading of water supply and sewage treatment facilities; crowding of local schools, hospitals, or other public facilities; overtaxing of community service; the description of people; lives in the local community caused by acquisition of land for the proposed site.

Chapter 9 is concerned with alternative energy sources and sites, words like coal, oil, gas, hydroelectric, geothermal are mentioned, but significantly the words solar and nuclear fusion do not appear. The implication, of course, is that at present these are not possible sources of electrical power.

Thus the intention of the USAEC to carry out the lofty aims enunciated in the National Environmental Policy Act is very clear. The problem, however, is that the methods by which the aims are to be carried out are not clear, so that at times it seems that "applicants" have not always acted and reacted most intelligently. The cost to the electric utility to prepare the report can range from $2M to $10M. Some of this money is spent in counting deers, pheasants, and field mice. One company in California went to the expense of removing very carefully undersized abalones from sea beds near the construction site to another bed some distance away, at an estimated cost of $8 per moved abalone! Another example is the nature center being planned for the Detroit Edison Greenwood Energy Center. The center is described in a brochure under the title "Nature Conservation, Environment, and Electric Power". Visitors to the Center in 1985 if there is enough gas then will no doubt be able to enjoy the facilities. But the question is whether or not there are better ways to spend the amount of money that would be needed to build and to maintain this facility.

One possible alternative might be to develop certain health and medical facilities for residents in an area of 5 to 10 mile radius from the power plant. The continuous release of small amounts of radioactive materials from such plants-whether nuclear or coalburning-is unavoidable, and there can be occasional accidental releases of excess radioactive and/or chemical pollutants. (An example is the recent excess soot from a plant in Detroit). The residents in the neighborhood will always be faced with the concern that such discharges might lead to diseases such as cancer, leukemia, and others. From them, it might be advisable to make available free clinical services, annually or biennially, that include certain advanced clinical tests, in addition to the routine ones. One possible such test might be karyotyping, the microscopic examination for chromosomal abnormalities. This is known to be a sensitive technique and has been used to study the effects of the so-called atomic bombs on the survivors and off-springs in Hiroshima and Nagasoki. Apparently, it can also be used to determine the presence of abnormalities in unborn babies, by examining the chromosomes in the amneonic fluid.

The above is only one suggestion. There may be others. The point is that there are risks in any technology, and it seems only reasonable that steps should be taken to ease the burden of those who are exposed to greater risks, in order to plan for a socially acceptable technology for the 1990 decade.

CHAPTER III

Energy Needs vs Energy Consumption

"The U. S., with 6% of the people, consumes 35 per cent of the energy".

E. Cook, in Scientific American, Sept., 1971

1. Comments

requerente

According to the AEC Regulatory Guide 4.2, the applicant for the construction of the nuclear power plant needs to justify its construction. The usual argument is that the demand for electric power has been growing exponentially, doubling approximately every 10 years. This trend has continued for a number of decades and no doubt will continue for the decade to come. For example, the Detroit Edison projection for 1983 is 65 billion Kwhr, compared to the demand for 38 billion Kwhr for 1973. But obviously this exponential growth cannot continue, there will be a limit, and our task is to see what can be done to curb the rate of energy consumption.

frear

For this, we shall first discuss our minimal energy needs, examine energy consumption in typical societies, attempt to assess the available energy resources, and then look at the startling facts of exponential growth. avaliar

alarmantes

2. Basic Energy Needs

We shall **define** this as the energy needed to keep an individual alive. Dieticians would tell us that the food energy we need is about 3000 big calories per day per person. A big calorie is one kcal, so that this amount to 3 Mcal/day/person. We shall introduce the acronym, ben, from **Basic Energy Needs,** as the basic unit, i.e.

$$1 \text{ ben} = 3 \text{ Mcal/day/person}$$

If we were to convert this into watts we would have

$$\frac{(3 \times 10^6)\ \ (4.2)}{(24)\ \ (3600)} = 145 \text{ w/person}$$

Thus if we could convert all of this energy into light energy, a person would be about as "bright" as 2 75 watt light bulbs, or even a medium fluorescent lamp. Stated somewhat differently, the value of 3 Mcal is about the amount of heat released by burning 0.1 gal of n-octane.

The energy consumption of 1 ben would be typical of a human society, possibly 1 to 2 million years ago-namely the days of the Java and Peking Man. Then there were no energy-consuming textile factories to make clothing, no steel mills, needed to make steel tools, etc. Then Man ate merely to keep alive. Clearly the hunting man had no luxury. Also the population density then was quite low. The estimate is that it takes about one square mile to support one hunting man.

3. Energy Consumption

Somewhat higher in energy consumption and also typical of a society providing a few luxuries is the primitive agricultural society. An example is the Tsenbaga tribe in the mountainous interior of New Guinea. The energy consumption was studied by Prof. Roy A. Rappaport of the U. M. Anthropology Department. The energy consumption is reported to be about 4 bens so that in this New Guinea society, individuals enjoy a few comforts and luxuries. The population density is about 64 per square mile in comparison to the 1 per square mile for the primitive man. These values are to be compared, for example, to Ann Arbor, with a population of about 100,000 in an area of 23 square miles has a population density of about 4000/square mile. The limited luxuries and higher population density for the New Guinea society became possible because of the very high rate of harvested food energy to the energy input. The ratio is reported to be about 16:1. Because of the high harvest to input energy ratio, excess food can be produced, so that about one half of the food crop is used to feed pigs. They enjoy a certain amount of leisure, find the time to build shelters, and even enjoy occasional barbecued pig feasts.

We need to note this society is dependent completely on solar energy. The price for this is that it takes about 10 years' growth of vegetation to fertilize the soil; at any one time, about 10% of the arable land is under cultivation while during the remaining 90% of the time the land is left fallow for vegetation to grow. Even when the land has been cleared, seedlings are protected. According to Rappaport, the Tsenbagans are almost as irritated when a visitor accidentally damages a tree seedling as when he carelessly tramples on a crop plant.

In passing, perhaps we should note that the high harvest effort ratio of 16:1 for the New Guinea society is very high even in comparison to U. S. standards. According to an article by Jeff Cox on **Factory Farming Is Not Efficient** in the June, 1973 issue of Organic Gardening, that this ratio for U. S. "factory farming" is 1:20. The reason for this startling small ratio is that huge quantities of fossil fuel are needed to harvest the products of solar energy. No doubt the per **capita** productivity of the U. S. farmer is exceedingly high, but this is achieved at the price of very high fossil energy consumption. Rene Dubos in the Feb. 23, 1973 issue of Science warns that "The present practices of agriculture are only possible as long as cheap sources of power are available. After the world supplies of fossil fuels are exhausted, the modern farmer will become ineffective". According to Cox's article, Chinese farmers are more efficient; for the Chinese practice of wet rice farming, the energy harvest to effort ratio is about 50:1, or energy-wise about 1000 times as our U. S. farming method.

4. Energy Consumption in Technological Society

In the September 1971 Energy and Power issue of the Scientific American, E. Cook notes that in an advanced agricultural society and in an industrial society, the energy consumption rates are about 9 and 26 bens respectively, but that in a technological society of which the United States is an example energy consumption is substantially higher, being about 77 bens. Stated differently, we can think of ourselves as having about 76 bens of luxuries; in other words, we are living as masters of 76 slaves!

Of the 77 bens, transportation consumes about 21 bens, industry and agriculture another 30 bens, 22 more bens for home and commerce, and as much as 3 bens for food. The bulk of the 21 bens is consumed by cars, trucks, and buses. Of the 30 bens for industry and agriculture, more than half are used for blast furnaces, smelters, oil refining and mining. Aluminium is an example of a heavy societal energy burden. About 20 million Btu's, or the equivalent of 15 tons of coal, are required to produce just 1 ton of the metal from 2 tons of alumina. The present U. S. aluminum consumption is possibly near the 5 M ton/year mark and accounts for about 10% of the industrial energy consumption.

Another wasteful process is the use of electric power for space heating, cooking, and water heaters. The efficiency of conversion of energy from fossils, like coal, oil, and gas, into electrical energy is quite low-about 32%. A much more energy-wise economical method would be to use these fuels directly for heating purposes.

Fig. 31., taken from the paper by E. Cook in the Scientific American, gives a graphical presentation of our energy consumption rate in comparison to those of other societies. Fig. 3.2 was taken from Nuclear News/July 1973 p. 33. Note the substancial increase in oil imports and nuclear energy for the year 1985.

In the Dec. 1973 issue of Science and Public Affairs, there is an article on **The energy Cost of Automobiles** by Stephen Berry and Margaret Fels. Their analysis indicates that the energy consumed to produce a 1967 car is about 37,000 KW hr., or about 32,000 M cal/car. Multiply this by the number of cars produced each year, we can begin to get a glimpse of the staggering energy cost to maintain just this one industry. Of course, keep in mind that the above energy cost does not include the energy cost of gasoline.

And finally, further energy savings can be affected by reducing per capita meat consumption. Note that in the U. S. energy economy, the food energy consumed is 3 bens. The reason for this is that about 2 bens are used to feed animals, which are effectively low efficiency protein factories. Of the 10 Mega cal/day (3.3 bens) of gross food production, about 15% is wasted in handling and processing. Of the remaining 8.5 Megacalories, 2.2 M cal is consumed directly as human food but 6.3 M cal go to feed animals that produce about 0.9 M cal of meat. Since animals do not make proteins-they merely concentrate proteins in plants-they can be thought of as a 14% efficient protein concentration factories. Furthermore, by eating meat we add to the transportation energy cost. For example, soy beans grown in Michigan are shipped to feed lots near Denver and the processed soy bean protein, in the form of beef or pork, is shipped back to Detroit. Substantial savings in energy can be brought about by consuming directly locally produced soy bean protein.

The issue at hand is to check the growth of energy demands by having fewer cars, less beer from cans, and less meat. The alternative is to face the consequences of explosive exponential growth of energy and power requirements.

5. Exponential Growth

The projected energy demands have been presented in a variety of graphical forms in newspapers and magazines. For example the Sunday New York Times (Dec. 2, 1973) gives a sketch showings that the oil equivalent of energy consumption in 1973 was about 40 M barrels per day, this will rise to 50 million barrels per day in 1985, and to 85 million barrels per day by the year 2000. The sketch shows that in 1985, perhaps there will be a small oil imput from Alaska, and that by 2000, coal production could increase a litlle, some small contributions from shale oil and solar energy. But the bulk of the increased energy demands would have to be met by a greatly expanded nuclear power technology.

Another sketch given in the energy crisis issue of Newsweek (Jan. 22, 1973) shows that U. S. coal consumption between 1972 and 1985 will increase from 40 lbs/day to 70 lbs/day, oil products from 9.5 gal/day to 15 gal/day, natural gas from 7 gal/day to 12 gal/day, and nuclear energy from 0.5 pint/day to 5.5 gal/day.

And even Senator Philip A. Hart from Michigan has put out a flyer, to educate his constituents of the staggering problems that lie ahead. He speaks of the "energy dilemma", outlines some of the steps that need to be taken to explore new energy sources, mentions the need for making unpopular decisions, and concludes with the comment,

> "We must take these steps now, if we hope to have them affect the future. Lead time is most important, and while we must take some short-range decisions for the immediate future, our strategic concerns must be for 1980 and beyond".

6. Michigan Electrical Power Consumption

In the November 1973 flyer, Senator Hart states during the 1960's there was a steep increase in the use of electrical power. The enormous projected electrical power requirements are indicated by the sales of Detroit Edison and Consumers Power, the two major electrical utilities in lower Michigan. The record for Detroit Edison, which serves Detroit, the Ann Arbor area, and the bulk of the Thumb area, is as follows:

Year	Billionwatt hours
1950	7,309
1960	14,006
1970	28,436
1972	32,671
(1980)	51,000
(1990)	100,000

The last two figures, of course, are projected figures and are based on the fact that the electrical energy output has been doubling every ten years, as indicated by the figures. Similar trends also appear in the Consumers Power Report for 1972, according to which

	1962	1972	
Residential	3,530	6,841	B whrs.
Commercial	2,000	4,699	
Industrial	4,846	9,576	
Misc.	142	235	
	10,519	21,352	

Thus if we take the Detroit Edison projections, the additional electrical energy capacity for southeast Michigan alone would have to increase by 50,000 B whrs. over the 1980 value. This amounts to

$$\frac{50{,}000 \times 10^9}{(24)\ (365)} = 5{,}700 \text{ Mw}$$

which means that about 6 additional 1000 Mw(e) nuclear power plants would have to be built in the Thumb area alone. Consumers Power would need to build a comparable number of such plants, and to meet the demands for Indiana and Illinois there would have to be many more in southwest Michigan along Lake Mighigan shores. The environmental impacts of the nuclear power plants in operation and in the planning are negligible. But when we start looking ahead to plan for 1990 decade, it will be prudent to take a much more critical look at our electric power consumption pattern and also the **total** impact of the electric power plants.

7. Exponential Growth

The words "exponential growth" are bandied about carelessly because many are not fully aware of the consequences. In **The Limits to Growth** by D. H. Meadows and others, the following comment appears:

> "A French riddle for children illustrates another aspect of exponential growth-the apparent suddenness with which it approaches a fixed limit. Suppose you own a pond on which a water lily is growing. The lily plant doubles in size each day. If the lily were allowed to grow unchecked, it would completely cover the pond in 30 days, choking off the other forms of life in the water".

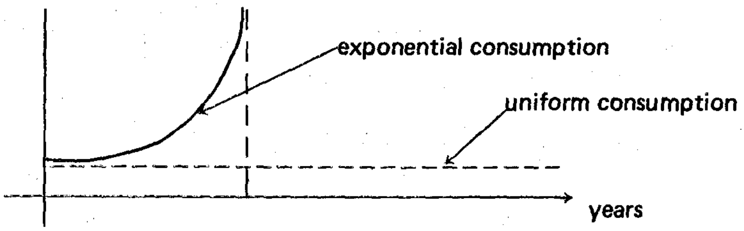
The comment was made that the known coal reserves in the United States is about 1.5 trillion tonnes (Metric ton). The rate of consumption in 1970 was about 3 billion tonnes. If we were to continue to use coal at this rate, the known reserves will last for

$$\frac{1.5 \times 10^{12}}{3 \times 10^{9}} = 500 \text{ years}$$

This is the number that is often quoted, and we need to stress that the assumption is **uniform** rate of consumption. Consider next the case for exponential rate of consumption. If we let R represent the rate of coal consumption in one year, and further assume 10 years for the doubling time, then clearly

$$R = 3 \times 10^{9} (2^{t/10})$$

This can be presented graphically as follows:



The dotted straight line is for constant rate of consumption; the area of this rectangle, of course, is just the known reserves. If the growth is exponential, the area under this curve again is just the known reserves. Therefore,

$$\int_o^T R\,a\,t = 1{,}5 \times 10^{12} \qquad \int_o^T 2^{\frac{t}{10}}\,dt = 500$$

We can integrate the left-hand side by using

$$\int b^{ax}dx = \frac{b^{ax}}{a\ln f}$$

where for our problem

$$b = 2 \qquad\qquad a = \frac{1}{10}$$

so that

$$\int_o^T 2^{\frac{t}{10}} at = \frac{10}{\ln 2}\, 2^{t/10} \int_o^T = \frac{10}{\ln 2}\left[2^{\frac{T}{10}} - 1\right]$$

$$2^{\frac{T}{10}} - 1 = \frac{\ln 2}{10}\,(500) = 50 \ln 2$$

$$2^{\frac{T}{10}} = 1 + 50 \ln 2$$

$$T = \frac{10}{\ln 2}\left[\ln (1 + 50 \ln 2)\right]$$

But

$$\ln x = 2{,}30^3 \log \lambda$$

so that

$$T = \frac{10}{\log 2} \log \left[1 + 5 \ln 2\right] \cong 52 \text{ years}$$

There are two points to be made. The first one is that this time to exhaust a natural resource is comparable to the lead-time needed to develop a technology. As indicated earlier, the engineering research and development lead time (pilot plant lead time) is about 10 years, and another 10 years for on-line planning and development. To this we need to add the very uncertain scientific research lead-time. Hence the time from scientific conception to on-line date is about 30 years or more.

There is however another point. According to the above assumptions, at the end of 42 years, we will have exhausted ½ of the known resources, and the temptation would be to relax because there is still one half of the resources left. But we need to realize that the remaining one-half will be used up in just 10 years. If in the meantime, the known reserves are doubled-for some reason or another-the equivalent of the newly discovered reserve will be used up during the following 10 years.

Thus, in an exponential energy economy, coal alone would last 52 years, but even coal and nuclear fuel using light water reactors would give us only 62 years to exhaustion.

We might examine the effect of extending the exhaustion time by increasing available energy reserves. Let

K - Known energy reserves

R - Energy consumption rate
T_2 - Doubling time
R_0 - Energy consumption rate now

Then

$$R = R_o\, 2^{t/T_2}$$

and

$$\int_o^T R_o 2^{t/T_2}\, dt = K$$

$$\frac{T_2}{\ell n\, 2}\left[2^{T/T_2} - 1\right] = \frac{K}{R_o}$$

so that

$$T = \frac{T_2}{\ell n\, 2}\, \ell n \left[1 + \frac{K}{T_2 R_o}\, \ell n\, 2\right] \cong \frac{T_2}{\ell n 2} \ell n \left[\frac{K}{T_2 R_o}\, \ell n\, 2\right]$$

Since the second term in the logarithm is large in comparison to 1.

The above exhaustion time T is based on the known reserve K. For example, we have found that if K = 1.5 trillion tonnes, then the time to exhaustion is 52 years. But suppose that luckily through discoveries of new reserves, technological advancement, and even scientific breakthroughs, the effective known reserves were to increase by some factor, say r. For example we've noted that if nuclear fuel for light water reactors are included, then the effective reserve is doubled, or r = 2. Then the time to exhaustion is

$$T + \Delta T = \frac{T_2}{\ell n\, 2}\left[\ell n\, \frac{rK}{T_2 R_o}\, \ell n\, 2\right]$$

$$= \frac{T_2}{\ell n\, 2}\, \{\ell n \frac{K}{T_2 R_o} \ell n\, 2 + \ell n\, r\,\}$$

$$= T + T_2\, \frac{\ell n\, r}{\ell n\, 2}$$

Thus the time to exhaustion is postponed by

$$\Delta T = T_2\, \frac{\ell n\, r}{\ell n\, 2} = T_2\, \frac{\log r}{\log 2} = 10\, \frac{\log r}{\log 2}$$

in which we are assuming that the doubling time is 10 years. Then

r	T (years)	
2	10	(Light water reactor)
100	66	(Breeder)
10^6	200	(Fusion)

The message is very clear: Exponential growth cannot go on for long. But to avert catastrophic consequences, brakes to growth have to be apllied several doubling periods earlier.

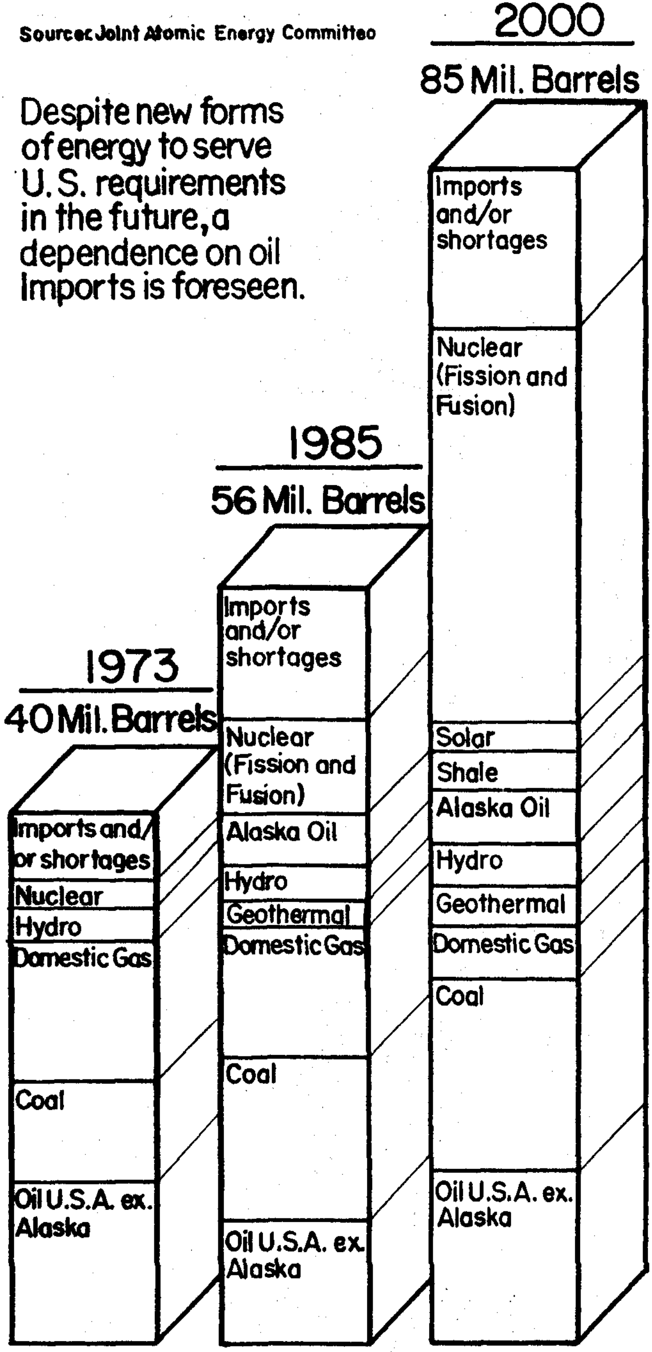
For this some far-sighted planning and decisions are essential.

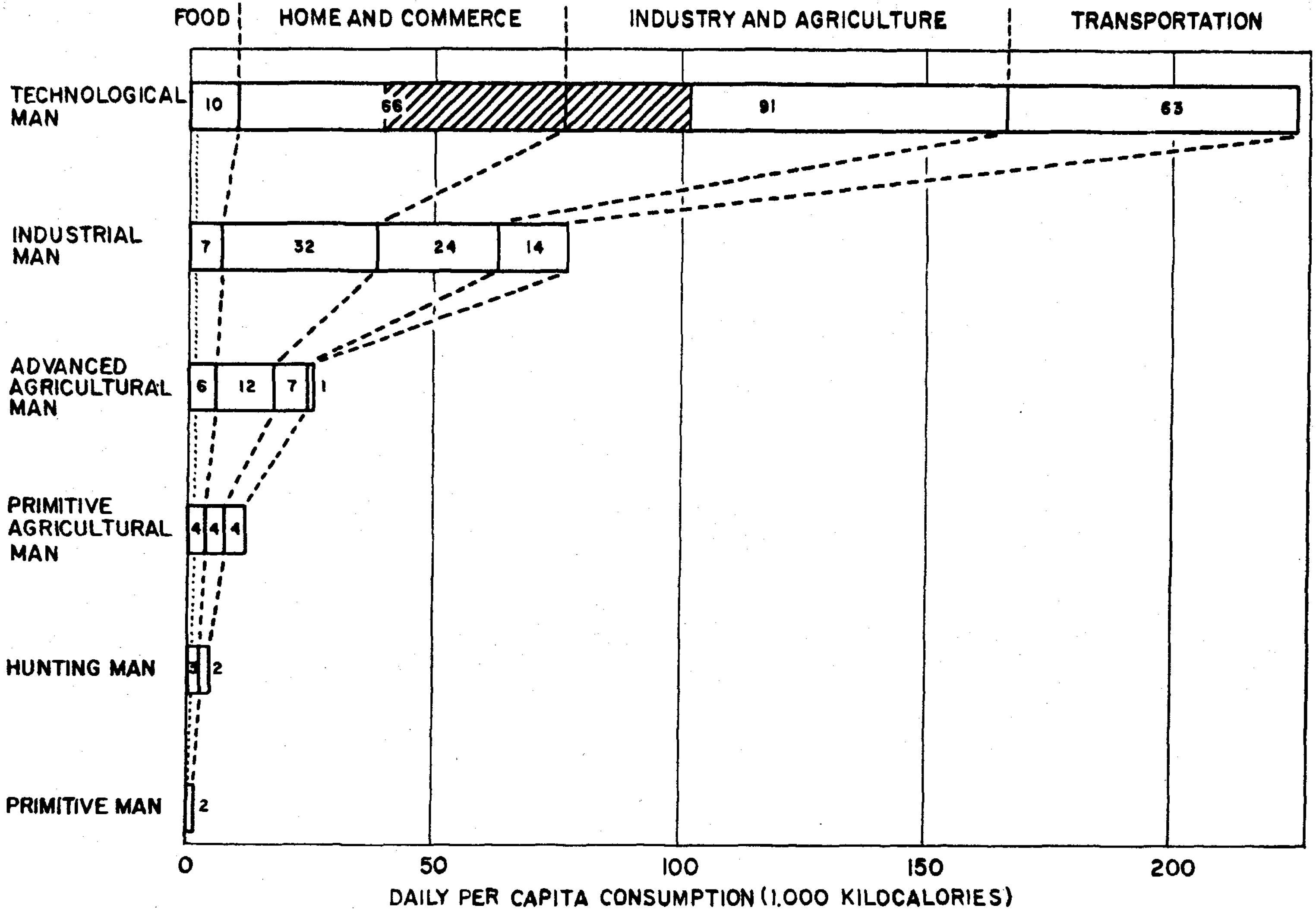
The Energy Outlook

(Million barrels per day of oil equivalent)

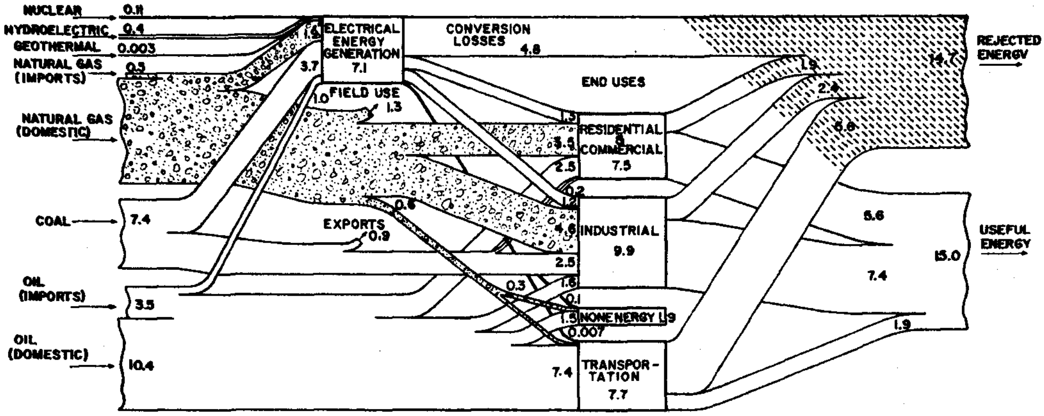
Source: Joint Atomic Energy Committee

Despite new forms of energy to serve U.S. requirements in the future, a dependence on oil Imports is foreseen.



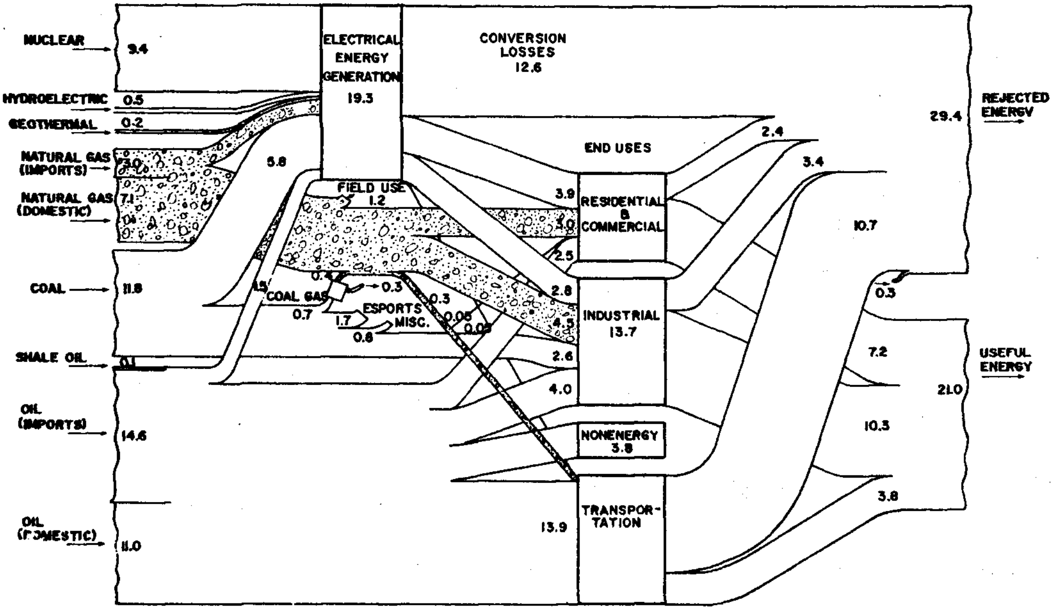

FOOD
HOME AND COMMERCE
INDUSTRY AND AGRICULTURE
TRANSPORTATION
TECHNOLOGICAL MAN
10
66
91
63
INDUSTRIAL MAN
7
32
24
14
ADVANCED AGRICULTURAL MAN
6
12
7
1
PRIMITIVE AGRICULTURAL MAN
4
4
4
HUNTING MAN
3
2
PRIMITIVE MAN
2
0
50
100
150
200
DAILY PER CAPITA CONSUMPTION (1,000 KILOCALORIES)

1970



(UNITS: MILLION BSLS./DAY OIL EQUIVALENT)

1985



(UNITS: MILLION BSLS./DAY OIL EQUIVALENT)

CHAPTER IV

Energy Sources and Alternatives

> "Energy needs will have to be weighed against environmental and societal costs; a decision to set a pollution standard or to ban the internal combustion engine or to finance nuclear power development can have major economic and political effects. Democratic societies are not noted for their ability to take a long view in making decisions. Yet indefinite growth in energy consumption, as in human population, is simply not possible".
>
> E. Cook, in Scientific American

1. Comments

The title of Chapter 9 of Regulatory Guide 4.2 is noteworthy. The point that comes through from the title, which is Alternative EnergySources, and the comments appearing in the opening paragraphs is that the viability of alternative energy sources for the generation of electric power is dependent upon the site of the power plant. In other words, the solution best suited for Montana may be different from the one for Callifornia, which in turn may be different from the one for Michigan. The suggested alternative sources to consider are nuclear, fossil fuel, hydroelectric, and geothermal. For Michigan the last two are out, and even fossil fuel is marginal because the coal would need to be shipped in from the west or from the Appalachians. Hence, for Michigan, for the 1990 decade, the only reasonably viable alternative is nuclear fission energy.

Another interesting point to note is that the words "solar" and "nuclear fusion" are not mentioned. The reason, of course, is that these two sources are not expected to share any appreciable fraction of the energy needed to generate electric power before the year 2000. This is not to say that there might not be pilot plants in operation by then; we mean that by then, the wide scale of the two energy sources for the commercial generation of electric power will not have come.

2. Nuclear, the Major Source of All Energy

The point most frequentely over-looked is that almost all of the energy we consume today is nuclear in origin. Only a small fraction, however, come directly from the nucleus; according to the article by E. Cook (Scientific American) only about 0.2% of the U. S. gross energy consumption comes from nuclear power plant. The rest can be traced to sun, which is a huge, lethal, highly radioactive nuclear reactor. The so-called fossil fuel is nothing but re-stored nuclear energy, because the energy was released long ago in the interior of the sun, radiated from the sun, captured and stored by plants and animals about 200,000,000 years ago.

The second point we need to bear in mind that this so-called fossil-fuel epoch is relatively short and transitory, viewed over the longer span of human history. Man has been in existence for about 2,000,000 years or more, and possibly fossil fuels will be of importance to man for only about 2000 years.

It is interesting to note that at one time coal was thought to be a curse and have questionable value. During the Middle Ages in England, people thought it filled the air with dangerous poisons that were injurious to health. In 1306, King Edward I of England issued a proclamation declaring the use of coal punishable by death, and at least one person was executed for breaking the law. In the United States, coal mining began about 1760, but for a time it was believed to be useless and in some places the sale of coal was declared a fraud punishable by law.

3. Fossil Fuel

It appears that there is very little coal in Africa, Western Europe, and South America, and the bulk of the known reserves are located in Asia and North America. Of the known reserves, the lion's share are owned by Russia and United States. The estimated amounts are as follows:

Russia	4.3×10^2	(Metric ton)
Asia, outside Russia	0.68	" "
U. S.	1.5	" "
N. Am. (except U. S.)	0.6	" "

As for oil, we've already begun to feel the effects of short supply. In one of the recent issues of Newsweek, EXXON printed an ad, under the caption **The World of Known Oil Reserves**, in which the size of a nation or nations is represented by the amount of oil reserves. According to thips map, the middle East is very large, with 53% of known reserves. Russia and Africa are comparable in size, with 15% and 16% of the known reserves. But the combined size of North and South Americas is less than Africa. Venezuela, with about 2% of the known world reserves takes up most of South America. The United States, including Alaska, has only about 5%. Japan is not even on the map.

There are a number of interesting commentaries on the history of petroleum in the World Book. In 1854, when an entrepreneur, George H. Bissel of New Haven, Conn., formed the Pennsylvania Rock Oil Company, investors were reluctant to buy stocks. About 5 years later, when Bissel and others formed another company, the Senecca Oil Company, drilling finally got under way and struck oil at 69.5 feet!

For many years, kerosene from lamps was the main product of the oil industry, and the lighter liquid, called gasolene, was explosive so that refiners often dumped gasolene into creeks and rivers to get rid of it.

4. Nuclear Fuel

There seems to be some gross misconceptions about nuclear fuel reserves. As Channcey Starr points, this source of energy is none too plentiful if used only for light water reactors. The table on p.43 of Scientific American, Sept. 1971 shows the following numbers.

	(10^{12} watt-years)
Coal	
Petroleum	
Gas	200-300
Nuclear (Light water reactor)	300
Nuclear (Breeder)	30,000

Thus, by extracting nuclear energy in light water reactors we merely double the available energy resources.

As we shall see, this doubling adds only 10 years to the time of exhausting known reserves of energy resources if energy consumption increases exponentially.

5. Michigan Geology

Sec. 2.4 of the Environmental Report calls for a description of the major geological features of the site area. The practice is to trace the geologic history of the site area for 100,000 years or so. In the Grenwood Energy Center report, the point is made that this area has been exceptionally geologically stable, with no major rock deformation since the Paleozoic Era. Also a stratigraph, given also in the report, shows that the Precambrian bedrocks lie at a depth of about 5000 feet, followed mostly by Paleozoic layers, with a thin layer of cenozoic glacial drift on top, amounting to no more than 300 ft. thick. After the Paleozoic deposits, there are the deep salt deposits of the Silurian Period occuring at depths of about 3000 feet. The limestone and the dolomite deposits, which were formed later during the Devonian period are located at depths of about 2000 feet. A significant point brought out by the stratigraph is that the Pennsylvanian layer is missing. It will be recalled that the vegetation growth of this period was responsible for the rich and high-grade coals of Pennsylvania.

To appreciate fully the exceptional geologic stability of Michigan, we need to look at the past geologic activities in other parts of the world. The part that is now Michigan rose, sank, and rose again. In the geologic past, this was once a shallow tropical sea, when the line extending from Hudson Bay to Mexico was at the Equator. To understand how these geologic changes have come about, geologists have developed the plate tectonics theory of land masses and oceans. The earth consists of an outher shell, called the lithosphere, which consists of several large pieces, called the tectonic plates. There are, for example the North American Plate, the Pacific Plate, the South American Plate, the African Plate, etc. The Pacific Plate meets the North American Plate along the West Coast, and the mountain formation and the seismic activities along the Pacific Coast is due to the motion of the North American Plate over the Pacific Plate. The two plates meet along the San Andreas Fault, so that the part that is on the Pacific Plate, like Baya California and Los Angeles is drifting slowly northward. In about 10 million years, geologists estimate that Los Angeles will have moved northward to the same latitude as San Francisco, and another 50 million years or later will be off the coast of Alaska, and eventually disappear underneath Alaska.

The tectonic plates are floating on an inner mantle of material constituting the so-called **asthenosphere.** The plates perhaps can be compared to ice floes. Or perhaps a better analogy would be the slag floating on molten iron. The solidified earth slag, i.e the tectonic plates, floating on the asthenosphere, move about, collide with each other, or even slip by each other. For example, as mentioned already, the North American Plate was in the tropics, with the Equator running diagonally across from the Hudson Bay area to Mexico. At that time, the part that is now the Sahara Desert was at the South Pole; this has been estimated to be about 440 million years ago. In terms of Michigan geology this was after the iron deposits in the Upper Peninsula had been formed, the outflow of lava and copper along the Keweenow Peninsula had stopped, and the land began to rise to form the salt layers that we know of today.

During the following 200 million years or so, it seems that the continental land masses drifted together, merged, to form what geologists call Pangea. At that time the land masses we know today were stuck together, interlocked, like pieces of a jig-saw puzzle. Geologists concept of Pangea can be found in several sources, such as in Newell's article on The Evolution of Reefs. Then North America was connected to Asia by Europe, Africa nestled along the eastern edges of North and South America, Antarctica was attached to the south eastern edge of Africa, and Australia, one end of which stuck to Antarctica, formed the outport of Pangea. An interesting fact is that a triangular land mass, which is now India, was wedged in between Africa and Antarctica. But about 200 million years ago, Pangea broke up into several pieces, and the African Plate, the Antarctic Plate, the Australian Plate caused these lands to drift apart.

What happened in Michigan while these continents were drifting apart will probably never be known. The reason is that the deposits for the Mezozoic Era are almost completely missing for Michigan, possibly due to glacial actions.

But in what is now the Indian Ocean some dramatic events were taking place. The Indian Plate broke off from Antarctica about 75 million years ago-about the time when dinosaurs were roaming over what is now Colorado-and scant 45 million years ago, the Indian land mass collided with the Eurasian Plate,forming the Himolayas that we know of today. This was also about the time the Alps were formed, but the Rockies, arising from the collision of the North American and Pacific Plates came somewhat later-about 31 million years ago. The relation of these two plates gave rise to the series of mountain ridges along the Pacific Coast and the Sierra Nevadas which were formed as recently as 18 million years ago.

The rest is almost recorded history. During the Ice Age (2,000,000 years ago) in the Pleistocene Period, sheets of ice swept across Michigan, wiping out geologic landmarks, and causing the earth's crust near the center of Michigan to sag under the enormous weight of sheets of ice. This sagging accounts for the outcrops of old geologic formations near the tip of the Lower Peninsula or in the southeast corner of Michigan, whereas the most recent geologic formations are found near the center-in the pocket of the catcher's mitt (See, for example, Greenwood Energy Center Environmental Report, Fig. 2.4 - 1).

The book on the Geology of Michigan by Dorr and Erchman gives a motorist's-eye-view of the geologic history of Michigan. The book shows where one should stop to see the various geological formations. The main point that one learns is that most of Michigan has been flat and geologically inactive for a long, long time. The exception possibly is the Keweenow Peninsula where there were volcanic activities about 700 million years ago, just about the time living organisms were beginning to adapt tremselves to life on dry land. Before then, the atmospheric oxygen content was too low, and the protective ozone layer to absorb the lethal ultraviolet radiations from the sun had not yet formed. Since then, Michigan has floated about over the surface of the earth, but there has been no major rock deformation.

6. Michigan Energy Sources and Consumption

An assessment of Michigan energy problems is given in the special reports to Governor Milliken (Feb. 1974) and to the Michigan Legislature, dated April 23, 1974.

The following figures taken from the report provide a comparison of the Michigan to

U. S. consumption:

	1960	1970
Michigan		
Energy Consumption, 10^{12} BTU	1756	2814
Population, millions	7.82	8.88
Consumption per capita, 10^6 BTU/person	224.5	316.9
U.S.A.		
Energy Consumption, 10^{12} BTU	44960	67220
Population, millions	179.3	203.2
Consumption per capita, 10^6 BTU/person	250.8	330.8
Michigan/U.S.A. (percent)		
Energy Consumption	3.9	4.2
Population	4.4	4.4

Thus the Michigan per capita consumption is just a trifle below the national average.

Michigan, however, produces only a small fraction of the energy it uses. Michigan presently derives 30% from coal, about 30% from natural gas, and about 38% from petroleum products. Michigan's 4000 crude oil wells and 1200 natural gas wells produce only about 4% of the total in-state energy requirements. Electrical energy requirements have been increasing at an annual rate of about 7%. In 1964, 98% of the electric power generated by Detroit Edison and Consumers Power was from coal, but this number dropped to 75% in 1973. Only 2% is hydroelectric power.

Oil was first discovered in Michigan at Port Huron in 1886, and in 1925 in the Saginaw area. The most recent finds have been near Jackson. The oil is obtained from all layers of the Paleozoic Era.

The reason for the limited production of oil and essentially zero production of coal seems to stem from the fact that Michigan has been dry, or nearly so, for the last 280 million years. The evidence for this is that the rocks of the Permian Period (the later of the Paleozoic), all of the Mesozoic Era (age of the dinosaurs) except a trace of the Jurassic Period, and most of Cenozoic Era (age of manuals) are missing. As noted earlier, while Michigan was flat and dry, continents drifted, the Atlantic Ocean was formed, and mountain ranges appeared.

Questions and Problems

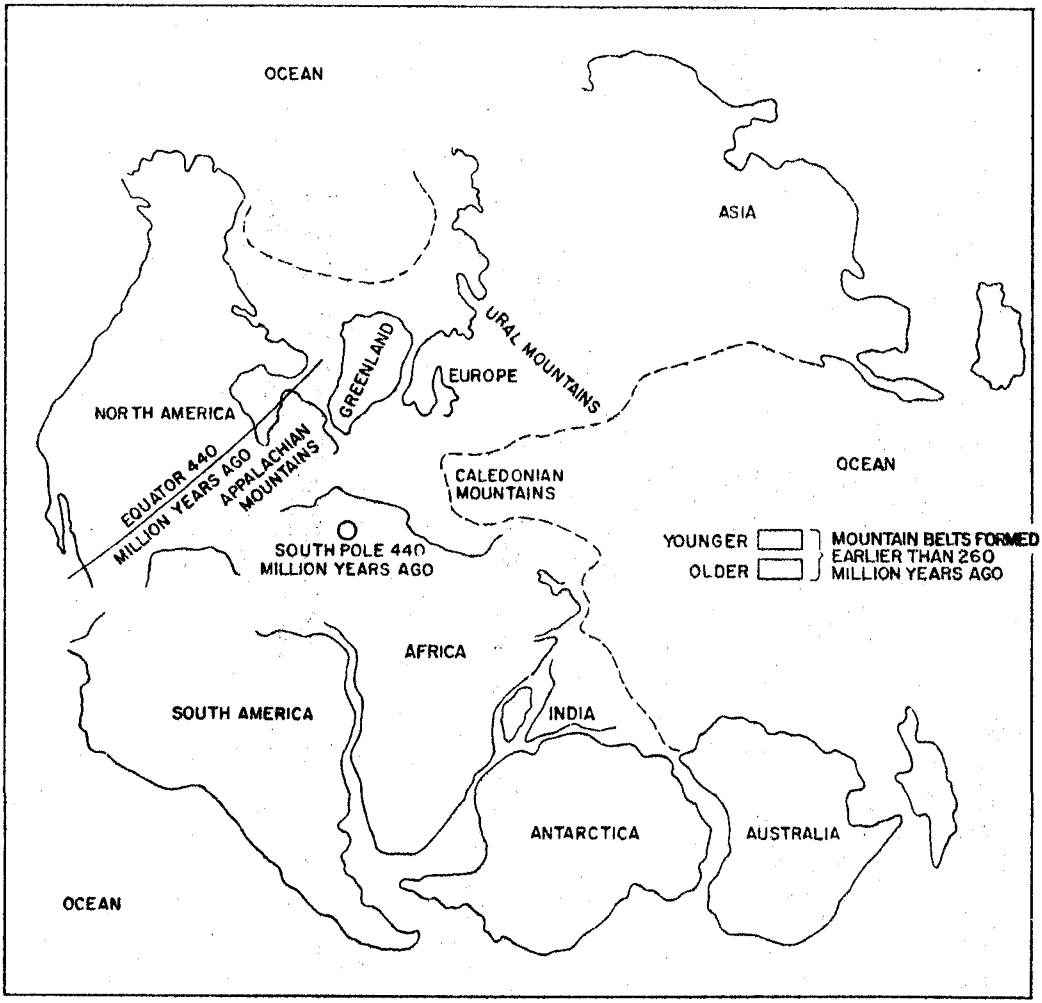
1. Trace roughly the geologic history of the area near your home. What additional information is needed to complete the sketch? What are the possible sources for the needed information?

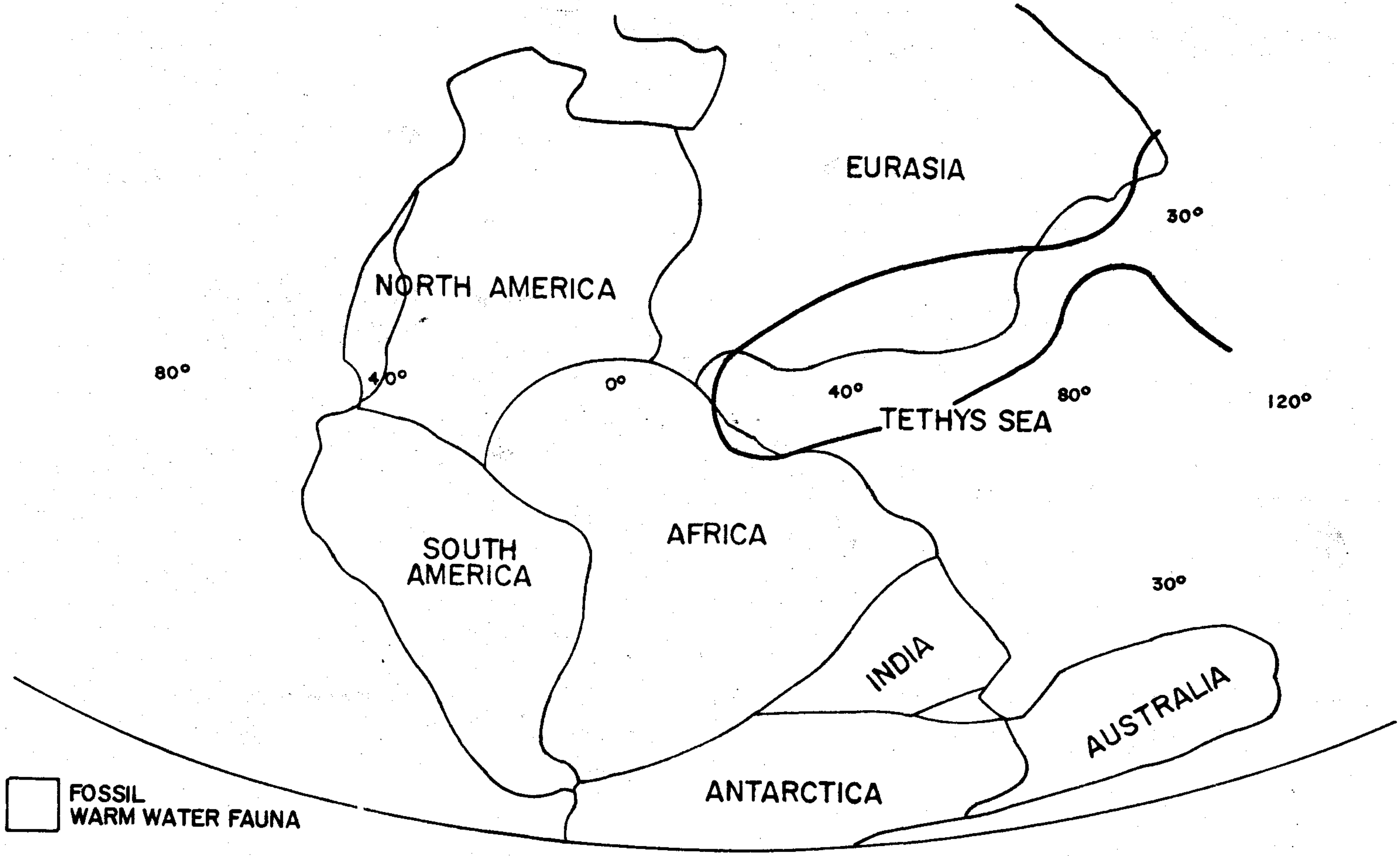
2. Assume that you are about to make a geological tour of Michigan. What geologic structures would you except to see near Rogers City? Near Mackinaw Island? Around Copper Harbor?

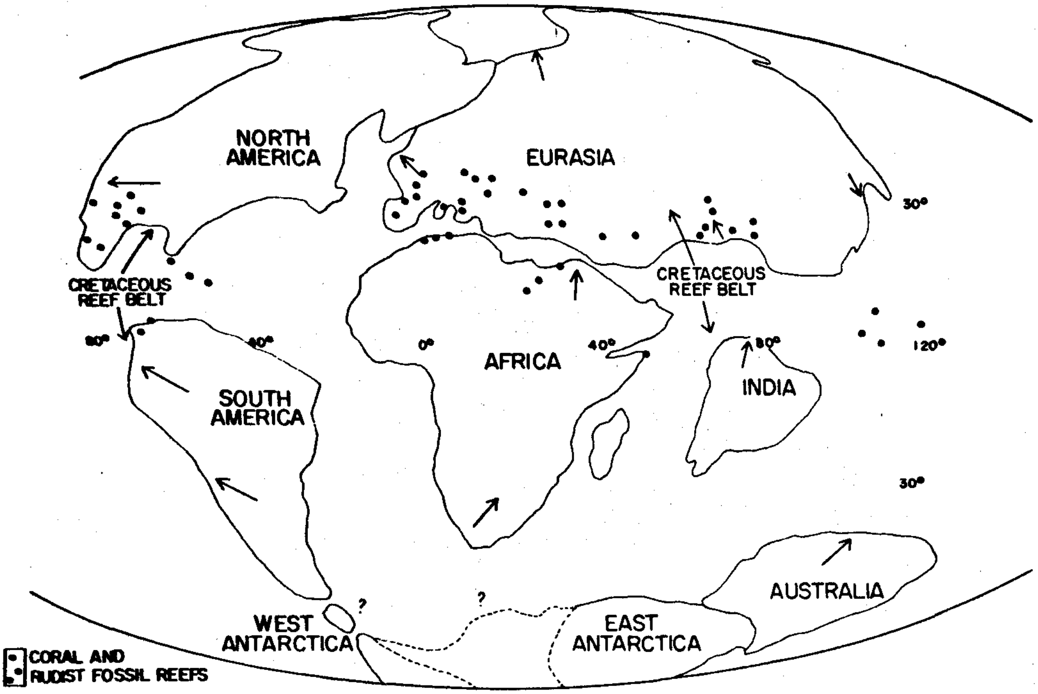
3. What are the prospects of striking oil in the southeast corner of Michigan? In the

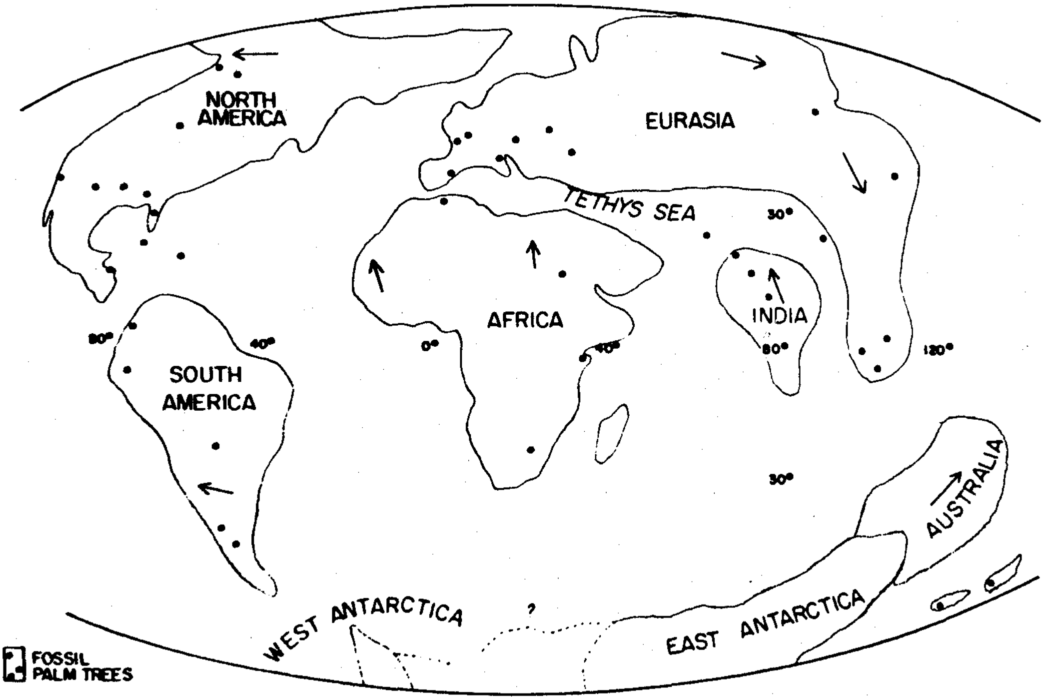
Mackinaw area?

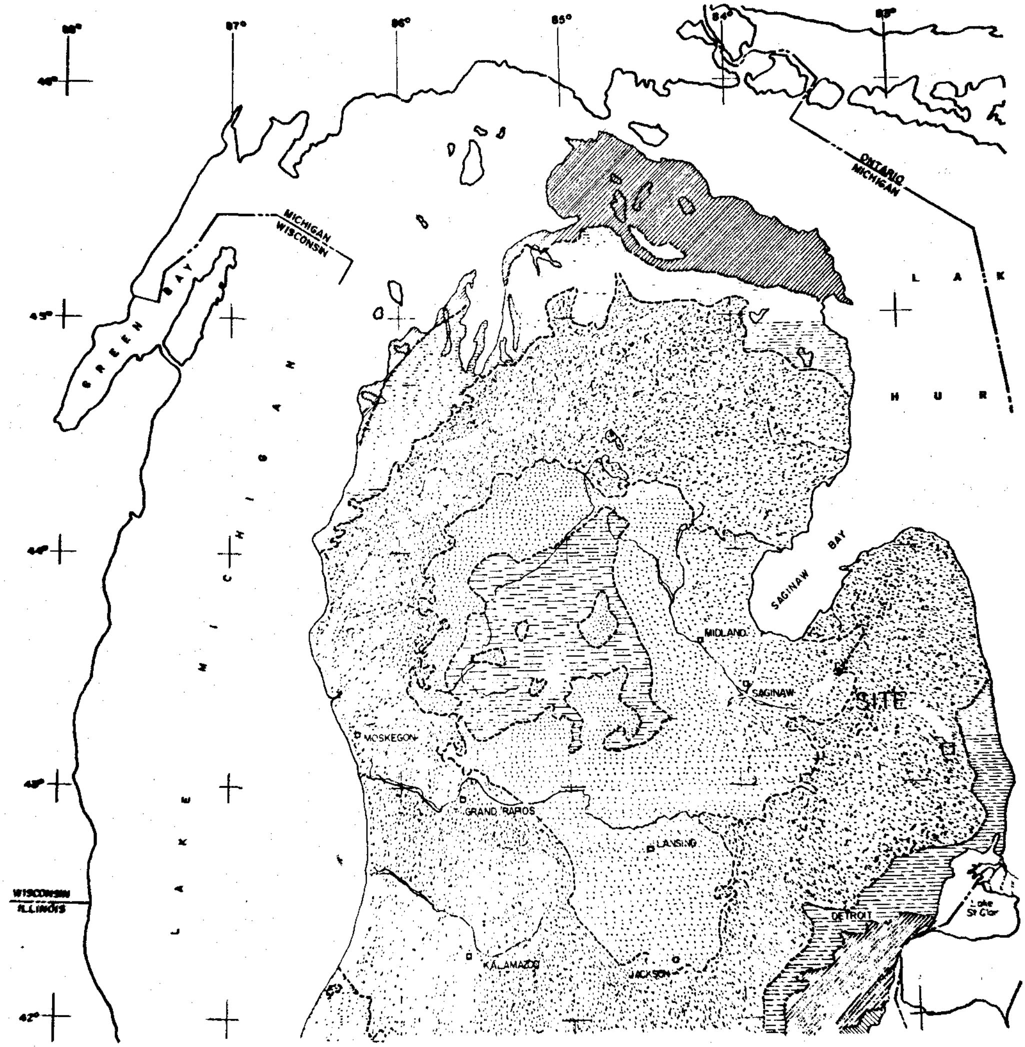
4. According to the Sunday New York Times, Jan. 6,1974, the shale oil reserves of the Green River Formation (near Colorado, Utah, Wyoming border) belong to the Cenozoic Era. How old is this formation, in comparison to the oil sources in Michigan?

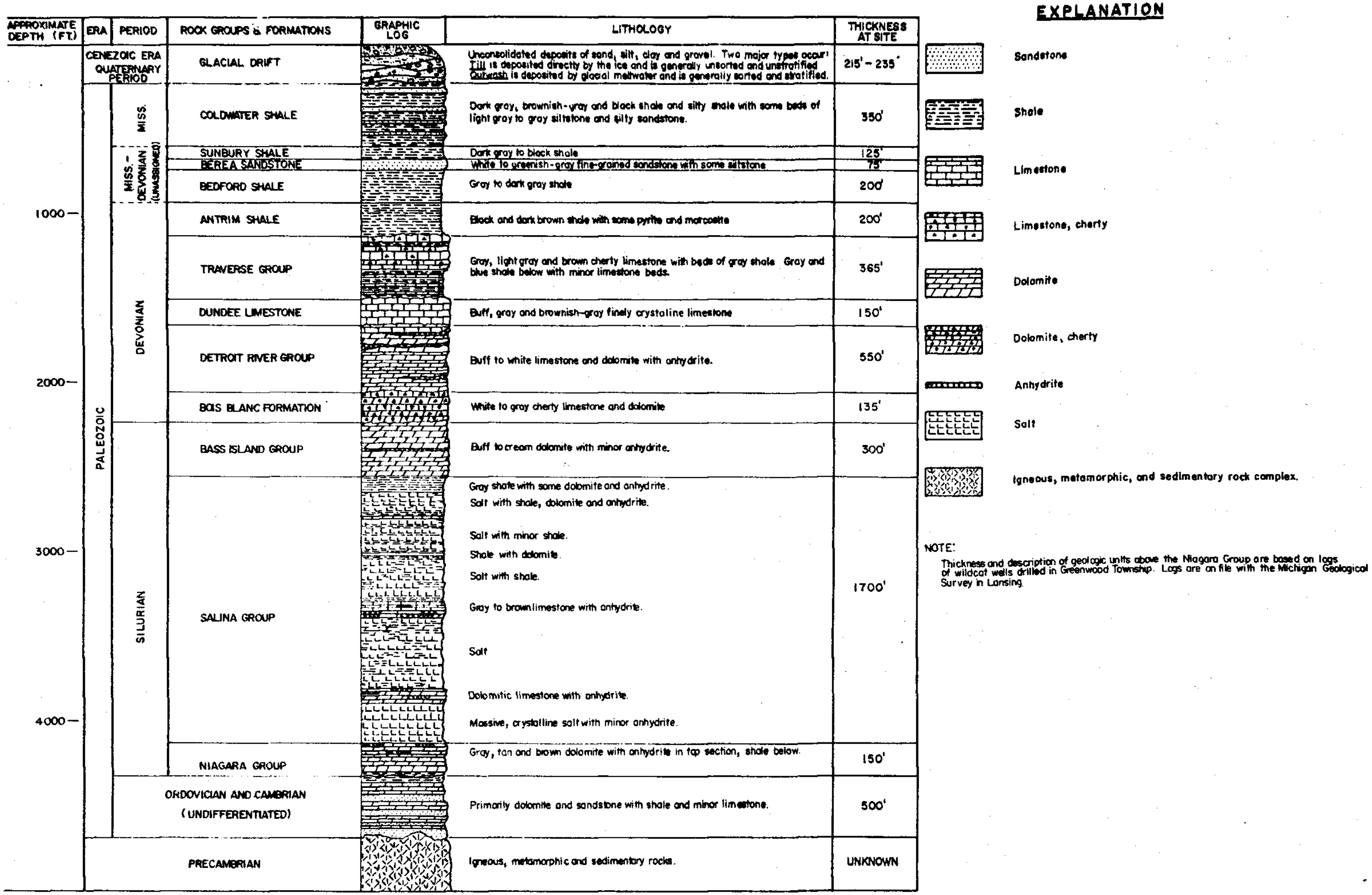



EURASIA
30°
NORTH AMERICA
80°
40°
0°
40°
80°
120°
TETHYS SEA
AFRICA
SOUTH AMERICA
30°
INDIA
AUSTRALIA
ANTARCTICA
FOSSIL WARM WATER FAUNA


NORTH AMERICA
EURASIA
30°
CRETACEOUS REEF BELT
CRETACEOUS REEF BELT
80°
40°
0°
40°
80°
120°
AFRICA
SOUTH AMERICA
INDIA
30°
AUSTRALIA
?
?
WEST ANTARCTICA
EAST ANTARCTICA
CORAL AND RUDIST FOSSIL REEFS


NORTH AMERICA
EURASIA
TETHYS SEA
30°
AFRICA
INDIA
80°
40°
0°
40°
80°
120°
SOUTH AMERICA
30°
AUSTRALIA
WEST ANTARCTICA
?
EAST ANTARCTICA
FOSSIL PALM TREES


88°
87°
86°
85°
84°
83°
46°
45°
44°
43°
42°
MICHIGAN
WISCONSIN
ONTARIO
MICHIGAN
GREEN BAY
LAKE MICHIGAN
LAKE HURON
SAGINAW BAY
MIDLAND
SAGINAW
SITE
MUSKEGON
GRAND RAPIDS
LANSING
KALAMAZOO
JACKSON
DETROIT
Lake St Clair
WISCONSIN
ILLINOIS



ERA	PERIOD	ROCK GROUPS & FORMATIONS	LITHOLOGY	THICKNESS AT SITE
CENEZOIC ERA QUATERNARY PERIOD		GLACIAL DRIFT	Unconsolidated deposits of sand, silt, clay and gravel. Two major types occur: Till is deposited directly by the ice and is generally unsorted and unstratified. Outwash is deposited by glacial meltwater and is generally sorted and stratified.	215' – 235'
PALEOZOIC	MISS.	COLDWATER SHALE	Dark gray, brownish-gray and black shale and silty shale with some beds of light gray to gray siltstone and silty sandstone.	350'
	MISS.-DEVONIAN (UNASSIGNED)	SUNBURY SHALE	Dark gray to black shale	125'
		BEREA SANDSTONE	White to greenish-gray fine-grained sandstone with some siltstone	75'
		BEDFORD SHALE	Gray to dark gray shale	200'
	DEVONIAN	ANTRIM SHALE	Black and dark brown shale with some pyrite and marcasite	200'
		TRAVERSE GROUP	Gray, light gray and brown cherty limestone with beds of gray shale. Gray and blue shale below with minor limestone beds.	365'
		DUNDEE LIMESTONE	Buff, gray and brownish-gray finely crystaline limestone	150'
		DETROIT RIVER GROUP	Buff to white limestone and dolomite with anhydrite.	550'
		BOIS BLANC FORMATION	White to gray cherty limestone and dolomite	135'
	SILURIAN	BASS ISLAND GROUP	Buff to cream dolomite with minor anhydrite.	300'
		SALINA GROUP	Gray shale with some dolomite and anhydrite. Salt with shale, dolomite and anhydrite. Salt with minor shale. Shale with dolomite. Salt with shale. Gray to brown limestone with anhydrite. Salt Dolomitic limestone with anhydrite. Massive, crystalline salt with minor anhydrite.	1700'
		NIAGARA GROUP	Gray, tan and brown dolomite with anhydrite in top section, shale below.	150'
	ORDOVICIAN AND CAMBRIAN (UNDIFFERENTIATED)		Primarily dolomite and sandstone with shale and minor limestone.	500'
PRECAMBRIAN			Igneous, metamorphic and sedimentary rocks.	UNKNOWN

EXPLANATION

▨	Sandstone
▨	Shale
▨	Limestone
▨	Limestone, cherty
▨	Dolomite
▨	Dolomite, cherty
▬	Anhydrite
▨	Salt
▨	Igneous, metamorphic, and sedimentary rock complex.

NOTE:

Thickness and description of geologic units above the Niagara Group are based on logs of wildcat wells drilled in Greenwood Township. Logs are on file with the Michigan Geological Survey in Lansing.

REFERENCES

1 - DORR, J. A. & ESCHMANN, D. F. *Geology of Michigan.* S. n. t.

2 - DEWEY, J. F. Plate tectonics. *Scient. Am.,* New York, 226 (5):56-68, 1972.

3 - NEWELL, N. D. The evolution of reefs. *Scient. Am.,* New York, 226 (6):54-65, 1972.

4 - DIETZ, R. S. Geosynclines, mountains and continent-building. *Scient. Am.,* New York, 226 (3):30-8, 1972.

5 - VALENTINE, J. W. & MOORES, E. M. Plate tectonics and the history of life in the oceans. Scient. Am., New York, 230 (4):80-9, 1974.

6 - HEEZEN, B. C. & MACGREGOR, I. D. The evolution of the Pacific. Scient. Am., New York, 229 (5):102-12, 1973.

7 - McKENZIE, D. P. & SCLATER, J. C. The evolution of the Indian Ocean. *Scient. Am.,* New York, 228 (5):63-72, 1973.

8 - PALMER, A. R. Search for the Cambrian World. *Am. Scient.,* New Haven, 62:216, Mar./Apr. 1974.

9 - MATTHEWS, S. W. This changing earth. *Natn. geog.,* 143:1, Jan. 1973.

10 - CANBY, T. Y. & BLAIR, J. P. California's San Andreas fault. *Natn. geog.,* 143:38, Jan. 1973.

11 - OUT of the Sea: the life story of a continent. S. l., The World Book Yearbook, 1965.

12 - McCRACKEN, P. W. & ROSENBERG, W. G. *Report to Governor Wm. G. Milliken by the Special Commission on Energy*[*Michigan.*]S. l., Feb. 1974.

13 - ROSENBERG, W. G. et alii. *Implementation of the emergency energy act: a report to the Michigan Legislature, by the Michigan Public Service Comission.* S. n. t.

CHAPTER V

Health Physics of Overdose - Radiation and/or Drugs

1. Comments

Overdose of anything can be dangerous. Overdose of oxygen to new-born infants is dangerous, overdose of drugs is dangerous, overdose of sunshine can also be dangerous. The same comment can also be made about radiations from radioactive sources. And as small doses of drugs maybe harmless and even beneficial, small doses of radioactive radiations may be harmless and may even be essential for life. The subject of low dose radiation will be taken up tomorrow; today, we shall discuss some of the effects of high doses of radiation.

Amounts of pharmaceuticals are often expressed in grains, milligrams, micrograms, etc. The amount of radioactive materials, on the other hand, are most frequently given in curies, although at times the amount of radioactive materials is given in grams. For example, the custom seems to be to use the unit **curie** for the amount of tritium from nuclear fission plants, but the unit **gram** for tritium to be used for nuclear fusion. Because of this confusion in units to describe the same radioactive material, I've noticed that some have a very strange attitude towards nuclear fusion. Once I met an intervenor who was all for nuclear fusion but was dead set against nuclear fission. The person was very much bothered by the kilocuries of tritium from nuclear fission power plants but completely unconcerned about a kilogram of tritium. But when I pointed out that 1 gram of tritium is about 10,000 curies, so that 1 kgm of tritium is 10 Megacuries, this intervenor, I've been told, stopped talking about nuclear fusion.

Another point we need to note is that the amount of the drug is not a complete description of it. Some drugs are more dangerous than others. A milligram of nicotine is not the same as one milligram of strychnine. What we need to do then is to consider those quantities needed to describe the characteristics of radioactive materials.

2. Quantity of Radioactive Material

This is most frequently expressed in curies, although at times it is given in grams. The conversion factors for a few of the common radioisotopes are listed in Radiological Health, pp. 104 and 105, under the healding "Activity Mass Relationship and Specific Activity". For example, this table shows that H-3, with 12.262 year half-life has 9780 curies for each gram, or 1.02×10^{-4} gm/curie. For Sr-90, on the other hand, there are 144 curies per gram. The method for computing the specific activity is indicated on p. 103 of the Radiological Handbook. To get specific activity in gms/curie, the following equations are to be used:

$$(1) \quad \text{SpA}(T_{1/2} \text{ in sec}) = \frac{1.13 \times 10^{13}}{T_{1/2}\,(\text{At. Wt})}$$

$$(2) \quad \text{SpA}(T_{1/2} \text{ in min}) = \frac{1.884 \times 10^{11}}{T_{1/2}\,(\text{At. wt})}$$

$$(3) \quad \text{SpA}(T_{1/2} \text{ in hrs}) = \frac{3.14 \times 10^{9}}{T_{1/2}\,(\text{At. wt})}$$

$$(4) \quad \text{SpA}(T_{1/2} \text{ in days}) = \frac{1.308 \times 10^{8}}{T_{1/2}\,(\text{At. wt})}$$

$$(5)\quad \mathrm{Spa}(T_{1/2}\text{ in yrs}) = \frac{3.59 \times 10^5}{T_{1/2}\,(\mathrm{At.\,wt})}$$

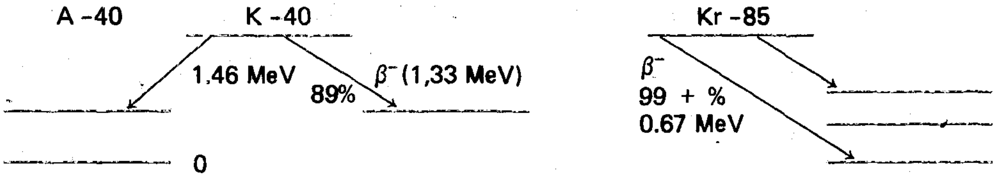
Thus for H-3,

$$\mathrm{SpA} = \frac{3.59 \times 10^5}{(12.262)\,(3)} = 9.78 \times 10^3 \text{ curies/gm}$$

Notice also that the number of curies decreases as the half-life increases. This is why the specific activity of Sr-90 with its half-life of 27.7 years, is 144 curies/gm, and for Pu-239, the specific activity is 0.0617 Ci/gm. Another example is I-131. The half-life is only 8.08 days, and the specific activity is 0.124 Mega Ci/gm.

3. Radiation Dose (Rad)

The amount of damage done to the body tissue depends upon the amount of energy absorbed in the body tissue and therefore depends upon the energy of the radioactive decay products as well as the amount of radioactive material. As examples, consider



Consider the relative effects of K-40 and Kr-85 to our body tissues, say our brains, if say 1 microcurie of each were in our brains. The two were selected because K-40 occurs naturally, whereas Kr-85 is a gas effluent from nuclear power plants. The energy of the electrons from K-40 is about 1.33 MW, compared to 0.67 MW for Kr-85. The electron energy from K-40 is about twice that from Kr-85, so that we can potentially expect twice as much bodily damage from k-40 compared to kr-85, on the curie to curie basis.

The amount of radiation energy deposited in the body tissues is most frequently given in rads, an acronym for Radiation Absorved Dose. One rad is defined as 100 ergs/gm. For example, consider 1 gm of heart muscle. One hundred ergs could be deposited in this 1 gram by outside radiation source, such as an x-ray machine, TV set, or it could come from radioactive materials in the heart muscle, such as K-40. The absorbed dose is still 1 rad, and the biological effects are the same regardless of the origin of the radiation.

Incidentally, we need to note that 1 rad is a small amount of energy. To make the point, consider one gram of water that has just absorved 100 ergs of energy. The absorbed dose, by definition, is just one rad. The absorbed energy will raise the water temperature. The specific heat of water is 1 cal/gm/C°, so that the temperature rise of the one gram of water will be

$$\frac{100 \times 10^{-7}\ (.24)}{1} = 2.4 \times 10^{-6}\,\mathrm{C}^\circ$$

If our skin were to absorb this amount of energy, we would not be able to feel the temperature change. On the other hand, our skin can certainly sense the temperature when we're out in direct sun light. By simple arithmetic, it would be easy to show that the absorbed dose from sunshine amounts to a few thousand rads!

4. Effects of Radiation

The details of the effects of radiation in body tissues is as little understood as the effects of drugs. We know that drugs will change cell chemistry and will even change the number of chromosomes in the cell. The chemical calchicine is populary used by plant breeders, and especially by breeders of exotic flowers. The following comments appear in Burpee Seeds, 1974, p. 128:

> "In addition to hybridization, Burpee breeders keep right up with many other scientific methods to help 'Mother Nature' produce better varieties. A valuable tool is the drug calchicine. This medicine, long used to treat gout, is also very effective in doubling the chromossome number in plants. Chromosomes, tiny particles found in all living tissues, carry genes that control hereditary features. The 'chromosome computer' determines whether plants will be tall or short, early or late to bloom, yellow or red-flowered, just to give a few examples. Double the chromosome number and often desirable changes occur such as stronger stems, darker green foliage, larger flowers, sometimes attractively ruffled, and richer colors."

Likewise, radiations can produce chemical and chromosome changes. One of the chemical changes, itappears, is that cells subjected to radiation dose lose their ability to maintain the proper potassium-sodium ratio. In normal cells, the potassium concentration inside the cell is high and the sodium concentration is low. Outside the cells, in the intercellular solution, the sodium concentration is high. It is as if our bodies have kept the marine environment from which life started. Cells damaged by radiation for some unknown reason lose their ability to retain potassium, and this results in syndromes comparable to potassium deficiency in the diet. The other effect of course is the chromosome change. Radiation tends to break up chromosomes, producing more than the normal quota of chromosomes. But again it should be noted that chemicals produce these changes, and it appears that chromosome defects increase with age.

5. High and Lethal Overdose

Radiation dose lethal to man is considered to be about 350 rads. This means that the chances that a person receiving this dose will survive is 50%. The AEC has conducted studies of the effects of the atomic bombs in HIROSHIMA and NAGASAKY, and there the suvivors have been estimated to have received 100 rads or more of whole body radiation. X-rays will also produce body tissue damage, but again the effects are produced by doses in the tens of rads. Gofman and Tamplin, in their book on Poisoned Power, have several pictures showing the effects of radiation. The crucial point, which unfortunately they did not stress, is that the reported effects were produced by very high overdoses of radiation. For example, the skin tumor on the rat was caused by 5000 rads of radiation, the human tissue cell mortality was caused by radiations of 100 rads or more, and the dentist's fingers and hand must have been subjected again to thousands of rads. What they failed to mention is that they were arguing that 170 mrad/yr is too high by presenting the effects of radiation produced by 5 million mrad on rat skin, 100,000 mrad on human tissue cells, and agains millions of mrads on the dentist's hands and fingers. They presented the effects due to high overdose of radiation, but absolutely no evidence for the effects of very low radiation doses.

6. Biological and Radioactive Half-Lives

Another point over-looked in the discussion of the effects of radioactive materials is the so-called biological half-life. The layman's word for this could be the body retention time. If by some accident radioactive material enters the body, it will not necessarily stay there forever. The lenght of time that the material remains in the body depends upon both the radioactive and the biological half-life. The reason for this is quite clear. Some of the radioactive material will disappear because of radioactive decay. Also, at the same time, body metabolism is going on, so that the effective residence time in the body is always shorter than the shorter of the two half-lives. To illustrate, consider:

	$T_{1/2}$	T_B
H-3	12 yrs	12 d
Sr-90	28 yrs	49 yrs
Sr-89	50 d	49 yrs
Cs-137	30 yrs	140 d

For the above radioisotopes the residence times in the body are expected to be less then 12 days, 28 yrs, 50 days, and 140 days respectively. Thus for example, for Cs-137, the potential radiation hazards are mitigated by the short body retention time. The quantitative relation is taken to be

$$\frac{1}{T_{eff}} = \frac{1}{T_{1/2}} + \frac{1}{T_B}$$

or

$$T_{eff} = \frac{T_{1/2}\, T_B}{T_{1/2} + T_B}$$

For example, for Sr-90, the effective residence time is

$$T_{eff} = \frac{28\,(49)}{28 + 49} = \frac{28\,(49)}{77} = 18 \text{ years}$$

7. Radiological Units

Terms such as the roentgen, curie, rad, rem RBE, etc. are used. The curie is a measure of radioactive source strenght. The roentgen, rad, and rem are units of dose rate, i. e. are units measuring the energy deposition in materials, like the human tissue. The terms rem (roentgen-equivalent-man) and RBE (Relative Biological Effectiveness) are quantities used to describe biological effects of radiation.

a) Radioactive Decay Rate and Curie

The curie (Ci) is a unit of radioactivity defined is that quantity for which the number of disintegrations is 3.740×10^{10} disintegrations/sec. That is, this would be the counting rate of a 100% efficient nuclear detector, which completely surrounds the source (4π-detector). Thus if the counting rate of 4π-detector is 6×10^4 per second, then the source strength is

$$\frac{6 \times 10^4}{3.7 \times 10^{10}} = 1.6 \times 10^{-6}\text{Ci} = 1.6\,\mu\text{Ci} \tag{7.1}$$

It is possible to relate the amount of radioactive material to the detector counting rate. Suppose, for example, that one electron is given off each time a nucleus disintegrates. If C is the counting rate and if dN/dt is the rate of change of the amount of radioactive nuclei, then

$$C = \left[\frac{dN}{dt}\right] \tag{7.2}$$

But

$$\frac{dN}{dt} = -\lambda N \tag{7.3}$$

so that

$$C = \lambda N \tag{7.4}$$

in which

$$\lambda = \frac{\ell n\, 2}{T_{1/2}} = \frac{0.693}{T_{1/2}} \tag{7.5}$$

The quantity N is the amount of radioactive material present at the time counting rate is being taken. If the radioactive sample has been out of a neutron source for some time say taken out of a reactor or after power plant shutdown the quantity present initially can be calculated from the relation

$$N(t) = N_0 e^{-\lambda t} \tag{7.6}$$

which is obtained by solving the differential equation (7.3) Now

$$e^{\ell nx} = x \text{ and } e^{n\ell nx} = x^n$$

so that we can write (7.6) in the form

$$N(t) = N_0 \exp\left(\frac{-t}{T_{1/2}}\ell n\, 2\right) = N_0\ (2^{-t/T_{1/2}})$$

$$N(t) = N_0 10^{-.30103\, t/T_{1/2}}$$

The last result is most useful in calculation using log tables.

Ex. 1. We consider first the amount of Sr-90 produced by a nuclear reactor under continuous operation for one year. A list of the production rates of important fission products in a reactor is given, for example in **Radiological Health Handbook**, p. 97. According to this table, the radioactivity from Sr-90 is 1430 Ci/Mw(t). Its half-life, as given on p. 96, is 27.7 years. Since 1 yr = 31 Msec, we find that

$$\lambda = \frac{0.693}{27.7\ (31 \times 10^6)}$$

and therefore

$$N = \frac{C}{\lambda} = \frac{1430\,(3.7 \times 10^{10})}{0.693/(27.7)\,(31 \times 10^{6})}$$

$$= 65 \times 10^{21} \text{ Sr-90 Nuclei}$$

$$= \frac{65 \times 10^{21}}{6.03 \times 10^{23}} = 11 \times 10^{-2} \text{ Moles of Sr-90}$$

$$= 90\,(.11) \cong 10 \text{ gms. of Sr-90}$$

Thus for a 1000 Mw(e) power plant, whose efficiency is about 1/3, the annual Sr-90 produciton can amount to 30 kgms.

Ex. 2. Consider next the radioactivity of a nuclear fusion power plant. According to the paper by Steiner and Fraas, "Preliminary Observations on the Radiological Implications of Fusion Power", Nuclear Safety, Vol. 13, 353 (Sept.-Oct. 1972) the tritium inventory is estimated to be about 6 gm/Mw(t). Since the atomic weight is 3 gm/mole, the number of tritium atom is

$$2\,(6.03 \times 10^{23}) = 12.06 \times 10^{23}$$

and since the half-life is about 12.3 years,

$$\text{Decay Rate} = \lambda N$$

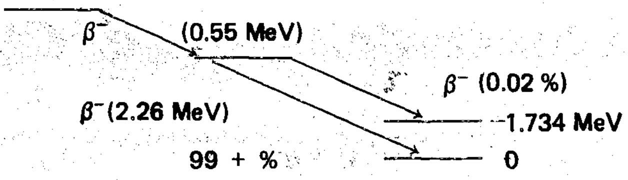
$$= \frac{0.693}{12.3\,(31 \times 10^{6})}\,(12.06 \times 10^{23}) = 2.4 \times 10^{15} \text{ Disint/sec}$$

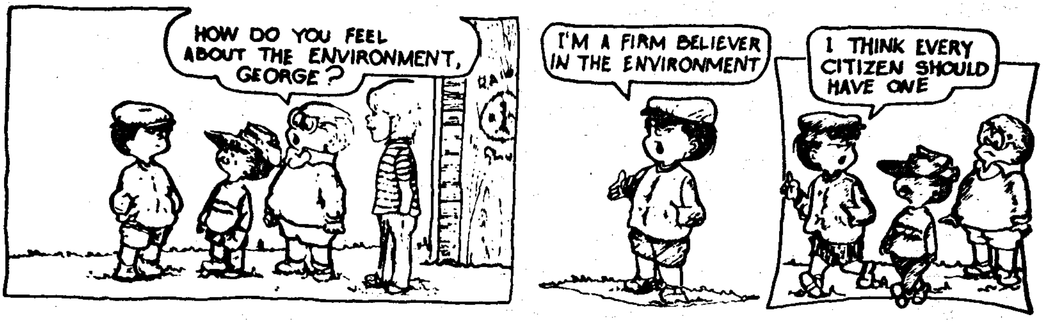
$$= \frac{2.4 \times 10^{15}}{3.7 \times 10^{10}} = 6.5 \times 10^{4} \text{ Ci/MW(t)}$$

If the efficiency is again assumed to be about 1/3, the radioactivity from tritium alone for a 1000Mw(e) fusion power plant would be about 19.5 x 10^7 Ci, or about 0.2 GCi (G, giga for billion).

Ex. 3. In assessing radiological hazards, we used to keep in mind that curie alone is not a complete description; we used to know also the amount of energy released per disintegration. Consider again Sr-90. The radioactive decay scheme is as follows: (Radiological Health Handbook, p. 278 and 279).

$${}^{90}_{38}\text{Sr} \xrightarrow{\beta^-} {}^{90}_{39}\text{Y} \xrightarrow{\beta^-} {}^{90}_{40}\text{Zr}$$





In the decay scheme the maximum energies of the electrons given off are 0.55 and 2.26 MeV, or a total maximum energy of about 2.8 MeV. The average energy of all the electrons given off is about 0.4 of the above value, or about 1.1 Mev. Hence the rate of energy radiation from Sr-90 is about

$$\text{RADIOACTIVE POWER} = 1430\ (3.7 \times 10^{10})\ (1.1)$$

$$= 5.8 \times 10^{13}\ \text{MeV/Sec} = 9.3 \times 10^{7}\ \text{ERGS/Sec}$$

$$= 9.3\ \text{Joules/Sec} = 9.3\ \text{Watts}$$

Compare this to I-131 produced in the same reactor. Its yield in one year is 25,200 Ci/Mw(t) so that the disintegration rate is

$$(25{,}200)\ (3{,}7 \times 10^{10}) = 9.3 \times 10^{14}\ \text{Disintegrations/Sec}$$

Its decay scheme is a little more complex (See Radiological Health Handbook, p. 325). The energy released per disintegration is about 0.6 MeV, so that the emitted power is

$$(9{,}3 \times 10^{14})\ (0.6) = 5{,}6 \times 10^{14}\ \text{MeV/Sec} = 89{,}\text{watts}$$

Thus the rate of energy release from I–131 is about 10 times larger. In addition the problems of shielding against from 1-131 are more difficult because energetic gama rays are given off.

b) Radiation Dose And Dose Rate

Materials, living or non-living, localized in a nuclear radiation environment, will absorb a portion of the radiation. The amount of absorbed energy is often in terms of roetgen (r) or rads. The dose (or absorved dose) is said to be 1 rad (acronyn for radiation absorbed dose) if the absorbed energy is 100 ergs in one gram of the material. The importance of this quantity stems from the fact that the dose for one gram of any material in a given radiation environment is approximately the same. Thus, if in a radiation environment one gram of water absorbs 100 ergs or 1 rad, then one gram of human tissue, say, will absorb nearly the samy amount of energy. The effects, however, are drastically different. 100 ergs is only 0.24×10^{-5} cal, so that the temperature rise of one gram of water will be only 0.000,002°C. The specific heat of human tissue is not expected to be very different, so that the temperature rise will be about the same; but the potential biological effects of 1 rad dose will be vastly different.

c) Biological Dose and Dose Rate

The rad, as defined, does not distinguish the possible side effects produced by different *types of radiation, i.e., the effect of 1rad of x-rays may conceivably be different from that of* 1 rad of fast neutrons. X-rays will produce predominantly ionization, whereas neutrons will produce both atomic displacements and ionization and consequenttly the probability of causing the break-down of biological materials is greater. In an attemp to take this into account, the rem (roentgen-equivalent-min) and the RBE (relative biological effectiveness) are introduced. The defining relation is

$$\text{rem} = (\text{rad})\ (\text{RBE})$$

The RBE for x-, γ-, and β - radiation is taken to be 1, for thermal neutrons 3, for fast neutrons and protons 10, and for alpha particles 20.

8. Standard Man

Biological calculations are based on the standard man. Tables giving the "specs" of the standard man can be found in such references as the ICRP (Internation Commission on Radiological Protection) by D. F. Rees, **Radiological Health Handbook**, and others. The quantities of interest to us for the discussion here are:

Total body	70,000 grams
Bones (without marrow)	7,000 grams
Water intake	2,200 cm^3/day
Air intake	2×10^7 cm^3/day

Another concept that enters into the calculation is the biological half-life, or the retention time in the human body. For example, the biological half-life of Sr is about 1.3×10^{14} days (35.6 yrs) compared to 70 days for Cs. The two long-lived isotopes produced in nuclear fission are Sr-90 with $T_{1/2}$ = 28 yrs and Cs-137 with $T_{1/2}$ of about 30 yrs. Both have comparable radioactive half-lives, but the problem of Cs contamination is not as serious because of the ***shorter** biological half-life. This is reflected in the ICRP standards, in which the maximium* permissible concentration of Cs-137 is set at 2×10^{-4} μ Ci compared to the value of 10^{-6} μCi for Sr-90.

Another factor is that not all ingested radioactive material is assimilated. For Sr, the fraction asssimilated is about 21%, but for Cs it is about 100%.

9. Body Burden

The question we want to ask and to answer is, "What is considered to be the safe amount of radioactive materials in the body?" This, of course, is determined by both external and internal sources of radiation and the total, according to ICRP standards, is not to exceed (occupational exposure)

$$\text{Dose} = 5(\text{N-18})\ (\text{rem})$$

in which N is the age of the person. The rate then is 5 rem/year or about 0.1 rem/wk. This means that the average energy deposition in the human body from radioactive sources is not to exceed

$$\frac{(0.1)\,(100)}{168\,(3600)} = 1.65 \times 10^{-5} \text{ ergs/grm/sec.} \tag{9.1}$$

$$= 10.3 \text{ MeV/grm/sec.}$$

The rate at which energy is released from radioactive materials in the body is given by

$$\frac{(\lambda N)\ \text{Eave}}{W} \tag{9.2}$$

in which λN gives the number of nuclei disintegrating an a second. E_{ave} is the average energy absorbed in the human body when a single nucleus disintegrates, and W is the weight of the organ in which the radioactive material is located. The ICRP standards require that

$$\frac{(\lambda N)\ \text{Eave}}{W} \leqq 10.3 \text{ MeV/grm/sec.} \tag{9.3}$$

Suppose then we consider Sr-90, which concentrates in the bone system. For the standard man, then W = 7000 gm. The half-life of Sr-90 is 28 years, so that

$$\lambda = \frac{\ell n\, 2}{T_{1/2}} = \frac{0.693}{2 < (31 \times 10^{6})} \text{ /seg.}$$

As indicated before, the average energy per disintegration is estimated from the radioactive decay scheme. When Sr-90 decays, electrons are given off with a maximum energy of 0.546 MeV, and this is followed by the decay of Y-90 upon emission of another electron of maximum energy of 2.26 MeV. The total maximum energy released is then about 2.80 Mev. The average energy released is about 0.4 of the maximum value, or about 1.1 MeV. Therefore

$$\lambda N \leqslant \frac{(10.3)\,(7000)}{1.1} = 6.5 \times 10^{14} \text{ dinsint/sec.}$$

$$= \frac{6.5 \times 10^{14}}{3.7 \times 10^{4}} \sim 2\,\mu\text{Ci} \tag{9.4}$$

This is the maximum permissible body burden of Sr-90 in the human body. The ECRP standards recommend then that the total amount of Sr-90 accumulating in the human body in 50 years should not exceed this value.

The accumulation rate obviously depends upon the rate of Sr intake from the environment. Sr-90 is contained in the food we eat, the air we breathe, and the water we drink. To simplify the analysis, we shall assume that the Sr intake comes entirely from drinking water. Then

$$\text{Accumulation Rate} = \text{Intake} - \text{Loss rate}$$

If N is the number of Sr-90 in the human system, then

$$\text{Accumulation rate} = \frac{dN}{dt}$$

The loss rate depends upon two mechanisms, one due to the radioactive decay of nuclei and the other due to the elimination given by

$$\begin{aligned}\text{Radioactive loss rate} &= \lambda N\\ \text{Biological loss rate} &= \lambda B^{N}\end{aligned}\qquad (9.5)$$

The intake rate depends upon the concentration in water, the rate of drinking water, and the fraction assimilated by the body, so that

$$\text{Intake rate} = N\,\frac{2200}{(.24)\,(3600)}\,f = .0054N = \rho \qquad (9.6)$$

When the maximum amount of Sr-90 has been accumualted in the body, the intake rate will just balance the loss rate; thus

$$0.0054\,N \ncong \lambda N + \lambda_{\beta} N = (\lambda + \lambda_{\beta})\,N \qquad (9.7)$$

The concentration N is the number of radioactive Sr-90/cm^3; the concentration in curies is obtained by multiplying by λ. Then (9.7) becomes

$$(\lambda N) = (\lambda + \lambda_{\beta})\,\frac{\lambda N}{0.0054} \qquad (9.8)$$

From (9.4) the body burden (λN) needs to be less than 2 Ci. Furthermore, taking the biological half-life of Sr to be 35.6 years, we find that

$$\lambda + \lambda_{\beta} = \frac{\ell n\, 2}{T_{1/2}} + \frac{\ell n\, 2}{T_{\beta}}$$

$$= \frac{T_{\beta} + T_{1/2}}{T_{1/2}\,T_{\beta}} = \ell n\, 2 = \frac{0.693}{16.4}\;\frac{1}{31 \times 10^{6}}$$

Therefore

$$\lambda N = \frac{2}{0.0054}\;\frac{0.693}{16.4\,(31 \times 10^{6})} = 0.52 \times 10^{-6}\,\mu\text{Ci/cm}^{3}$$

The above sample calculations were carried through to show how for the maximum body burden and (MPC)$_W$ for Sr-90 is obtained. ICRP standards for other radioactive nuclei are obtained in the same way.

10. Environmental Radioactivity

Before taking up examining nuclear radiations in our environment, it might be helpful to look at the "bath" of electromagnetic radiation, in which we live. Sunlight, like gamma and x-radiations, is electromagnetic radiation. Without it, we would perish, but we also need to remind ourselves that sunlight would be injurious to most human tissues, were it not for the protective layer of the skin. Skin is less than 0.5 mm thick, of which about 0.07 mm is the epidermis. The absorption coefficient of visible and ultra-violet radiation is in the neighborhood of 10^5/cm, so that the bulk of the solar radiation is absorved in the skin and very little penetrates deeper (excepting possibly long wave lenght infra-red radiation). The solar radiation absorbed in the skin warms it, thereby giving us the feeling of well-being when in the sun.

Earlier, we discussed the rad as the unit of absorbed dose. Let us then estimate the **rad equivalent** of solar radiation. The solar constant is about 2 cal/cm^2 /min.; this is the amount of energy flux through in area of 1 cm^2 at the top of the earth's atmosphere. The amount reaching the earth's surface is about one-half of the above value. In addition there is another possible loss of about 50% due to reflection from skin. The rate of energy absorption then is about 0.5 cal/min of 1 cm^2 of skin, or about 0.035 w/cm^2. For the standard man, the mass of the skin and subcutaneous tissue is taken to be about 6,100 gm; the skin area is considered to be about 18 ft^2, or about 18,000 cm^2, which gives

$$\frac{6{,}100 \text{ grm}}{18{,}000 \text{ cm}^2} = 0.34 \text{ grm/cm}^2$$

This amount of human tissue absorbs 0.035 w/cm^2 or 35 x 10^4 ergs/cm^2/sec., so that we obtain

$$\frac{35 \times 10^4 \text{ ergs/cm}^2\text{/sec}}{0.34} \sim 10^6 \text{ ergs/grm/sec.}$$
$$\sim 10{,}000 \text{ rads/sec.}$$

For x-rays or gamma-rays, the human tissue is almost transparent, and the skin offers no protection. The mass absorption coefficient of water for 50 kev x-rays (medical and dental) is about 0.2 cm^2/gm. Since the density of water is 1 gm/cm^3 (also the approximate density of human tissues), the above quantity implies that the x-ray penetration depth is about 5 cm, i.e., the body is effectively transparent, and therefore no part of the body is shielded from the x-radiation.

The radioactivity of our environment stems from the fact that a large fraction of **naturally** occurring isotopes is radioactive. All isotopes of elements heavier than 82 (Pb) are radioactive. In addition there are H-3, C-14, K-40, V-50, Rb-87, In-115, Sb-123, Te-130, I-129, La-138, Nd-144, Su-147, Lu-176, W-178, and Re-187; of these, the 0.0118% abundant K-40 gives the most significant contribution to internal radiation. The AEC pamphlet lists the following values for radiation dose rates stemming from radioactive deposits in our bodies:

Radioactive Nuclei	Dose Rate (mrad/year)
K - 40	20
Rb - 87	0.3
C - 14	1.
Ra - 226, -228	1.
H - 3	2.
Total Internal	= 24 mrad/yr.

In addition, we receive some external radiation. This can vary over a large range of values. As noted earlier, in parts of Brazil, the background radiation is as high as 12,000 mrad/yr. Cosmic rays can contribute a significant fraction of our external radiation dose; at sea level this is almost zero, but at 20,000 feet the dose is estimated to be about 1500 mrad/yr. The radiation background in Denver, Colorado is higher than it is in Detroit. Medical x-irradiation provides additional radiation dose, amounting to about 30 mrad/year, and because of the past atomic bomb tests there is possibly about 30 mrad/year coming from fallouts. In any case, the background **external** radiation, exclusive of medical and fallout radiation, is taken to be about 100 mrad/year.

Often, the **average** total (external plus internal) radiation dose rate coming from natural sources is taken to be about 125 mrem/yr.

11. Radiation Standards

An excellent readable account of this subject is given in L. S. Taylor, **Radiation Protection Standards**, CRC Press, 1971. The NCRP (National Council on Radiation Protection and Measurements) recommendations are summarized on p. 97. The key numbers to keep in mind are as follows;

Occupational Exposure	5000 mrad/yr
General Public	500 mrad/yr
a. Any one individual (1/10 of above)	170 mrad/yr
b. Average (1/30 of occupational exposure)	120 mrad/yr
Natural Background	

Questions and Problems

1. What is meant by man-rem?
2. Suppose that a worker accidentally ingests 2000 microcuries of H-3 (max. permissible amount). After how many days will the absorbed dose from h-3 drop to 0.01 rem/wk? The biological half-life of H-3 is given as 12 days.
3. The biological half-life of Sr is estimated to be about 18,000 days. If a person discovers that he has 70 microcuries of Sr-85 in his body, after how many days will his Sr activity fall to 18 microcuries? (The max. permissible body burden is 70 microcuries).

REFERENCES

1 - KASTNER, J. *The natural radiation environment.* Washington, D.C., USAEC, 1968
2 - STEINER, D. & FRAAS, A.P. Preliminary observations on the radiological implications of fusion power. *Nucl. Saf.*, Washington, D. C., 13:353, Sep./Oct. 1972.
3 - LOUTIT, J. F. *Irradiation of mice and men.* Chicago, University Press, 1962.
4 - LEWIS R. S. *The nuclear-power rebellion: citizens vs. the Atomic Industrial Establishment.* S. l., Viking Press, 1972.
5 - REES D. J. *Health physics: principles of radiation protection.* London, Butterworths, 1967.
6 - MORGAN, K. Z. & TURNER, J. E., eds. *Principles of radiation protection: a textbook of health physics.* New York, Wiley, 1967.
7 - FOREMAN, H. *Nuclear power and the public.* S. l., University of Minnesota Press, 1970.
8 - EISENBUD, M. & PETROW, H. G. Radioactivity in the atmospheric effluents of power plants that use fossil fuels. *Science,* New York, 144:288, Apr. 1964.
9 - NATIONAL ACADEMY OF SCIENCES, Washington, D. C. *The effects on populations of exposure to low levels of ionizing radiation.* Washington, D. C., 1972.
10 - EISENBUD, M. *Environmental radioactivity.* 2ed. New York, Academic Press, 1973.

CHAPTER VI

Natural Radioactivity Environment

> "The intriguing observation that radiation may be necessary for life itself, perhaps as a stimulant has been suggested both in analysis of some experimental observations of plants and by at least one set of experiments in which a frog heart maintained in vitro continued beating when a radioactive isotope of potassium was a component of its nutrient but stopped when this component was replaced by a nonradioactive potassium isotope; when the radioactive isotope was again used, the heart resumed its beating".
>
> H. F. Henry
> **Fundamentals of Radiation**
> **Protection**, p. 133

1. Regulatory Guide Requirement

According to Sec. 2.8, the applicant is required to report regional radiological data. The reason for this is that unless the preoperational background radiation characteristics are known, it would not be possible to evaluate the amount of radioactive materials released during the plant operation. It happens that in general the bulk of the radiation is expected to be due to natural radioactvity. Next in magnitude is the radiation from fallout fission products. The radioactive emissions from nuclear power plants, according to AEC standards, are to be about 1/10 of the natural radioactivity radiations.

Because natural radioactivity constitutes the major portion of the environmental radioactivity, we shall discuss this in some detail. An excellent discussion of this subject is given in the AEC pamphlet, **The Natural Radiation Environment.**

2. Discovery of Radioactivity

The environment we live in is radioactive and has been so as long as life has existed on earth. In fact, as we shall see later, when life started on earth about 2 billion years ago, the environment was substantially more radioactive than it is today. The first discovery of radioactivity was made in Feb. 1896, by the French physicist H. Becquerel, who found that a poweful penetrating radiation emanated from uranium and its compounds, and coined the word "radioactive" to describe the newly discovered effect. In April of the same year, G. S. Schmidt and Mme Curie announced the radioactivity of thorium. Furthermore, she (Mme Curie) noticed that the radioactivity of certain uranium minerals, especially pitch blende, showed radioactivity considerably in excess of that to be expected from the amount of uranium they contained. Thereupon the husband and wife-Pierre and Marie Curie-set about their heroic experiments to concentrate the more radioactive ingredients present in pitch blende ores by chemical crystallization methods. In this way the element polonium and then radium were discovered. And by 1918, nearly 40 radioactive isotopes had been found with mass numbers greater than 206 and atomic numbers greater than 80.

Of the 92 or so elements known to exist in nature, almost 30% are known to be radioactive. First there are the elements with atomic numbers greater than 81, that are the results of radioactive decay of uranium and thorium. The atomic numbers of the elements, a typical radioactive isotope and its half-life are listed below:

Element	Symbol	Radioisotope	Half-Life
81 Thallium	Tl	Tl - 208	3.10 m.
82 Lead	Pb	Pb - 212	10.6 hr.
83 Bismuth	Bi	Bi - 214	19.7 m.
84 Polonium	Po	Po - 218	3.05 m.
85 Astatine	At	At - 219	0.9 m.
86 Radon	Rn	Rn - 222	3.82 d.
87 Francium	Fr	Fr - 223	22 m.
88 Radium	Ra	Ra - 226	1620 years
89 Actinium	Ac	Ac - 227	21.6 years
90 Thorium	Th	Th - 232	1.39×10^{10} years
91 Protoactinium	Pa	Pa - 231	3.43×10^{4} years
92 Uranium	U	UA- 238	4.5×10^{9} years

There are other radioisotopes not part of the radioactive series and scattered throughout the periodic table.

Element	Symbol	Radioisotope	Half-life (yrs)
1 Hydrogen	H	H - 3	12.26
6 Carbon	C	C - 14	5770
19 Potassium	K	K - 40	1.47×10^{9}
23 Vanadium	V	V - 50	4×10^{14}
37 Robidium	Rb	Rb - 87	5.0×10^{10}
49 Indium	In	In - 115	6×10^{14}
57 Lanthanum	La	La - 138	1×10^{11}
60 Neodynium	Nd	Nd - 144	3×10^{15}
62 Samarium	Sm	Sm - 147	1.25×10^{11}
71 Leuticium	Lu	Lu - 176	4.5×10^{10}
75 Rhenium	Re	Re - 187	4×10^{12}

There are two elements whose existence had been suspected because of the gaps in the Periodic Table but which were not discovered until rather recently. The two elements do not occur normally in the earth's crust because their half-lives are short in comparison to the age of the earth. One element is technicium (Tc), atomic number 43, first-produced in 1937. Tc-97 and Tc-98 have half-lives of 2.6 and 1.6 million years respectively. Although this element is not found in the earth's crust, it is one of the common elements in stellar atmospheres, where the Tc isotopes are being produced continuously through a series of nuclear reactions. The other element is astatine (At), atomic number 85, first synthesized in 1940 by bombarding bismuth with alpha particles. All of the isotopes have short half-lives, the longest being At-210, with only 8.3 hour half-life. It occurs between polonium (Po, Z = 84) and radon (Rn, Z = 86) and is one of the decay daughter products of U-233 (At-217; 0.02 sec) and of U-235 (At-219, 0.9 min).

In addition, there should be sub-trace amounts of fission products and trans-uramic elements occurring **naturally** in uranium bearing ores. The reason for this is that both the uranium and thorium isotopes **spontaneously** undergo fission, producing neutrons as the result. If such neutrons are captured by U-238, for example, Np-239 will be produced, leading to the production of Pu-239. The discovery of Pu in natural uranium was reported rather recently. Np-237 has been found in lunar samples.

3. Abundance of Certain Radioactive Elements

The following is a list of the abundances of certain select elements in the earth's crust.

Element	Order of Abundance	Abundance in parts/million
O	1	466,000
Si	2	277,200
Al	3	81,300
Fe	4	50,000
Ca	5	36,300
Na	6	28,300
K	7	25,900
H	10	1,400
Th	39	12
Ge	41	7
U	50	4
I	64	0.3
Ag	67	0.1
Au	73	0.005

This table shows that although the radioactive elements Th and U are among the rare elements, they rank as number 39 and 50 respectively, and are more abundant than some of the elements familiar to us. For example, the familiar elements silver (Ag) and gold (Au) rank as number 67 and 73 respectively. The biologically essential element iodine (I) is number 64 in abundance.

To get an appreciation for the amount of radioactive materials in the soil, consider as an example the amount of Th and U on the Grenwood Energy Center 6 square mile site, in the top 1 foot layer only. Soil specific gravity is about 1.4, and since the density of water is 62.4 lb/ft^3 and 1 sq. mile contains 2.79×10^7, we find for the weight of soil 1 foot deep on the 6 sq. mile site to be

$$(62.4)\ (1.4)\ (2.79 \times 10^7)\ (6)\ \text{lbs}$$

$$\doteq \frac{(62.4)\ (1.4)\ (2.79 \times 10^7)\ (6)}{2000} = 7.3 \times 10^6 \text{ tons}$$

Since the amount of uranium is 4 parts per million, the weight of uranium amounts to

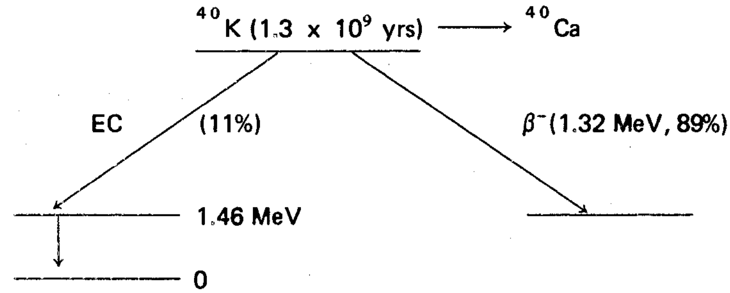
$$(7.3 \times 10^6)\ (4 \times 10^{-6}) = 29.2 \text{ tons}$$

Th is 3 times as abundant so that its weight is about 90 tons, giving a combined weight of 120 tons or so of U and Th. This amount of radioactive Th and U is comparable to the amount of U to be placed in the Greenwood plant reactor core.

3. Radioactive Potassium

The element which gives the greatest amount of radiation to our body tissues is the potassium isotope, K-40. Radiation from this source is significant because k is an essential element. Potassium is important for crop yield; potash, which is mainly potassium is used as fertilizer. Potassium concentrates mostly where the action is-in muscles and nerve cells. Lack of potassium leads to certain syndrones, such as lack of muscle tone or heart disorders. The amount of potassium in an average person is about 140 grams compared to 105 gms of radium. And significantly, k is inside the cell-in the intracellular fluid-whereas Ra is outside the cell-in the intercellular cell. Potassium consists mostly of k-39 (93.1 isotopic abundance) and k-41 (6.88% *isotopic abundance), but also contains* k-40 (0.0118%), whose half-life is 1.3 billion years.

The following diagram summarizes the relevant nuclear properties for k-40



We notice that 89% of k-40 decays by emitting a 1.32 MeV beta particle. This is a charged particle, is readily absorved, so that its energy is deposited in a small region where it originated. The gamma ray of energy 1.46 MeV resulting from the electron capture, is not easily absorbed so that much of it could escape to the outside. Thus, as has been pointed out, in a crowd, the absorbed dose from the k-40 radiation will increase.

An interesting application of k-40 radioactivity is often pointed out, as for example in the AEC booklet, The Natural Radiation Environment. Potassium is muscle seeking so that it is possible to assess the lean-to-fat ratio of beef cattle by means of whole body counters. It is hoped in this way to breed cattle that will produce leaner meat.

Note also that the potassium content of soils of arable lands is controlled by the use of fertilizers. It has been estimated that about 1160 Ci of k-40 has been added to the U. S. soil in 1958.

The potassium-40 concentration in seawater is about 300 p Ci/liter. Its concentration in Lake Michigan, according to the report Lake Michigan Environmental Survey by John C. Ayers, is about 1.1 p Ci/liter. The question that arises is to what extend is the radioactivity of Lake Michigan water increased by the liquid effluents from nuclear power plants.

4. Radioactivity in Food and Water

A detailed account of Ra-226 (uranium 238 series) and Ra-228 (Thorium-232 series) appears in the latest edition of Eisenbud's book on Environmental Radioactivity. Because uranium and thorium occur naturally in the environment, trace amounts of radium-226 and radium-228 occur in our food and water supply. For example the Detroit water contains about 0.018 p Ci/liter and this value is very nearly the same as the national average. There are, however, certain areas where the water radium content is abnormally high. One such example is Joliet, Ill., where the water is drawn from deep wells, and the radium content is 6.54 and 5.79 p Ci/l before and after treatment. A study of the Ra-226 content of foods indicate that the range is from 0.52 to 0.73 p Ci/Kgm. But its content in nuts grown in Brazil is abnormally high, about 14000 p Ci/Kgm. Consuming high radium content in water and food, of course, leads ultimately to higher body burden of radium. For example, study shows that the skeletal content of radium-226 for a person in Illinois drinking normal water is about 32p Ci, compared to 100 p Ci for those living in the high radium areas of Illinois.

5. Michigan Environmental Radioactivity

An important source of information on this subject is the paper "Environmental Radioactivity in Michigan, 1970, by S. Wieder, J. E. Logsden, & C. P. Froom, Radiation Data and Reports 13, Number 1, Jan. 1972. The following table, taken from the report, gives an inventory of radiation sources and doses for Michigan.

Sources		Dose (mrem/yr)		
Natural (External)				
Terrestrial gamma ray		60	to	85
Cosmic rays		35	to	60
Natural (Internal)				
Potassium -40		17		
Carbon -14		0.7		
Natural (Internal) con't				
Radium -226, radium -228 (and progeny)		0.6		
	Subtotal	113.	to	153
Fallout from nuclear tests				
Cesium -137		1.2		
Strontium -90		0.25		
Carbon -14		0.7		
Tritium		0.001		
	Subtotal	2.0		
Medical X-rays				
Diagnostic		55		
Therapeutic		5		
Radio pharmoceuticals		1.2		
Occupational		1		
Dials, TV, etc.		2		
	Subtotal	64		
	Total	180	to	220

Residents, Big Rock Vicinity	
External	0.65
Internal (ingestion)	1.

The last numbers apply to residents within 50 mile radius from the plant. Note that the radiation dose is comparable to that from miscellaneous sources, such as TV, luminous dials, etc.

Problems and Questions

1. An interviewer once expressed unconcern about fusion plants because only a "few grams of tritium are involved." Calculate the number of curies in 1 gram of H-3.
2. Calculate the number of curies in one microgram of (a) U-238, (d) Sr-90.
3. Concentration of the rare gases in the atmosphere are as follows:

Neon	08×10^{-6}	(by volume)
Helium	5.2×10^{-6}	
Krypton	1×10^{-6}	
Xenon	0.08×10^{-6}	
Radon	0.06×10^{-12}	

a. Calculate the number of stable (non-radioactive) krypton atoms per cubic meter. Note: Avogadro's number is 6.03×10^{23} atoms/gram mole.

b. The concentration of the radioactive Kr-85 near Petoskey is estimated to be about 5×10^{-9} microcuries/cubic meter. What is the concentration of Kr-85 atoms per cubic meter? Half-life of Kr-85 is about 10.4 years.

REFERENCES

1 - KASTNER, J. *The natural radiation environment.* Washington, D. C., USAEC, 1968.

2 - LIEBERMAN, J. A. Ionizing-radiation standards for population exposure. *Physics to-day,* New York, 24 (11):32-8, 1971.

3 - WIEDER, S. et alii. Environmental radioactivity in Michigan, 1970. *Radiat. Data Rep.* 13 (1):3, Jan. 1972.

4 - ADAMS, J. A. S. & LOWDER, W. M., eds. *The natural radiation environment.* Chicago, Univ. Press, 1964. (CONF-136).

5 - AYERS, J. C. Lake Michigan environmental survey. *Spec. Rep.* (49), Nov. 1970.

6 - COPELAND, R. A. & AYERS, J. C. *Trace element distribution in water, sediment, phytoplankton, zooplankton, and benthos of lake Michigan:* a baseline study with calculations of concentration factors and buildup of radioisotopes in the food web. Michigan Env. Research Group, May 1972. (Inc. report)

7 - FIELDS, P. R. et alii. Np-237 and U-236 found in lunar samples. *Nucl. News,* Hinsdale, Ill., 15 (2):44, 1972.

CHAPTER VI

Appendix

Comment 1.

Comments made by an editor of the St. Louis Dispatch back in 1903 are interesting. The occasion was the 1904 St. Louis World Exposition at which a small amount of radium was to be on display. The editor wrote:

> "It is even possible that an instrument might be invented which at the touch of the key would blow up the whole earth and bring about the end of the world."

Comment 2.

Of course no discussion of natural radioactivity would be complete without some comments on Brasilian radioactivity. Brazil nuts, etc. There are two radioactive hot-spots in the world.One is in the Kerala region of India. The other is Brasil.

A good discussion of the Brasilian natural radioactivity can be found in Chapter 7 of Eisenbud's text on **Environmental Radioactivity.** More details are given in two papers appearing in **The Natural Radiation Environment,** edited by J. A. S. Adams and W. M. Lowder, Chicago Press, 1964. Reports indicate that programs investigating the effects of this radioactivity are in progress. For example in Health Physics 19, 657 (Nov. 1970), there is a paper by E. Penna-Franca and others on the "Radioactivity in the Diet in High Background Areas of Brazil". These studies indicate that the Ra-228 (from Th-232) body burden of high-intake group in Tapira is about 1000 times above normal, and that the Ra-226 (from U-238) is about 10 times that of those living in normal areas of Tapira. The paper states that chromosome studies are in progress.

CHAPTER VII

Recent Advances in Environmental Radiation Monitoring

> "That's what's so frightening about radiation. It's not pink or blue or purple. It's just not visible".

1. Comments

The concerns for the effects of radiation on human beings dates back to the end of the last century. The announcement of the discovery of x-rays was made by W. Roentgen on November 8, 1895. But before that date many individuals were experimenting with high voltage electric discharge in vacuum tubes, and one of the manufacturers of such tubes-called Crookes tube, after the discoverer, Sir William Crookes-was an E. H. Grubbe, who by January 27, 1896 received enough radiation to develop acute dermatitis, which later developed into skin cancer and he then had to have his hand amputated. By 1925, the potential dangers of x-rays were well known. A grim reminder of the radiation dangers is the monument erected in Berlin in memory of the doctors who died as victims of x-rays.

In 1928, the International Society of Radiology sponsored the International Commission on Radiological Protection (ICRP) which since that date has been one of the organizations setting and revising radiation standards. But the dose limits that were considered safe in those early days are very high in comparision to modern standards. For example, between 1925 and 1932, the accepted limits of radiation dose was from about 0.04 to 2.0 roentgen/day.

According to the latest standards, the occupational exposure is to be limited to 5000 m rem/yr, the maximum dose rate an individual of the public-at-large is 500 m rem/yr, and the average population exposure is not to exceed 170 m rem/yr. In addition, the recommendation was made that the radioactive emissions from nuclear power plants be kept as "low as practicable". This recommendation led the AEC in June 1971 to set 10 m rem/yr as the so-called nuclear power plant fence-post valve.

This reduction in the allowed radioactive emission levels is placing some severe demands upon radiation detection instruments. To date the electric utilities have relied mostly on the so-called TLD's, i.e. the thermoluminescent detectors, with occasional use of ionization chambers. In the very near future, the ionization chamber will become the standard equipment, augmented by the more sophisticated instruments known as the NaI scintillation detector and the Ge (L_i) detector, i.e. the lithium drifted germanium detector. The purpose of the discussion to follow will be to discuss some of the recent developments in radiation detection systems, to monitor very low level radiations.

The pressure for the use of more sophisticated detection systems is coming from another direction, namely from the public. The standard comment from the utilities has been that radioactive emissions from their nuclear power plants are too low to be detected beyond the fence-post. At the same time they point out that their instruments are sensitive enough to detect the increase in atmospheric radioactivity in the spring when farmers plow their fields. But reactions to these comments are at best neutral. Intervenors talk about the invisible radiations; Ralph Nader made the same comment when addressing a group on the U of M campus. Listening to these and others, some may get the impression that there is a conspiracy to keep the radiactions from becoming visible.

To answer these criticisms, we have set the goal to build a mobile radiation monitoring station that can detect radioactive radiations coming from nuclear power plants five to ten miles away. The problem will not be an easy one, because as we have seen, the background natural radioactive radiations and the man-made fallout radiations are expected to be very large in comparision to those coming from nuclear power plants. But it can be done, and our hope is that when we do so we will be able to allay the fears that some have towards nuclear power plants.

2. TLD (Thermoluminescent Detector)

We began by discussing this type of detector. It consists of components like L_iF and $CaSO_4$. The mechanism for thermoluminescence is briefly as follows. Electrons in the valence band are excited into the conduction band by energetic radiations, such as alpha particles, beta particles, x-rays, and gamma rays. The electrons wander about in the conduction band for a short time, some will return to the valence band but others will become trapped at impurity or even crystal defect sites. We can compare the incoming radiation to a gust of wind, setting up a spray, whose droplets might get caught on a rock, a leaf, or other objects. The electrons trapped on the impurities or at defect sites will slowly return to the valence band, but their return can be accelerated by warming the crystal. This is the reason for the word element "**thermo**". As the electrons return to the valence band, the excess energy is given off as visible radiation, i.e. the crystal will luminesce.

Some of the research carried out in our laboratories have provided definitive information about the mechanism for thermoluminescence. The material chosen four our study was calcium tungstate ($CaWO_4$), a material of high luminescence efficiency and also a good laser material. For laser action the material is doped with the rare-earth neodynium (Nd), which in turn is stabilized by adding another dopant, namely niobium (Nb). If such a crystal is irradiated in the Co-60 source, or even the reactor, where the gamma radiation intensity is high, while the crystal is refrigerated in liquid nitrogen, we were able to show that the electrons get trapped in the neighborhood of the niobium impurities. If the crystal is then warmed, it will glow green, and by a careful analysis we were able to show that the electrons return to the valence band from the niobium centers via the tungsten defect center.

The usefulness of TLD as radiation dosimeters stem from the fact that the amount of light it gives off after warming-its thermoluminescence-depends upon the radiation dose, i.e., larger the radiation dose, larger is the amount of thermoluminescence. The devices are simple, rugged, and can be small enough to be carried around. It can be used to detect radiation dose of about 1 m rem in one month, so that its limiting sensitivity is comparable to the AEC radiation standards of about 1 m rem/month. But at these low doses, the errors can be quite large if commercially available equipment were used. The estimated uncertainties is about 50 m rems/yr, unless unusual precautions are taken in handling, transportation, and readout of the dosimeters. The other limitation is that the TLD registers the total radiation dose regardless of the source, and hence is useful in areas where the nuclear power plant radioactive emissions are large in comparison to natural radioactivity. A TLD is unable to distinguish the radiation from Kr-85, a nuclear fission product from a nuclear power plant, from that of K-40, say, which is part of our environment.

3. Ionization Chamber

The advantage of this detector over TLD is its sensitivity, of about 1 m rem/yr in comparison to 50 m rem/yr for the latter. The chamber consists of argon gas under high pressure. The incoming radiation ionizes the gas in the chamber, producing a small electric current to flow. The current is directly proportional to the radiation intensity.

The usefulness of this device for monitorin **total** radioactive emissions from nuclear power plants is discussed in papers presented at an International Symposium on Rapid Methods for Measuring Radioactivity in the Environment, Neuherberg, Germany, 5-9 July 1971. The results prescribed by Beck and others in the June 1972 issue of Nuclear Technology is noteworthy. Fig 2 in this paper for example, gives a record of radiation dose rate at a point inside the fenceline of an unspecified boiling water type nuclear power plant. The line is plotted along the horizontal, the record starting at noon on day 1. About 24 hours later, we notice that there was a pulse of radioactive emission and then some more 20 hours later. The vertical is the dose rate given in microrems/hr. Notice that there is a steady background radiation, amounting to about 9 μ rems/hr, or about 79 m rem/yr. The results of Fig 4 are even more striking. The figure gives the radiation dose rate record during one week at these different places. The site A is a point inside the fence-line, site B a point about one and a quarter mile away, and C several miles away. At each site, the radiations from the nuclear power plant can be identified by the line dependence. These are spikes appearing above a steady base line caused by natural radiation. By means of such instruments radiation dose rates of about 0.8 m rem/yr above natural radiation background can be measured. This is about 17% of the natural background.

A shortcoming of the ionization chamber is that it also measures total radiation and does not distinguish the sources. For example, a farmer working in a nearby field could cause an increase in the instrument readings. Ideally then we also need an instrument that can distinguish the sources from which the radiations are coming.

4. NaI (Tl) Scintillation Detector

The principal merit of this detector is that it is a spectrometer, capable of partially identifying the sources from which radiations arise. This device is rather complex. The detector consists of the luminescent material NaI doped with a small concentration of thallium (Tl), a photocathode, and an electron multiplier. The purpose of NaI is to convert the energy of the incoming radiation, say a gamma ray, into flashes of light, called scintillations. These flashes of light strike the photocathode, causing electrons to be emitted; the mechanism-and even the material-is similar to that of TV cameras. These photo-electrons are then amplified by means of the electron multiplier.

A typical gamma spectrum of backgroud radioactivity is given on p. 506 by Beck and others in the 1971 International Symposium Proceedings. Note that there are several fairly prominent peaks. The one of the highest energy is due to the 2.62 MeV gamma rays from Tl 208. This is one of the progenies of Th-232 that occurs naturally. Going to lower energies, there is the 1.76 MeV peak due to Bi-214, called also Radium C, which is a decay product of U-238. The next lower peak is K-40, which as stressed already, is everywhere, including our body tissues. There thus is a weak peak assigned to the fallout fission products Zr-95 and Nb-95 and then a somewhat stronger peak due to the 0.662 MeV gamma ray from still another fallout fission product Cs-137.

The limitations of the NaI (Tl) scintillator is relatively poor resolution. For example, we note this detector connot distinguish the Zr-95 0.724 and 0.757 MeV gamma rays from the Nb-95 0.768 MeV gamma ray.

5. Ge (Li) Detector

Substantially greater resolutions are obtained by means of this germanium semi-conductor detector. The device is a germanium PN junction and the detection mechanism is somewhat similar to the photovoltaic effect in the silicon solar cells. For these, the energy from the sun is used to create electron and holes, which drift across the PN junction, giving rise to a pulse of current in the external circuit. For the Ge (Li) detector, the energy to create the eletrons and holes came from the gamma rays. A very striking result is prescribed in the paper by Beck et al. This gives the details of the lower one-third of the spectrum taken with NaI (Tl) scintillator. The two prominent peaks at the high end of the spectrum are due to actinium-228, one of the decay products of Th-237. Notice now that the Zr-95 0.757 MeV gamma is clearly distinguishable from the Nb-95 0.768 MeV gamma ray. Note also that the Cs-137 0.662 MeV gamma is clearly resolved from the Bi-214 0.609 MeV line, so that the relative heights of these peaks could be used to determine the effects of fallout contamination.

Another striking result also obtained by Beck and others, shows the effects of wind direction upon radioactivity. The spectrum given by the solid line was taken at the fence line of a BWR when the wind was carrying the effluent plume away from the measurement location, and the dotted line shows the changes when the plume was overhead. The unmarked peaks are due to natural radioactive materials or fallout fission isotopes mentioned earlier. Notice that when the plume is overhead, there is a small increase in radioactivity, and the additional radioactivity can be traced to the effluent gases such as Kr-87, Kr-88, Xe-135, and even Cs-138.

6. FIDLER (Field Instrument for the Detection of Low Energy Radiation)

This instrument also reported at the International Symposium has the capability of detecting Xe-133 released from radioactive decay holding tanks. At a distance of 0.4 mile away from a pressurized water reactor (PWR), releasing Xe-133 at the rate of 3000 microcuries/sec., the instrument response was about 6 times the background reading. The Xe-133 in the plume even at a distance of 1 mile was easily detectable. The greater sensitivity of this instrument is achieved by using NaI (Tl) and by use of fillers.

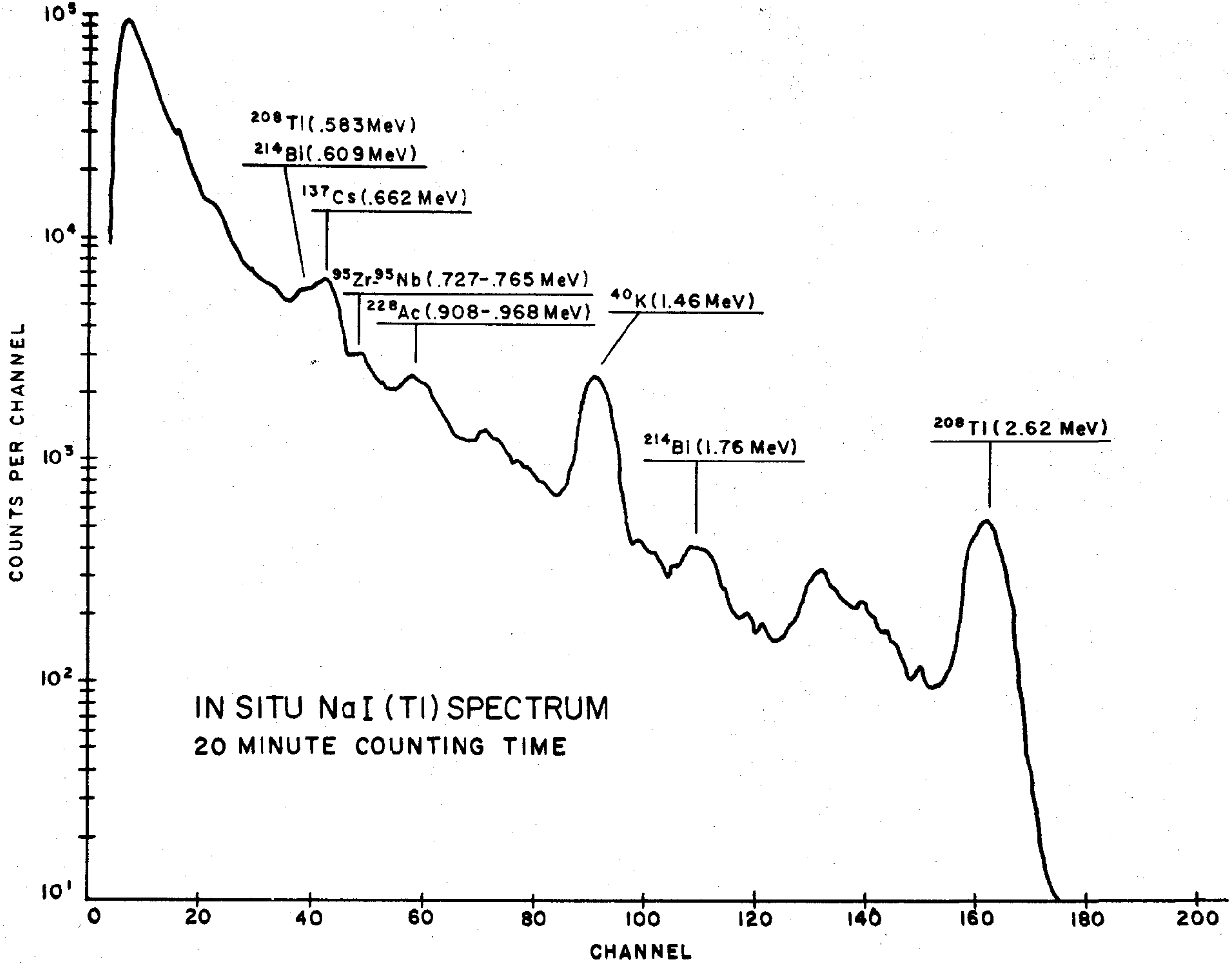


Figure 6. *In situ* spectrum, northeastern U.S.A. location, taken in 1971 with 10 cm by 10 cm NaI(Tl) crystal, 20 minute counting time.

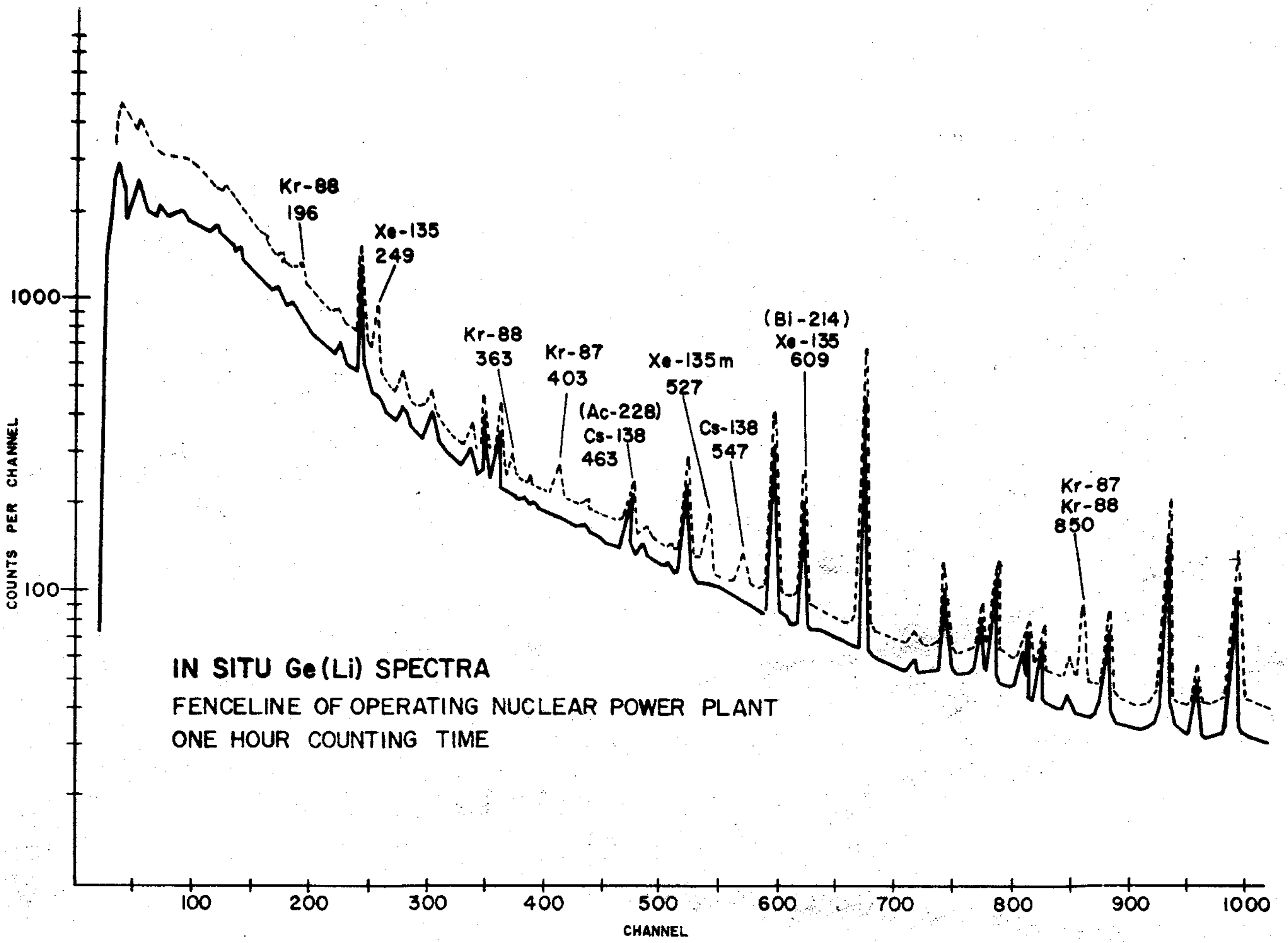
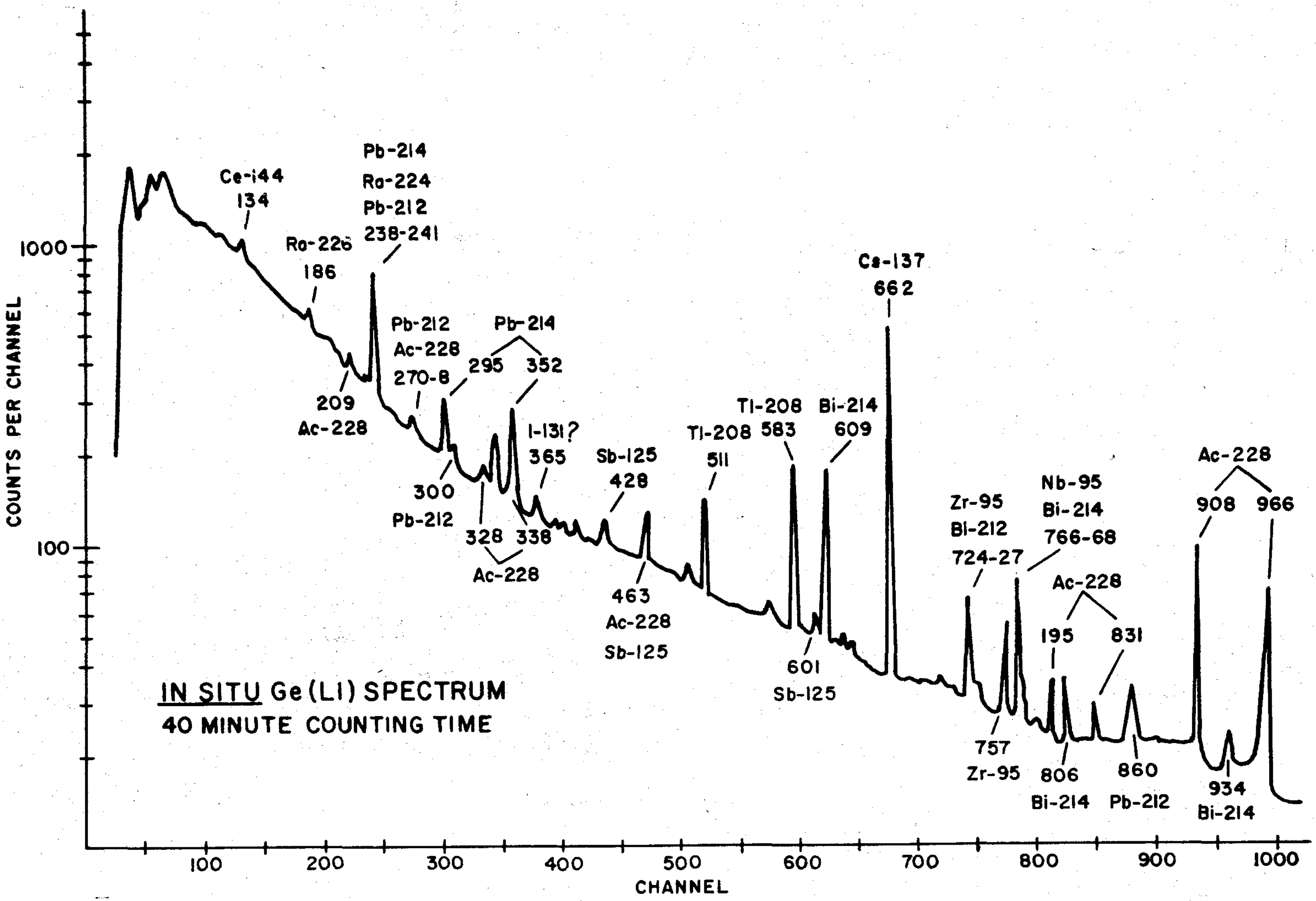
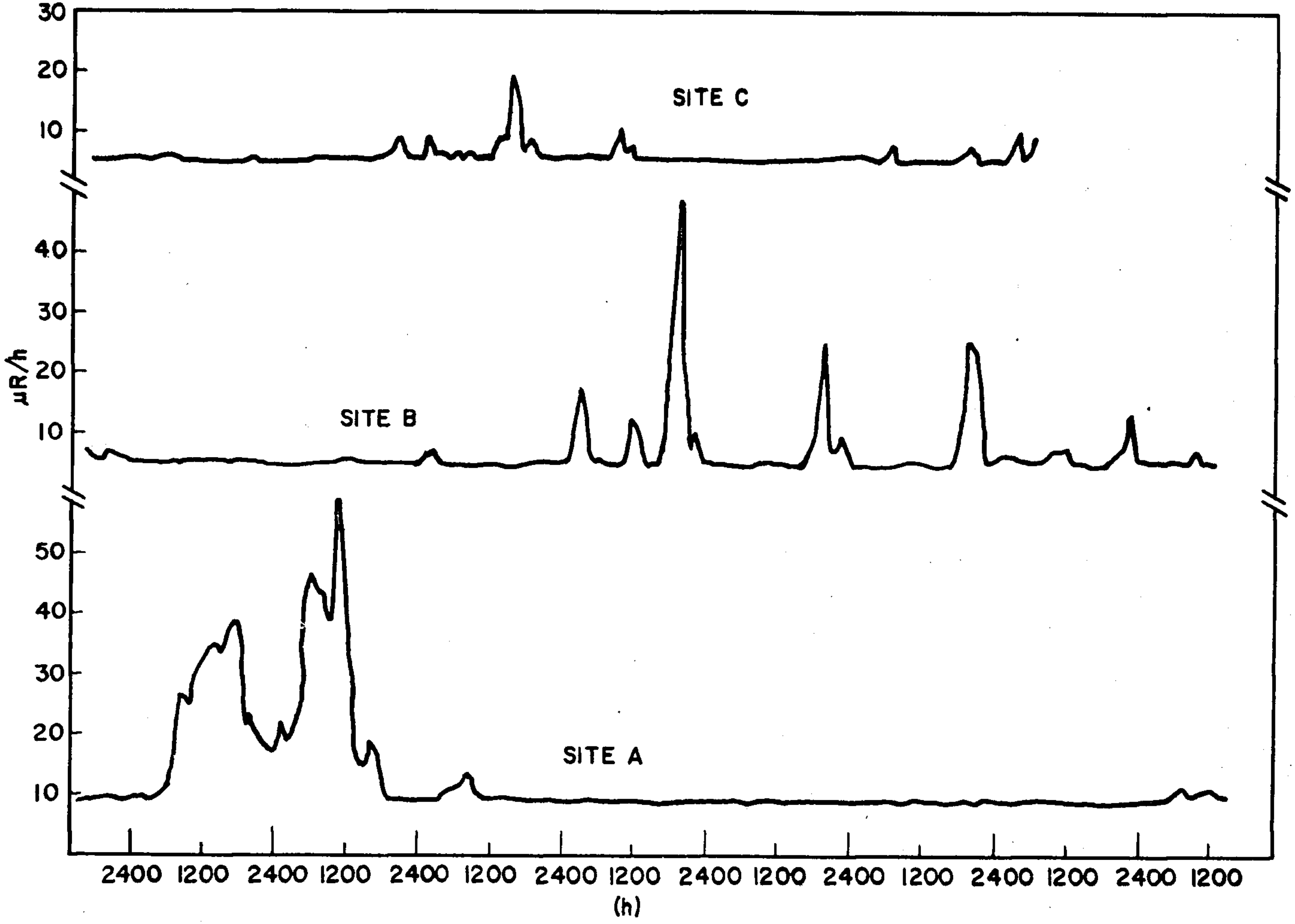


Figure 8. IN SITU Ge (Li) SPECTRA AT FENCELINE OF BOILING WATER REACTOR. UPPER SPACTRUM WITH GASEOUS PLUME OVERHEAD, BOTTOM SPECTRUM WITH WIND BLOWING AWAY FROM DETECTOR.



IN SITU Ge (LI) SPECTRUM
40 MINUTE COUNTING TIME


30
20
10
SITE C
40
30
20
10
SITE B
µR/h
50
40
30
20
10
SITE A
2400
1200
2400
1200
2400
1200
2400
1200
2400
1200
2400
1200
2400
1200
2400
1200
(h)

REFERENCES

1 - INTERNATIONAL ATOMIC ENERGY AGENCY, Vienna. *Rapid methods for measuring radioactivity in the environment:* proceedings. . .held in Neuherberg bei München, 5-9 July 1971. Vienna, 1971.

2 - BECK, H. L. et alii. New perspectives on low level environmental radiation monitoring around nuclear facilities. *Rector Tech.,* 14:232, June 1972.

3 - DeCAMPO, J. A. et alii. *High pressure argon ionization chamber systems for the measurement of environmental radiation exposure rates* New York, USAEC, Health and Safety Lab., Dec. 1972. (HASL-260).

4 - BECK, H. L. et alii. *In-situ (Ge(Li) and NaI(T1) gamma ray spectrometry.* New York, USAEC, Health and Safety Lab., Set. 1972. (HASL-258).

5 - MASON, D. R. et alii. Identification of defect sites in $CaWO_4$ from the correlation of ESR and thermoluminescence measurements. *Phys. Rev. Lett.,* New York, 20:451-2, 1968.

6 - PHELPS, P. L. et alii. *Ge(Li) gamma ray spectrometers of high sensitivity and resolution for biological and environmental counting.* Livermore, California Univ., Lawrence Radiation Lab., May 1968. (UCRL-50437).

7 - ANSPAUGH, L. R. et alii. *Field spectrometric measurements of radionuclide concentrations and external gamma exposure rates at the Nevada Test Site:* a demonstration study. Livermore, California Univ., Lawrence Radiation Lab., July 1973. (UCRL-51412).

8 - INTERNATIONAL ATOMIC ENERGY AGENCY, Vienna. *Advances in Physical and biological radiation detectors:* proceedings of a symposium. . . held in Vienna, 23-27 Nov. 1970. Vienna, 1971.

9 - KARCHES, G. J. et alii. Field determination of dose from Xe-133 in the plume from a pressurized water reactor. In: INTERNATIONAL ATOMIC ENERGY AGENCY, *Rapid methods for measuring radioactivity in the environment:* proceedings. . . held in Neuherberg bei München, 5-9 July 1971. Vienna, 1971. p. 515-23.

CHAPTER VIII

Radiation Doses and Effects

> "The intriguing observation that radiation may be necessary for life itself, perhaps as a stimulant has been suggested both in analysis of some experimental observations of plants and by at least one set of experiments in which a frog heart maintained in nitro continued beating when a radioactive isotope of potassium was a component of its nutrient but stopped when this component was replaced by a non-radioactive potassium isotope; when the radioactive isotope was again used, the heart resumed its beating".
>
> H. E. Henry
> Fundamentals of Radiation Protection,
> p. 133

1. Comments

In Chapter 5 of the Environmental Report the environmental impacts of power plant operation need to be discussed. Sections 5.2 and 5.3 deal with the biological impact on biota and man respectively. The headings of subsections include words like exposure pathway, radioactivity in the environment, dose rate estimates, etc. The various routes by which radioactive materials can find their way to man are shown schematically in Appendix 2, 4.2-72 of the Guide. The key word is bioconcentration. What we need to bear in mind is that bioconcentration is an essential mechanism in supporting life, so that the bioconcentration of radioactive materials is critically tied to the chemistry of the environment. This point is too often overlooked and hence will be discussed in some detail in the discussion to follow.

Also certain historical facts need to be kept in mind. Words like environment, ecology, pollution, etc., have become household words since about 1970. But for mamy years before that, both national and internation nuclear energy organizations have been concerned with the environmental impact of radioactive materials. Perhaps one of the first papers to consider the problem of bioconcentration was published in 1952. The publication date of the NAS-NRC report on "The Effects of Atomic Radiation on Oceanography and Fishes" is 1957. Volume 18 of the 1958 Proceedings of the Second International Conference on the Peaceful Uses of Atomic Energy is devoted exclusively to the topic of Waste Treatment and Environmental Aspects of Atomic Energy.

Consequently, the purpose of the discussion to follow will be to study the information gathered during the past two to three decades, in order to evaluate the merits of the criticisms by some of the opponents of nuclear power.

2. Natural Radioactivity

For emphasis, a pictorial representation of the radiation environment in which we live, appearing on p. 30 of the 1957 NAS—NRC report is reproduced on the next page. Note that the radiation background increases with altitude, due to the increased intensity of cosmic radiations, being about 0.207 rad/yr at 10,000 ft. and the least on sea, where it could drop to a value as low as 0.052 rad/yr. There are, as noted earlier, localities where background radiation level is abnormally high, such as in parts of India (0.2 - 2.6 rad/yr) and in parts of Brazil where doses up to 12 rad/yr have been recorded.

An intriguing experiment, suggesting the need of nuclear radiation to sustain life, has been reported by Hungarian ivestigators, E. Eernst, J. Tigyi, and A. Niedetzky in vol. 24, p. 189 of the 1958 Second U. N. International Conference on the Peaceful Uses of Atomic Energy. The following comments appear in their paper:

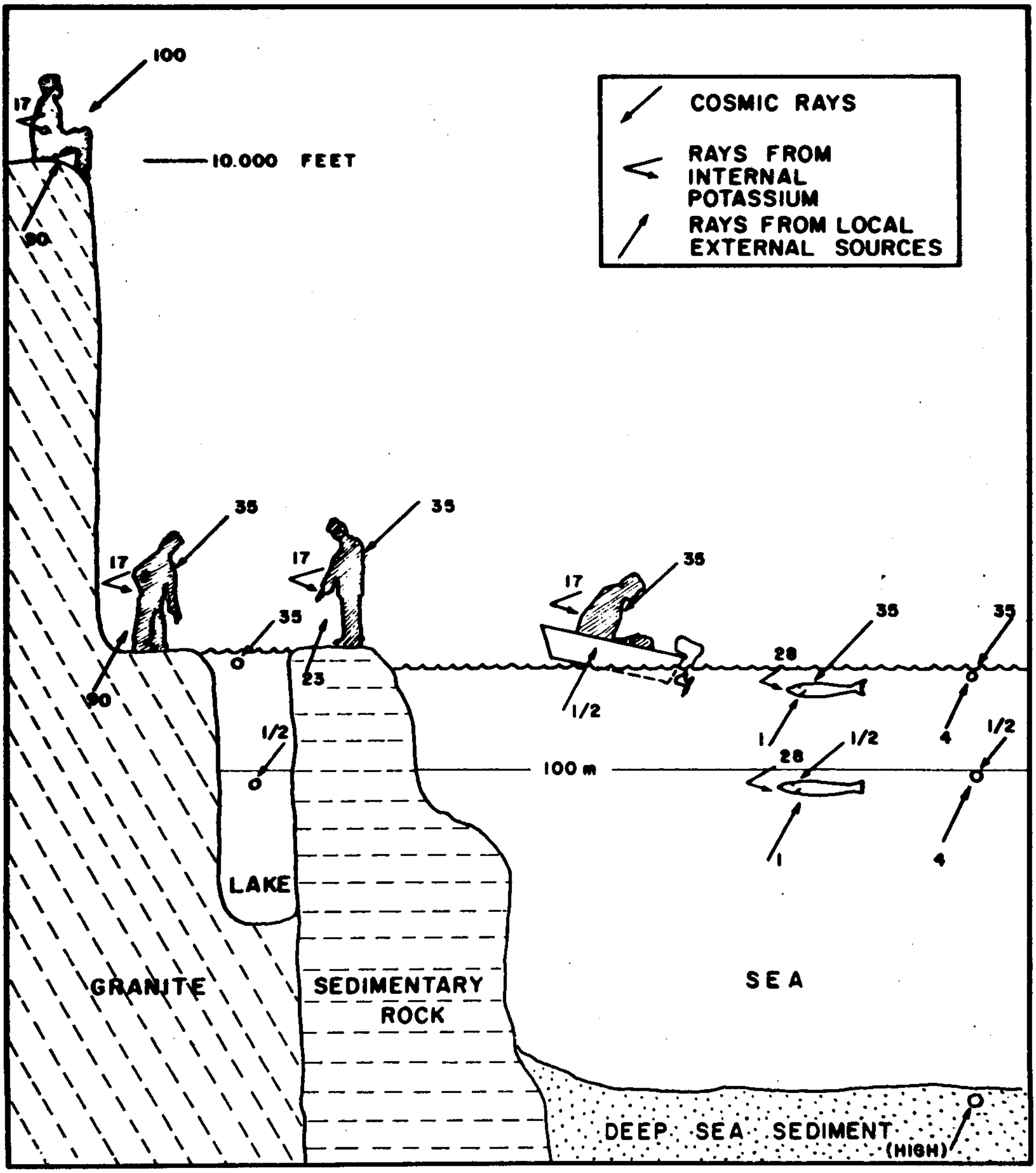
> "In our experiment, the isolated frog heart (Straub) was promptly arrested by changing over from normal Ringer to a solution in which a corresponding amount of NaCl was replaced by 0.3% KCl. If this K-rich Ringer solution is replaced by another of the same composition, but containing K-42, the arrested heart starts beating. The heart can be repeatedly arrested and restarted by replacing the potassium-rich Ringer without K-42 with another of the same potassium concentration containing K.42. The K-42 can be replaced by Na-24 or P-32. The sensitivity of individual hearts varies greatly, and in many experiments negative results were obtained. Nevertheless, the 250 experiments perfomed during all seasons of the year indicate that radioactivity, and especially the beta rays of K-42, Na-24, and P-32, are responsible for restarting the heart arrested by a potassium-rich solution".

Note that the human body contains slightly more K than Na, namely about 140 gms and 105 gms respectively, whereas K/Na ratio in sea water is about 0.038. Sodium consists 100% of the non-radioactive Na-23 isotope. Potassium, on the other hand, consists of K-39 (93.08%), K-40 (0.0119%), and K-41 (6.91%), of which the first and last are stable, but K-40 is radioactive with half-life of about 1.25B years. K-42, referred to in the quoted paper, is radioactive having half-life of about 12 hours. It would be interesting to repeat to check the experiment.

In addition to radiation from natural sources, there are certain man-made sources. Estimates of doses from the different sources are as follows:

Man-Made Sources	**rad/yr**
A. Medical Procedures	
1. Diagnostic x-rays	.050
2. Radiotherapy	.010
3. Internal diagnosis	.001
B. Nuclear Ind. Lab.	.0002
C. Lum. Watches, T. V., Radioactive Materials Waste	.002
D. Radioactive Fallout	.004
	.067 rad/yr

Note that the bulk of the radiations from man-made sources arises from medical practices. For this reason, the recent (Nov. 1972) NASNRC report stresses the need of reducing radiation in the practice of medicine. (See also the last paragraph in the N. Y. Times article, Nov. 16, 1972).



TOTAL NATURAL DOSES (mrad/year)

MAN OVER GRANITE		MAN OVER SEDIMENTARY ROCK	MAN OVER SEA	LARGE FISH IN SEA		MICRO-ORGANISM IN SEA	
10.000	m.s.l.			AT SURF	100 m	AT SURF	100 m.
267	142	75	52	64	30	39	5

3. LD-50 Lethal Dose-50% Mortality).

This is taken to be 450 rems, i.e. 50% of the individuals exposed to this radiation dose are expected to die. Certain details of radiation effects on living organisms are given in Lapp's book, **Radiation.**

For example the LD-50's for several species are as follows:

Guinea Pig	175-250
Dog	325
Goat	350
Man	400-450
Mouse	530
Rabbit	800
Weevil	1,000-2,000
Bacteria (spore-forming)	20,000-50,000
Virus	50,000-1,000,000

The effects of several levels of radiation dose are as follows:

a) 0-25 No observable effects produced directly.
b) 25-50 Blood change, as manifested by blood count.
c) 50-100 Symptoms of radiation sickness, temporary blood change, full recovery of body function within a few days.
d) 100-200 Radiation sickness in about 25% of exposed group. Probably no death attributable to radiation. Possibly disability due to radiation effects.
e) 200 50% radiation sickness, about 2% death.
f) 300 90% radiation sickness, 25% radiation death.
g) 400-500 Lethal dose to 50%.
h) 600 or more Nearly all exposed expected to die within 30 days.

To obtain a better feeling for these radiation doses, we need to keep in mind that within a radius of about 3 Km of an exploding atomic bomb, the radiation dose can be between 200-600 rem. For the 23 Japanese fishermen on the tuna trawler Lucky Dragon 5, which had become accidentally contaminated by the fallout from the March 1, 1954 H-Bomb test, the radiation dose is estimated to be about 200 rem; one fisherman died about 6 months later from causes "diagnosed as liver disorder". Excellent discussion of case histories can be found in Chapter 7, **Atomic Accidents** by Schubert and Lapp.

There is also an amusing side to the fishermen story. Japanese scientists analyzed the radioactive ashes on Lucky Dragon 5, identified a radioisotope Np-237, which is produced by the (n, 2n) reaction of U-238, as had been discovered by Prof. Nishina before the outbreak of World War II. From the existence of Np-237, the Japanese worker inferred that the cheap U-238 had been used to increase the explosive power of the atomic weapon. The results were published, discussed by scientists all over the world, and by U. S. scientists who were not connected with the bomb development. The ones who had worked on the project, however, were unable to discuss the matter because the information was still classified.

4. Medical Radiation Doses

To emphasize the dangers of radiation, Gofman and Tamplin in their book on **Poisoned Power** show several pictures of documented cases of effects of x-rays. We need to keep in mind that they are arguing for radiation standards lower than the 0.170 rad/yr as the average dose to the general public, but that these illustrations have to do with exceptionally high doses. On p. 38, they show the hand of a physician, and the caption underneath states that the physician was exposed to "small doses" of x-rays for 15 years. The point we need to keep in mind is that the so-called small x-ray doses can be large-by modern nuclear standards-and probably the effects were the result of over a thousand rads of x-ray dosage. The large rate skin tumor shown on p. 51 is probably the result of 5000 rads of beta radiation, since the same photograph appears in R. E. Zirkel's **Effects of External Beta Radiation**, p. 210. The photographs of the tissue cultures on p. 65, showing the effects of radiation on tissue cells were taken from a paper in the Scientific American (April 1960), in which radiation doses varying from 50 to 10,000 rads were used.

Thus, these pictures show what high levels of ionizing radiation will do, but we do not really know what low levels of the same radiation will do.

5. Biocentration

This is a problem of concern to the public and comes about because of the ability of living organisms to concentrate minerals essential for their existence. Living organisms need Na and K, so that if the environment is deficient in these materials, it will tend to concentrate and use other elements of Group IA (Na, K, Rb, Co) of the Periodic Table of Elements. Ca is essential, so that Sr tends to be assimilated along with it, because both are Group IIA elements (Ca, Sr, Ba, Ra).

We have already encountered one example of bioconecentration, in setting the $(MPC)_w$ (maximum permissible concentration in water) of Sr-90. The human body contains about 0.14 gms of non-radioactive Sr (Sr-84), 0.5%; Sr-86, 9.86%; Sr-87, 7.02%; Sr-88, 82.56%) compared to 1,050 gms of Ca. The body Sr/Ca ratio is about 1 part to 10,000, compared to the 1 part in 1000 in the earth's crust. Thus, there seems to be a slight tendency for the body to reject Sr. If Sr-90 is in the water used for cooking and drinking, a fraction will become assimilated mainly into our skeletal system. The radiation standards are set so that if a person were to use the Sr-90 contaminated water for all cooking and drinking, the total amount accumulated in the body after **many** years will not exceed 2 Ci. The amount in the body will increase according to the relation of radioactivity.

$$N = (2\ \text{Ci}) \left[1 - 2^{(t/T_{eff})}\right]$$

in which

$$T_{eff}\ \frac{T_{1/2}T_B}{T_{1/2} + T_B} = \frac{28\ (35.6)}{28 + 35.6} = 16\ \text{yrs.}$$

EFFECTS OF EXTERNAL BETA RADIATION

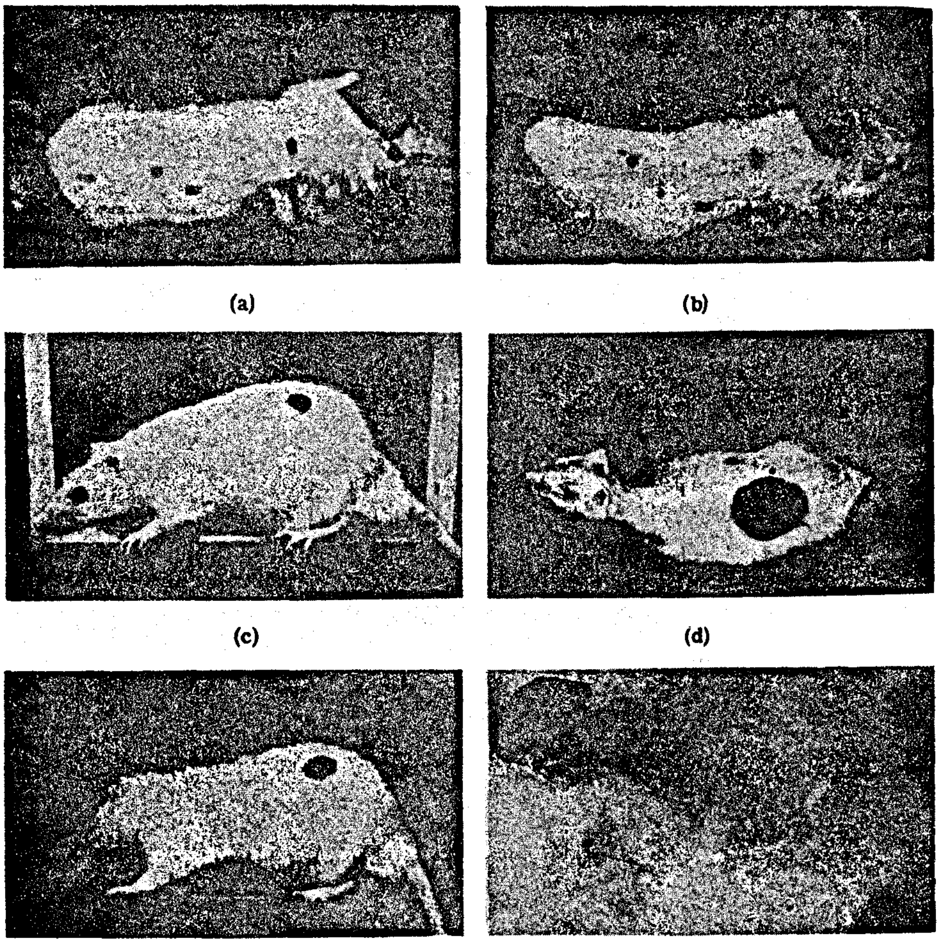


Fig. 13.5—Tumor induction in rats with single doses of beta rays. (a) Note distribution of tumors along median dorsal band; 4000 rep on Oct. 26, 1944. (b) Subcutaneous tumor; 4000 rep on Oct. 26, 1944. (c – e) Developmental sequence; 5000 rep on Oct. 28, 1944. (f) Detail of small warty tumors shown in e.

Thus 16 years after starting to live on Sr-90 contaminated water, the amount in the body will be 0.5 Ci; in 32 years, 1.5 Ci; etc. To insure that the total amount after a long period of time will not be more than 2 Ci of Sr-90, the $(MPC)_w$ or Sr-90 is set at 0.5×10^{-6} Ci/cm^3.

Some of the concentration factors for fish are listed in the following table:

Element	Conc. in Sea Water g/1	Conc. Factor		Conc. in fresh water / Conc. in sea water	Fresh water Conc. Factor
		Soft	Skel		
Na	10^7	0.07	1	6.3×10^{-4}	100
K	3.8×10^5	5	20	6.0×10^{-3}	
Cs	0.3	10		6.7×10^{-2}	9000
Ca	4.1×10^5	1	200	3.7×10^{-2}	
Sr	8×10^3	1	200	1×10^{-2}	20,000
Fe	3	1000	5000	200	100
P	90	40,000	2M	.2	100,000

From the above table, we notice that the concentration factors in fresh water are high if the mineral concentration is low. Thus, for Na, in sea water, the soft tissue actually rejects it (concentration factor is less than 1) whereas in fresh water, it is concentrated. For Cs the concentration factor is high because K concentration in fresh water is generally low. An interesting point to note is that the K/Na ratio in sea water where living organisms originate is about 0.038, whereas living tissues require about the same amounts. For P, the fresh water/sea water ratio is not very different from 1, so that the problem of P-32 assimilation by marine animals and plants becomes important. For Fe, we note that the concentration factor in sea water is greater than in fresh water.

The concentration factor depends upon a complex set of conditions, such as the chemical and physical state of the elements in the environment, chemical composition of the organisms, concentration in the environment, specific activity (radioactive isotope/all isotope of same element), presence of other elements, etc., so that there does not appear to be any simple countermeasure.

On land, radio-concentration also occurs and the problem of I-131 and Sr-90 has been investigated in considerable detail. Some possible countermeasures are discussed in the monograph by Garner on the "Transfer of Radioactive Materials from the Terrestrial Environment to Animals and Man".

6. Radiation, Leukemia, and Cancer

Gofman and Tamplin (**Poisoned Power**) claim that the present radiation standard of 0.17 rad/yr for the population average will produce about "32,000 extra cancer and leukemia deaths". The recent NAS–NRC report claims that the number is more likely to be 5,000 to 7,000 range (See p. 91). And R. E. Lapp, in the third of his articles on the Nuclear Plant Controversy (New Republic, Feb. 27, 1971) estimates "5 extra cancer deaths per year and probably less than 1".

Our problem is to see how these widely different estimates arise.

The steps by which Gofman and Tamplin arrive at the number 32,000 extra cancer deaths per year are given in the Tamplin and Gofman, **"Population Control" Through Nuclear Pollution.** They start with the estimate that the leukemia risk is between 1 and 2 per million exposed population perrad per year. The estimate comes from ABCC (Atomic Bomb Casualty Commision) study of the Hiroshima and Nagasaki bomb survivors. This is a generally accepted value for radiation induced leukemia risk, but qualification is made that the above risk rare strictly speaking applies to whole-body doses of the order of 100 rads or more and that the number need not necessarily apply to low doses and low dose rates. For low doses and low dose rates, body defense mechanisms could possibly repair the damage produced by radiation, but for the sake of safety, the high value of risk rate is used. Since the U. S. leukemia rate is about 60 per million per year, the upper limit of additional leukemia cases per rad is between 100/60 - 1.7% and 200/60 - 3.3%. The value 2% is often used.

Tamplin and Gofman point out furthemore that radiation produces not only leukemia but also other forms of cancer, at possibly the same rate. The U. S. spontaneous rate of cancer occurence is about 320,000 cases/yr., so that a dose of 1 rad/yr would lead to about 6,400 new cases each year. Since according to the present radiation standards, 5 rads in 30 years are permitted, the extra cancer cases amount to (6,400) (5) = 32,000. The inconsistancy, of course, is that this is the number of new cancer cases to be expected during the 30 year period, and is not the rate of new cases occuring every year.

The altenative approach using a more complex model is presented on pp. 167-174 of the NAS–NRC report. The analysis suggests that the most likely value to be approximately 3,000-4,000 cancer deaths, or a 1% increase in the spontaneous rate, if the U. S. population is exposed to 100 mrad/yr radiation. For 170 mrad/yr exposure, the above estimate should be increased to 4,100-6,800 per year.

In the above analisys, it is assumed that by some means or another, the radiation background increases by 170 mrad/yr, or almost double the radiation dose rate we receive now. In R. E. Lapp's analysis, it is pointed out that the excess radiation level cannot be anywhere close to the permitted level of 170 mrad/yr, if the radioactive release rate is limited to 500 mrad/yr at the fence post 100 m from the nuclear reactor stack. As indicated earlier, the radiation level falls off very rapidly with distance, so that if the number of nuclear plants is small, the radiation level will not be much above natural radiation level. Lapp's result is based on 300 nuclear power plants.

There have been assertions that all forms of cancer are induced by radiation. Statistics, however, seem to contradict this statement. For example, the new leukemia cases in the U. S. is reported to be 60 per million population per year. If we assume that these cases arise from natural radioactive radiation (125 mrad/yr = 1/8 mrad/yr) then the leukemia risk at low dose rate turns out be

$$\frac{60}{1/8} = 480 \text{ per million/rad}$$

which is substantially larger than the high dose rate leukemia risk of 2 per million per rad per year, Or stated differently, if it is assumed that the low dose rate leukemia risk is also 2 per million per rad per year, then the natural radiation background of 1/8 rad/year would account for about

$$2 \times 10^{-6}\ (200 \times 10^{6})\ (1/8) = 50 \text{ extra cases/year}$$

in the U. S., in comparison to the total new leukemia cases of 12,000/yr.

Furthermore, we should bear in mind that in recent years there has been a marked increase in cancer death rates and that the incidence of cancer in urban areas is much higher than in rural areas. For example, the following graph was taken from John F. Loutit's **Irradiation of Mice and Men**, p. 70. The reasons for these are not completely understood.

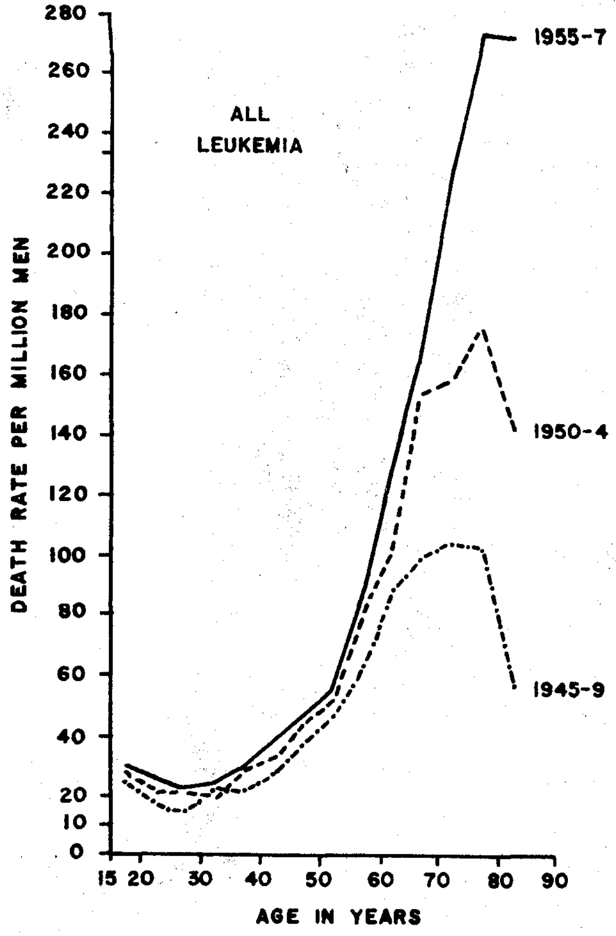


Fig. 23

Mortality from all forms of leukemia among men at different ages (from 15 years upward) in England and Wales in 1945-49, 1950-54, and 1955-57. (From W.M. Court Brown and R. Doll, in *Brit. Med. J.,* 1 (1959): 1063, Fig. 1.)

REFERENCES

1 - NATIONAL ACADEMY OF SCIENCES, Washington, D. C. *The effects on populations of exposure to low levels of ionizing radiation.* Washington, D. C., 1972.

2 - TAYLOR, L. S. Radiation protection standards. *Radiology,* St. Paul, 74:824-31, 1960.

3 - RIES, D. J. *Health physics.* S. n. t.

4 - MURRAY, R. L. *Introduction to nuclear engineering.* 2. ed. Englewood Cliffs, N. J., Prentice-Hall, 1961.

5 - RUSSELL, C. R. *Reactor safeguards.* New York, Macmillan, 1962.

6 - SCHUBERT, J. & LAPP, R. E. *Radiation: what it is and how it affects you.* New York, Viking Press, 1957.

7 - NATIONAL ACADEMY OF SCIENCES, Washington, D. C. *The effect of exposure to the atomic bombs on pregnancy termination in Hiroshima and Nagasaki.* Washington, D. C., s. d. (Publ. 461).

8 - GLASSTONE, S. *The effects of nuclear weapons.* Washington, D. C., USAEC, 1962.

9 - LAPP, R. E. The nuclear power plant controversy, 3. *New Republic*:17-21, Feb. 1971.

10 - NOVICK, S. *The careless atom.* S. n. t.

11 - ASIMOV, I. & DOBZHANSKY, T. *The genetic effects of radiation.* Washington, D. C., USAEC, 1966.

12 - ZIRKLE, R. E. *Effects of external beta radiation.* S. n. t.

13 - PUCK, T. T. Radiation and human cell. *Scient. Am.,* New York, 202:142-53, Apr. 1960.

14 - WORLD HEALTH ORGANIZATION, Geneva. *Protection of the public in the event of radiation accidents.* Geneva, s. d.

15 - UNITED NATIONS, Geneva. *Proceedings of the Second United Nations international conference on the peaceful uses of atomic energy, held in Geneva, 1 September - 13 September 1958,* v.18: Waste treatment and environmental aspects of atomic energy. Geneva, 1958.

16 - NATIONAL ACADEMY OF SCIENCES, National Research Council, Washington, D. C. *The effects of atomic radiation on oceanography and fisheries.* Washington, D. C., 1957. (Publ. 551).

17 - GARNER, R. J. Transfer of radioactive materials from the terrestial environmental to animals and man. *CRC - Crit. Rev. Environm. Contr.,* 2(3):337-85, 1971.

18 - EISENBUD, M. *Environmental radioactivity.* 2. ed. New York, Academic Press, 1973.

19 - NATIONAL ACADEMY OF SCIENCES, Washington, D. C. *Radioactivity in the marine environmental.* Washington, D. C., 1971.

20 - GOFMAN, J. W. & TAMPLIN, A. R. *Poisoned power.* S. n. t.

21 - RADIOECOLOGY: proceedings of the First International Symposium on Radioecology. S. l., Col. State Univ., 1961.

CHAPTER IX

Solar Energy - A Form of Nuclear Energy

> "Provided that government support for technology development and proof of feasibility is available, it has been estimated that 1 percent of the total electrical generation in the nation could be provided by solar energy through either one of the two routes in the year 2000; this would be 0.43 percent of the total energy consumption. In addition, through photovoltaic systems on buildings, 0.45 percent of the total national energy consumption could be provided in the year 2000".
>
> Martin Wolf, Science, 19 April 1974

1. Comments

The entire 19 April 1974 issue of Science is devoted to the multi-faceted problems of energy. The significant point to note is that there is a block of articles under the heading **Oil, Coal, Gas, and Uranium: The Developed Technology,** followed by the block on **Sun and Earth; Developing Technology.** In this last block, there are only papers, the first is **Geothermal Electricity Production,** the second is **Solar Energy by Photosynthesis.** and the third paper is **Solar Energy Utilization by Physical Methods.** This is the last paper of the entire issue as well as of the block. This sequence of papers in this issue gives some indication of the magnitude of the technological and economic problems that need to be overcome, if any significant fraction of our electric energy demand is to be met by solar energy.

Another misconception that should be dispelled is that sun has not always been the beneficent source of heat and light we think it to be. Radiation from the sun is dangerous. In fact life started about 2 billion years ago in the ocean which shielded living organisms from direct sunlight. In the primordial atmosphere there was very little oxygen, and therefore little or no ozone, to absorb the ultra-violet radiations from sun, so making land uninhabitable to living organisms. But as plant life evolved, oxygen was released into the atmosphere, the ozone layer built up, so that about 600 million years ago, living organisms began to invade dry land.

The sun itself is a huge thermonuclear reactor, so that the direct radiations from it, like radiations from any thermonuclear source, can be lethal. Fortunately there are a number of nature's safeguards built into this source of energy, so that most of the time we can go about without being concerned about the risks of solar energy.

We shall first examine the sun from the standpoint of a thermonuclear reactor, then some of nature's safeguards, and then finally consider some of the proposed technologies to harness this source of energy.

2. Sun As A Thermonuclear Reactor

First we need to recognize that almost all of the energy that we consume today is nuclear in origin. Fossil fuel energy, for example, is nothing but stored nuclear energy, released from the interiors of the sun many million years ago. Hydroelectric energy is another example of solar nuclear energy released a short time ago, possibly only about thousands of years ago.

The so-called carbon-nitrogen cycle is believed to be the mechanism for nearly all of solar energy release. To see what this is we need understand the notations and certain basic concepts of nuclear reactions. These are very much like those of chemical reactions. The basic building blocks of the nucleus are protons and neutrons. The number of protons in the nucleus is the same as the nuclear charge, and this in turn is the same as the atomic number. For example the atomic number of oxygen is 8, so that the number of protons in the oxygen is also 8. The number of neutrons is uncertain because a nucleus having a fixed number of protons might have different number of neutrons. That is to say, an oxygen nucleus can contain 7,8, even 9 neutrons. These nuclei with different neutron numbers give rise to the different isotopes of an element. Consider carbon as another example. It's atomic number is 6 and the atomic weight is often listed as 12.011 gm/gm mole. The proton number must then be 6, and the neutron number is somewhere in the neighborhood of 6. It turns out that the two principal isotopes of carbon are ${}^{12}_{6}C$ and ${}^{13}_{6}C$ The left subscript on the symbol denoting the element is the atomic number i.e. the proton number, and the left superscript is the mass number, i.e. the total number of protons and neutrons.

We know that chemical reactions need to be balanced. We also need to balance nuclear reactions. For this, there are two basic principles that need to be kept in mind, namely the principle of conservation of charge numbers and the conservation of mass numbers. In other words, the number of charges before the reaction must be the same as after the reaction. In addition, the combined number of protons and neutrons must ~~be~~ the same before and after the reaction. To apply these principles, there are a few details we need to remember. These are the mass numbers and charge numbers of neutron, electron and the positron. To balance nuclear reaction these particles are represented by

$${}^{1}_{0}n, \; {}^{0}_{-1}\beta^-, \; {}^{0}_{1}\beta^+$$

respectively. The first is the neutron with zero charge number and 1 mass number, next is the electron with -1 charge number but zero mass number, and the last is the positron with +1 charge number and again zero mass number. Earlier we discussed the radioactive decay of ${}^{40}_{19}K$. This nuclear reaction is then to be written in the form

$${}^{40}_{19}K \longrightarrow {}^{40}_{20}Ca + {}^{0}_{-1}\beta^-$$

The total charge number before and after the reaction is 19 and the total mass number is 40.

The conservation of mass number, however, does not imply the conservation of mass. As a matter of fact, the important point is that the total mass changes, and this in mass accounts for the release or absorption of energy from nuclear reactions. In chemistry the terms exothermic andendothermic are used to describe reactions which release and absorb chemical energy. The same terms can be used to characterize nuclear reactions. The decrease in mass is related to the energy released by the Einstein relation, namely

$$(\text{decrease in mass})\, C^2$$

where C is the velocity of light.

There is however one point that needs to be kept in mind, namely that mass tables give the masses of **neutral** atoms, and not of the nucleus alone. Stated differently, the tabulated values are the **sum** of nuclear mass and the masses of the corresponding Z electrons.

To illustrate, consider

$$^{14}_{6}C \longrightarrow {}^{14}_{7}N + {}^{0}_{-1}\beta$$

which is involved in radio-carbon dating. The energy released is

$$NM\,(^{14}_{6}C) - \left[NM\,(^{14}_{7}N) + NM\,(\beta^-)\right]$$

$$= AM\,(^{14}_{6}C) - AM\,(^{14}_{7}N)$$

showing that the energy released for β decay is just equal to the change of atomic masses.

In contrast consider

$$^{13}_{7}N \longrightarrow {}^{13}_{6}C + {}^{0}_{1}\beta^+$$

which is believed to be a step in the so-called carbon-nitrogen cycle, responsible for the bulk of solar energy production. The energy released in the process is given by

$$NM\,(^{13}_{7}N) - NM\,(^{13}_{6}C) - M\,(\beta^+) = AM\,(^{13}_{7}N) - AM\,(^{13}_{6}C) - 2\,me$$

Thus the energy released is the atomic mass change energy decreased by twice the electron energy.

In calculating energy changes, it is useful to keep in mind that

$$1\ am\mu \equiv \frac{1}{16}\,AM\,(^{16}O) = 931\ MeV$$

and

$$M\,(\text{electron}) = 0.511\ MeV$$

Most recently, the mass standard has been changed to C-12, so that frequently the relation

$$1\,\mu \equiv \frac{1}{12}\,AM\,(^{12}_{6}C)$$

is used.

3. Solar Energy Production

There is an informative article on the structure of sun's interior in the Science Year 1967 of The World Book Science Annual. The sun is about 1,000,000 miles in diameter, with density about 100 gm/cm^3 at the center and temperature about 20,000,000 °K also at the center. The densities of lead, uranium, and the densest metal osmium are 11.35, 18.68, and 22.48 gm/cm^3 respectively. Thus the sun's core density is 8.8 times that of lead, 5.4 times that of uranium, and 4.5 times the densest metal known on earth. The density, however, falls off rather rapidly with distance from the center. At about 200,000 miles, the density is down to above 1 gm/cm^3. The temperature falls off less rapidly. At the edge of the photosphere, which is responsible for the sun's color, the temperature is about 6000° K.

The so-called carbon-nitrogen cycle is believed to be responsible for nearly all of solar energy production. This cycle consists of the steps

$$\begin{aligned}
{}^{1}\mathrm{H} + {}^{12}\mathrm{C} &\longrightarrow {}^{13}\mathrm{N} + \gamma \\
{}^{13}\mathrm{N} &\longrightarrow {}^{13}\mathrm{C} + \beta^{+} \\
{}^{1}\mathrm{H} + {}^{13}\mathrm{C} &\longrightarrow {}^{14}\mathrm{N} + \gamma \\
{}^{1}\mathrm{H} + {}^{14}\mathrm{N} &\longrightarrow {}^{15}\mathrm{O} + \gamma \\
{}^{15}\mathrm{O} &\longrightarrow {}^{15}\mathrm{N} + \beta^{+} \\
{}^{1}\mathrm{H} + {}^{15}\mathrm{N} &\longrightarrow {}^{12}\mathrm{C} + {}^{4}\mathrm{He}
\end{aligned}$$

$$\begin{array}{lcl}
\text{Atom mass of 4 H atom} & = & 4{,}032568 \\
\text{Atomic mass of He atom} & = & \underline{4{,}003873} \\
 & & 0.028695
\end{array}$$

$$= 26.7 \text{ MeV}$$

The gamma rays emitted during the nuclear processes are energetic. For example, for the first process, the energy is about 19.3 MeV. These gamma rays move outward, colliding with hydrogen and helium in the sun, losing energy in the process. These gamma rays generated near the center of the sun take such a tortuous journey out that they may be on their way for tens of thousands of years (see, for example Ayres and Scarlott, p. 189) before reaching the surface of the sun. Keep in mind that the speed of light is 186,000 mi/sec, so that if uninterrupted, a gamma ray would reach the surface in a few seconds!

The rate of "burning" hydrogen in the solar interior staggers the imagination. About 564 million tons of hydrogen are converted into about 560 million tons of helium, releasing an equivalent of 4 million tons of energy every second. This outpouring of energy from the sun into space in one second alone is estimated to be about a million times the earth's original stock of fossil-coal, oil, and natural gas.

For obvious reasons, the region of the solar interiors where the sustained thermonuclear reactions are going on is not certain. However, estimates based on calculations indicate that the thermonuclear reactions take place only deep inside the sun. The radius of the sun is about half a million miles or about twice the radius of the moon's orbit. The temperature at the center of the sun is estimated to be about 20 x 10^6 °K and the density there to be about 100 gm/cm^3, or one hundred times the density of water on earth. The densest metal on earth is osmium; its density is 22.5 gm/cm^3. But both the solar interior temperature and density fall off very rapidly with distance. At two tenths solar radius out from the sun's center, the temperature drops to about 10 million degrees K and the density to about a quarter of the value at the center. Consequently, the solar thermonuclear reactor core is probably no more than 100,000 miles radius. The heat transfer and the refueling of the solar furnace are accomplished by the blanket of thermo convective sphere, which makes up the bulk of the sun. The convective currents in the sun's interior remove heat and the thermonuclear waste products-mostly helium from the inferiors and brings in fresh fuel, rich in hydrogen. The convective layer is also the primary shield, so that by the time the radiation reaches the photosphere the bulk of the lethal, high-energy radiations has been removed.

4. Sun As A Black Body Radiator and Solar Constant

It was stated that the sun's surface temperature is about 6000°K. This temperature was not measured by placing a thermometer there. Then how is this temperature measured?

This is done by making use of a well known observation that there is a relation between temperature and color. For example, the color of a heating unit on a Kitchen range changes as it gets hotter. When it is first turned, it is dark, but soon turns dull red, and then becomes progressively bright red. The final temperature may be somewhere in the neighborhood of at 700°K. The electric light bulb looks yellowish, and its color temperature probably falls in the range of 1000 to 2000°K. The fluorescent lamp looks even whiter, so that its color temperature is around 3000°K. And at even higher temperatures, say at 10,000,000°K and 100,000,000°K, the color is bluish; the examples are the bluish stars.

These observed facts can be accounted for by Planck's black body radiation law, given by

$$\mu_\lambda = \frac{8\pi ch}{\lambda^5}\,\frac{1}{(e^{ch/kT}-1)}$$

in which

μ_λ radiation energy density at wave length λ

c velocity of light

h Planck's constant

k Boltzmann's constant

The last can be thought of as the ideal gas constant per molecule or atom, in contrast to R, the ideal gas constant per mole. The ideal gas constant, it will be recalled is,

$$R = 8{,}317 \times 10^7 \text{ erg/°K/mole}$$

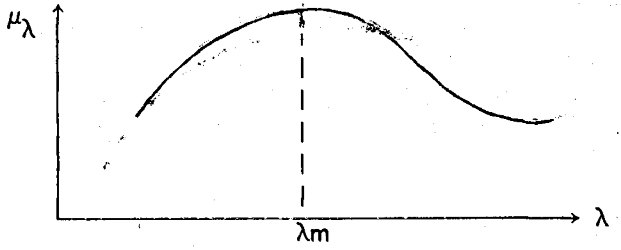
and since the Avogadro's number is

$$N_0 = 6.03 \times 10^{23}\text{/mole}$$

we find that

$$k = \frac{R}{N_o} = 1.380 \times 10^{-16} \text{ erg/°K}$$
$$= 8.6167 \times 10^{-5} \text{ ev/°K}$$

Two very important results can be deduced from the Planck's radiation law. According to Planck's law, the radiated energy from a black body is distributed continuosly throughout the entire electromagnetic spectrum, starting with gamma rays, x-rays and ultraviolet radiation at the short wave lenght end of the spectrum (to about 3800 A), through the visible region (3800-7200A), then into the infra red, and even into the microwave and radio wave region. The distribution in energy throughout eletromagnetic spectrum is given quantitatively by the Planck's law, which when plotted gives a curve that is somewhat as follows:



Thus the electromagnetic energy densities in the short and long wave lenght regions are small, reaching a maximum at some intermediate wave lenght. The peak in this curve is determined only by the temperature of the radiating body. The quantitative relation is the Wien displacement law, given by

$$\lambda m\, T = 0.288 \text{ cm } {}^\circ K$$

Thus according to this law, if the temperature is 6000°K, then the peak in the spectral energy density curve should come at

$$\lambda m = \frac{0.288}{6000} = 4.8 \times 10^{-5} \text{ cm} = 4{,}800 \text{ A}$$

or conversely, knowing the peak in the spectral density curve, the temperature can be deduced.

The second important consequence of the Planck's radiation law is the Stefan-Boltzmann law, which states that the total energy density of a black body is given by

$$\mu = \int_0^\infty \mu_\lambda d\lambda = aT^4$$

$$a \equiv \frac{8}{15} \frac{\pi^5 k^4}{(ch)^3} = 7.568 \times 18^{-15} \text{ erg/cm}^3/{}^\circ K^4$$

A quantity more useful for experimental investigation is the energy radiated by a black body. This is given by

$$w = \sigma T^4$$

in which

$$\sigma = \frac{1}{4} ca = 5.676 \times 10^{-5} \text{ erg/sec/cm}^2/{}^\circ K^4$$

$$\sigma = 5.676 \times 10^{-8} \text{ W/M}^2/{}^\circ K^4$$

As one example, let us use this value to estimate the solar constant. If the solar surface temperature is 6000° K, then the rate of radiation is

$$W = \sigma T^4 = (5.676 \times 10^{-8})\,(6000)^4$$

$$= 7.34 \times 10^7 \text{ W/m}^2$$

The sun's radius is about 0.5 million miles, and the distance to earth is about 100 million miles. Consequently the amount of solar energy flowing through an area of 1m^2 is

$$7.34 \times 10^7 \left(\frac{0.5}{100}\right)^2 = 1.8 \text{ KW/m}^2$$

This is in good agreement with the measured value of 1.395 Kw/m^2, or about 2 cal/min.

The following table, taken from **Patient Earth**, by J. Harte and R. H. Socolow, gives an indication of the amount of solar energy given off and how it is used on earth.

Energy Transfer	Rates in cal/yr
Energy radiated by the sun into space	2.8×10^{33} (1.1×10^{14}Q)
Solar energy incident on earth	1.3×10^{24} (5100Q)
Solar energy entering atmosphers	8.1×10^{23} (3200Q)
Energy used to evaporate water	2.2×10^{23} (800Q)
Solar energy used in photosynthesis	9.4×10^{20} (3.7Q)
Food eaten by man	2.9×10^{18} (0.01Q)

The number in parentheses are energies in units of Q, defined by

$$1\text{ Q} \equiv 10^{18} \text{ Btu}$$

The global annual energy consumption is about 0.2Q, so that the quantities in the table indicate the tremendous amount of energy we receive from the sun.

5. "Perils of the Benevolent Sun"

Solar radiation is indispensable for the maintenance of life. Yet we need to keep in mind that under certain circunstances solar radiation can be dangerous.

The solar energy spectrum can be divided roughly into the following regions.

x-rays and gamma rays	< 10A
ultra violet	10 - 3800A
visible	3800 - 7200A
infrared	7200A - 1000μm
micro-and radio-waves	< 1000μm

Very roughly, about 7.3% of the solar energy is in the region below 3800A, about 43.5 in the visible (3800-7200A) and about 49% in the infra red an beyond.

The 7.3% of solar radiation in the ultra-violet, x-ray, and gamma-ray region would be lethal to living organisms, if the radiations were to reach the earth's surface. Fortunately, much of the energetic radiation is absorbed by the ozone in the atmosphere. It is believed that once in the beginning when microorganisms were beginning to develop, the earth's atmosphere had no ozone, so that such organisms lived in the ocean, where the ultraviolet radiation was filtered out by water. But as time went on, oxygen was released, ozone began to form, so that about 6,000,000,000 years ago, dry land became safe for living organisms. And of course as time went on, land animals developed thick protective layer, like the skin, which is very effective in sheilding the inner delicate tissues from the lethal energetic radiation.

Perhaps we should keep in mind that solar radiation does produce skin cancer.

Then to recapitulate, the primary shield for the solar furnace is the convective layer. The photosphere provides additional attenuation of the lethal radiations. There is further substantial attenuation by distance the thermonuclear reactor is about one hundred million miles away. But there is still the residual 7% or so of ultraviolet radiation, the bulk of which is absorbed by the blanket of ozone in the earth's atmosphere. A very small residual amount of ultraviolet radiation is absorbed in a tough layer on the outside of our body. The skin then is our ultimate defense against the damaging effects of solar radiation.

6. Photosynthesis

Of the 5100 Q/yr solar radiation coming into the Earth's atmosphere, about 27% is absorbed by evaporating water, about 0.12% for photosynthetic biomass production, and only about 0.00036% ultimately converted into human food. Stated a little differently, about 0.31% of the biomass energy is used as human food. The low photosynthesis efficiency may seem surprising. There are several reasons why the effective efficiency is low. One is that only about 25% of the solar radiation reaching the Earth's surface is useful for photosynthesis. A little less than 50% of the solar radiation is in the infrared region; these radiations, however, are not directly involved in photosynthesis.

The graph on p. 90 of the article "Flow of Energy in the Biosphere" by David M. Gates of the U. of Michigan Botany Department provides an insight to the amount of solar energy converted into stored plant energy. The insolation is about 1.7 million Kcal/m^2/yr. Of this amount 24% (410,000 Kcal/m^2/yr) is absorbed by the photosynthetic biomass, giving gross biomass production of 20.8 Mega cal/m^2/yr. The rest is rejected as heat (What is the thermodynamic efficiency of a biomass heat engine?). But this is not all. There is an additional producer plant respiration loss, amounting to about 12 Mcal/m^2/day, so that the **net** production of biomass amounts to only 8.8 Mcal/m^2/day, giving an overall thermodynamic efficiency of about 2.1%. It also amounts to about 0.52% of the incoming solar radiation, to be compared to the value of 0.12% quoted earlier. The difference stems from the fact that the diagram in Gates' article is based on a study carried out in Florida where the photosynthesis efficiency is relatively high; the global average, of course, is expected to be substantially smaller.

7. Fuel Wood and Water Power

The solar energy stored in water and in plants can be used but even the most optimistic estimates indicates that only a small fraction-say about 5%-of the world's energy needs can be met from these sources. For detail the reader is referred to Putnam, **Energy in the Future.**

8. Photosynthesis Engineering

In the search for novel methods of collecting solar energy, a number of ideas have been proposed, and one is the algae, or chlorella, farm, estimated to be at least 100 times more effective in using solar energy.

The problem is to close the gap between the available useful solar energy and the net biomass energy. As indicated earlier, the solar energy intercepted by the earth is about 5100 Q/yr, of which about 3200 Q/yr enters the atmosphere. Of the latter amount, about 84 Q/yr reaches land areas other than the Arctic and the Antarctic; the part incident on continental United States is about 50 Q/yr. However, not all of this energy is suitable for photosynthesis. Wave lengths shorter than 4000 A and longer than 10,000 A do not appear to play any part in photosynthesis. Chlorophyll can convert solar energy in the range of 4000 to 7000 A. Under certain conditions the purple and green bacteria can convert some of the energy in the near infrared, up to about 10,000 A. Thus at least 20% of the solar radiation energy reaching the Earth's surface, namely the 4% in the ultraviolet and 16% above 10,000 A, is not useful for photosynthesis. Thus about 80% of the solar radiation on land, or about 670 Q/yr is available for some one of the several photosynthetic processes. If we take the efficiency of photosynthesis to be 0.1%, then the energy stored in the biomass is about 0.67 Q/yr. For the solar radiation on the United States, energy amounting to 0.05 Q/yr can be obtained, but this is less than the energy consumption of 0.065 Q for 1970.

One proposal is to build chlorella farms, which offers the posssibility of 100-fold or even larger increase in biomass production. Several factors contribute to the increased efficiency. One is that the entire alga plant, which consists of one cell, is involved in photosynthesis, whereas for plants like trees as an example, there are the branches, trunk, and roots that do not take part in photosynthesis but add to the plant respiratory losses. Another factor is at low light intensities chlorophyll can utilize 20% or more of the solar energy but the fraction drops to 2 to 3% for full sunlight. And, furthemore, photosynthesis rate falls off as the CO_2 concentration is reduced. On an algae farm, on the other hand, it is possible to increase the yield by optimizing both the light intensity and the CO_2 concentration dissolved in the water.

The drawback, of course, is the cost. Estimates based on pilot plant studies suggest that chlorella used as fuel is about 100 times more expensive than coal. Also, if the U. S. appetite for gasoline were to be met by chlorella, then the chlorella farm area would be about the state of Louisiana.

There is, however, one fact that should not be overlooked. The protein yield per acre of a chlorella farm is about 200 times that of soy beans!

9. Solar Farms

The merits of this system are outlined in the October 1971 issue of the Bulletin of the Atomic Scientists, in the paper by A. B. Meinel and Marjorie P. Meinel of the University of

Arizona Optical Sciences Center. The main merits are that such farms can be 30 times more efficient than conventional farming, and furthemore deserts, not useful for conventional farming, can be used.

The system, in principle, is like a conventional nuclear power plant, with an IHX (intermediate heat exchanger) where the heat from the liquid coolant NaK is transferred to steam to drive the turbine. The difference is that the solar energy is the heat source, rather than the nuclear fission energy.

The problem, however, is that the solar energy needs to be "harvested" from a very large area. The size of the farm for a 1000 MW (e) is easy to estimate. For this, the peak power output (at noon) needs to be about 13,000 MW (t). The solar constant, it will be recalled, is about 1.395 Kw/m^2, of which about 63% (3200Q/5100Q) reaches land surface, so that solar energy on 15 square Km, perpendicular to the sun's rays needed to be collected. Consequently, the Meinels' estimate that about 45 Km^2 of horizontal surface area is needed, or an area of a square, 4 miles each side.

A problem not mentioned in their paper is the heat engineering of the liquid metal NaK, with IHX input temperature of 560°C (1040°F!). For the nuclear fission reactor, the liquid metal pipeline is only a few hundred feet at most; for the solar farm, it would be miles, and the thermal insulation problem will be greater because of the higher temperature.

10. The SSPS

This is another highly imaginative proposal, made by P. E. Glaser of Arthur D. Little, Inc. in 1968. A more detailed discussion of the SSPS (Satellite Solar Power Station) is given in IEEE Spectrum, March 1973).

The idea is to put a satellite into an equatorial synchronous orbit, about 22,400 miles above the earth. There will then not be the day-night cycle problem, and be also relatively independent of atmospheric conditions. The satellite, to be designed for 3000 to 15,000 MW capacity, is to consist of two huge panels, each about 100 sq. Km, covered with solar cells. The D. C. panel is then to be converted to 4 Ghz microwave power, beamed to the earth where the energy will be reconverted to D. C. Estimates indicate that 50 such satellite stations could meet the U. S. electrical power requirement in year 2000.

11. Auxiliary Energy Sources

In the discussions presented so far, of fossil energy, nuclear energy, or even of solar energy, the assumptions are made that electrical power needs will continue to increase and furthermore will be generated at central stations. Probably very few will question the first assumption, but the second one needs scrutiny. To a large extent, we Americans have become accustomed to the excellent services from electric utilities;for example, I was impressed with the speed with which electrical service was restored after a recent storm. In many parts of the world such excellent prompt service is not available. (Once in Taiwan, a person used the excuse of the telephone being out of order for not making contact). But with the developing fuel shortage, we may soon be forced to put up with certain incoveniences of operating auxiliary energy saving generating sources. By means of such a system, it will be possible to reduce the load on the central system, thereby possibly reducing the environmental impact of large power plants, be it fossil or nuclear.

For this, we need to keep in mind that there are basically two categories of power consumers, namely the industrial plants that require high concentrations of power and the household consumers that need about 1 Kw or so. Probably the continued dependence of industrial plants on fossil and nuclear power plants is unavoidable, but for household uses, perhaps steps should be taken to make more effective use of solar radiation.

There are two ways that this can be done. One is to use solar heat directly and the other is to convert a portion of the solar energy into electrical energy. The first will be commented on briefly. Solar water heaters, for example, are very simple devices, relatively cheap, and are commercially made in Australia, Israel, Japan, USSR, and to a limited extent in the U. S. Solar water heaters are standard items of household equipment in parts of Australia and Japan. It used to be common in Florida, but disappeared when natural gas became available, but is now having a comeback. In Australia, installations for institutions such as schools, hospitals, etc. are beginning to appear. No doubt, even here in the U. S., the number of such units, and the more sophisticated house heating and cooling units, will increase.

Here, however, we shall focus our attention upon a solid-state mechanism, known as the photovoltaic effect, that will make it possible to convert solar energy into electrical energy. One reason for this is that the device depends on the use of one of the most common elements in the earth's crust, namely silicon (28% abundant) and the other reason is that the same mechanism, but known under a slightly different name of electron voltaic effect, can be used to convert energy from nuclear waste products into useful electrical energy.

Excellent discussions of such uses of radioisotopes are given in the AEC booklets like **Direct Conversion of Electricity** and also the one on **Power from Radioisotopes.** Power supply of weather stations in remote inaccessible areas are thermoelectric generators using the radioactive waste Sr-90. The lunar station is powered by Pu-238. And more recently, compact nuclear batteries have been developed for heart pacers.

12. Power from Coke Bottles (Photovoltaic Effect).

We wish to show that Si,which is the principal ingredient in coke bottles, can be used to generate more electric power than is required for an average household!

Si is a Group IV element and its relation to other elements can be seen by referring to the following portion of the Periodic Table of Chemical Elements:

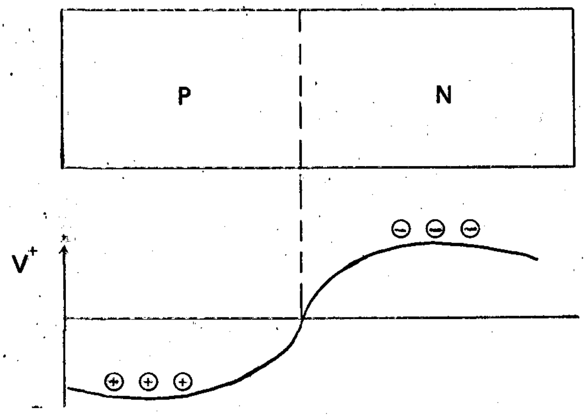
II	III	IV	V	VI
Be	B	C	N	O
Mg	Al	Si	P	S
Zn	Ga	Ge	As	Se
Cd	In	Sn	Sb	Te

The element Ge is known as the first transistor material. The element C, in the form diamond, is an excellent semi-conductor. Many of the Ge transistors are now being replaced by Si, which happens to be the second most abundant element in the Earth's crust. Estimates indicate that oxygen constitutes about 47% of the Earth's crust, Si about 28%, compared to H of 0.14% and U of about .0004%.

Another very important property of semiconductors like Si is that the electrical properties can be altered drastically by adding small amounts of Group III or Group V elements. If Group V elements are added, the electrical conduction is due to electrons in the conduction band; if Group III elements are added, the electrical conduction results from vacancies in the valence band, called holes. The group III and V elements are known as acceptors and donors. Semiconductors whose conductivity is due to electrons is said to be N-type, and if due to holes, it is said to be P-type.

Suppose next that we form a junction by putting P-and N-type materials together. The result is what is called a P-N junction, or a diode. A transistor, on the other hand, is a more complicated junction made, for example, by making a P-N-P junction.

To see how such devices work, we need to recall one fact in electricity and magnestism. It will be recalled that positive charges, if left to themselves tend to move into and stay in the region of low voltage, whereas electrons move into and stay in the regions of high voltage. In the P-N junction, the electrons (negative charge) and holes (positive charge) are free to move about, but the hole concentration is high in the P side of the junction. Similarly the electron concentration is high on the N-side. We see then that the voltage plot in the P-N junction is as follows:



That is, as we go from left to right, the voltage is negative and almost a constant while in the P-type material, but begins to rise very rapidly near the junction region. The separation between the conduction band and the valence band is about 1.1 ev for Si. In other words this amount of energy is needed to lift the electron from the valence band to the conduction band. This is like the photoelectric effect, and the band gap of 1.1 ev can be compared to the ionization energy. The photon that can provide this energy is given by

$$h\nu = E_G = 1.1 \text{ ev (for Si)}$$

Since

$$h = 6.625 \times 10^{-27} \text{ ergs sec} = 4.15 \times 10^{-15} \text{ ev sec}$$

we see that

$$\nu = 1.1 \text{ ev}/4.15 \times 10^{-15} \text{ ev sec} = 2.65 \times 10^{14}/\text{sec}$$

or converted to wave lenght

$$\lambda = \frac{c}{\nu} = \frac{3 \times 10^{8} \text{ m/sec}}{2.65 \times 10^{14}/\text{sec}} = 1.1 \times 10^{-6} \text{m}$$

in which

$$1\text{A} = 10^{-8} \text{ cm} = 10^{-10} \text{ m}$$

Now, it happens that the solar spectrum, after being filtered by the atmosphere peaks at about 1.1 μ m. In other words, electron-hole pairs can be generated in Si by solar radiation.

The effect of solar radiation then is to create electron-hole pairs, the electrons will then drift into the N-region, and the holes into the P-region, so that there will result a current flow through an external circuit, if completed. This basically is the mechanism for the photovoltaic cell, or the solar battery.

Of course, clearly, we can irradiate the junction with nuclear radiation. Again, electrical energy will be generated. If the junction is used this way, it is said to be a nuclear battery. The effect is referred to as the electron-voltaic effect.

The energy falling on one square cm at normal incidence, outside the earth's atmosphere known as the solar constant, is about 2 cal/min, which is about

$$\frac{2\,(4.185)}{60} = 0.14 \text{ w/cm}^2$$

To be conservative, we shall take the solar radiation to be 0.1 w/cm^2. Since

$$1 \text{ ft}^2 = 930 \text{ cm}^2$$

we see that

$$0.14 \text{ w/cm}^2 = 93 \text{ w/ft}^2 = 873 \text{ w/yd}^2$$

The efficiency of solar batteries is about 7%, so that electrical power generation amounts to about 60 w/yd^2. Thus if the roof area is 1000 ft^2, about 7 Kw can be expected at noon.

The Si needed to make the solar batteries can be obtained from a few dozen coke bottles or comparable weight of sand. Because Si absorbs solar radiation strongly, the junction depth is made about 1 μm beneath the surface facing the sun. To give them mechanical strenght, the cells are made about 1 mm thick, so that the amount needed per square yard is about 100 cm^3, or about 0.24 Kgm, which is approximately ½ lb. The principle constituent of glass is silica (SiO_2) whose molecular weight is $28 + 2(16) = 60$. Furthemore, for most glasses the silica content is more than 50%, so that at least one-fourth of glass is Si. Consequently, 2 lbs of glass or sand contains more than an adequate amount of Si for 1 square yard of solar battery, and from a few hundred pounds of glass or sand, we can obtain enough Si to shingle the roof completely.

Unfortunately, at present the cost of solar power is very high. According to one estimate (See Zorem and Erway, **Introduction to the Utilization of Solar Energy**, p. 218) the cost is about $100 per kwhr. But with further research, mass production-and when environmental **costs** are included-perhaps solar electric power can be made competitive with other sources.

13. Thermoelectric Devices

As indicated earlier, the electron-voltaic effect is a possible scheme for the conversion of nuclear energy into electrical energy. Unfortunately the conversion efficiency is low and further, the device is readily degraded by nuclear radiation. The reason for this is that the PN-junction is what is called a minority carrier device and the minority carrier lifetime is a very sensitive function of radiation damage. Consequentely, in developing energy conversion devices using nuclear radiation, much of the research effort has gone into thermoelectric devices.

The basic principle is the same as that for the thermocouple, used almost invariably for measurement of temperatures above and below room temperatures. When two ends of a conductor are kept at different temperatures, electrons (or holes) tend to flow from the hot to the cold end, because of the larger electron K.E. at the hot end. The effect was first reported as long ago as 1821 by a German physicist T. J. Seebeck (1770-1831), and the other early contributors to the effect are J. C. A. Peltier (French, 1785-1845), and W. Thomson (1824-1907), who perhaps is better known as Lord kelvin. Recent impetus to study the thermoelectric effect came about as the result of the intense research efforts in semiconductors. Perhaps one of the spectacular achievements is the development of the thermoelectric refrigerator.

As indicated earlier, some of the SNAP systems (odd-numbered ones) depend upon the thermoelectric effect and the results have been very successful. The first to be tested was at the Axel Heiberg weather station located only 700 miles from the north Pole. A two year test began on August 21, 1961. The system was designed for 5 watts, derived from a noxious radioactive waste, Sr-90. Another system SNAP-7C was installed in 1962, about 700 miles from the South Pole. Also several systems have been developed as navigational aids. These systems also use Sr-90. Possibly the most recent one to attract public attention is the SNAP system on the Moon. This one, however, derives its power from Pu-238.

Possibly the most attractive feature about these devices is that they can make use of a radioactive waste product. Of the various radioactive waste products, Sr-90 presents the most troublesome problems because its radioactive half-life is long (about 28 years) and because it occurs directly beneath Ca in the Periodic Table of Chemical Elements it enters the body metabolism as does Ca. In addition the biological half-life, i.e. the retention time in the body, is very long, being about 36 years.

The method of preparing Sr-90 is interesting. For example, for the first Axel Heiberg Island weater station, Sr-90 was extracted from liquid radioactive wastes in storage tanks near Richland, Wash. The material is precipitated as $SrCO_3$, and later converted to $SrTiO_3$. The merit of being in the last form is that the material is effectively insoluble in water and furthermore the melting point is very high, about 1910°C, or about 3700°F.

Since radioactive wastes are the unavoidable by-produces of nuclear fission, and because such wastes generate large amounts of energy, we need to find out how to make use of these waste products.

Questions and Problems

1. List 3 benefits and 3 risks associated with each of the following technologies.

TECHNOLOGY	BENEFITS	RISKS
SOLAR	1. 2. 3.	1. 2. 3.
FOSSIL	1. 2. 3.	1. 2. 3.
NUCLEAR FISSION	1. 2. 3.	1. 2. 3.
NUCLEAR FUSION	1. 2. 3.	1. 2. 3.

2. When did coal produce 50% of electrical power? About when do you think nuclear fission will be producing 10% of the present U. S. demand? When might these dates b for nuclear fusion? for solar energy?
3. Ask a friend what he or she thinks are the possible benefits and risks. Ask the person also when he or she thinks solar and/or nuclear fusion might become available.
4. List additional information needed to evaluate the benefits and risks of the 4 technologies.
5. Compute the amount of energy released by "burning" one gram-mole of H-1 and one gram-mole of C-13 to produce H-14. What is the gasoline equivalent of this amount of energy?

REFERENCES

1 - GLASER, P. E. Power from the sun: its future. *Science,* Lancaster, Pa., 162 (3856):857-61, Nov. 1968.

2 - BULLETIN OF THE ATOMIC SCIENTIST, Chicago, Oct. 1971.

3 - BROWN, W. C. Satellite power stations: a new source of energy. *IEEE spectrum,* New York, s. p., Mar. 1973.

4 - NATIONAL AERONAUTICS AND SPACE ADMINISTRATION, Washington, D. C. *An assessment of solar energy as a national energy resource, prepared by the NSF/NASA solar energy panel.* S. n. t.

5 - ZENER, C. Solar sea power. *Physics to-day,* New York, 26:48-53, 1973.

6 - CORLISS, W. R. *Direct conversion of energy.* Washington, D. C., USAEC, 1968.

7 - ——— & MEAD, R. L. *Power from radioisotopes.* Washington, D. C., USAEC, 1971.

8 - CAPTURING the sun. East, 9 (5):10, 1973.

9 - ROBINSON, N., ed. *Solar radiation.* Amsterdam, Elsevier, 1966.

10 - ELLISON, M. A. *The sun and its influence.* London, Routledge, 1955.

11 - GATES, D. M. The flow of energy in the biosphere. *Scient. Am.,* New York, 225 (3):89-100, 1971.

12 - HARTE, J. & SOCOLOW, R. H. *Patient earth.* S. n. t.

13 - NEY, E. P. The sun under surveillance. *Science year,* s. p., 1967.

14 - CALVIN, M. Solar energy by photosynthesis. *Science,* Lancaster, Pa., 184 (4134):375-81, 1974.

15 - WOLF, M. Solar energy utilization by phisical methods. *Science,* Lancaster, Pa., 184 (4134):382-6, 1974.

CHAPTER X

Radioactive Wastes

> "Alternative storage areas considered have included the artic ice cap, deep ocean trenches, and solar orbit, with underground salt deposits still the most favorable"
>
> Physics Today
> August, 1973

1. Comments

The Second Law of Thermodynamics states that for a heat engine, waste heat is inevitable. We can enunciate a comparable law for technology, namely that for any technology, waste products are unavoidable. And the knotty problem of nuclear technology is the disposal of radioactive wastes. To avoid generalities, we shall consider one aspect of the rad-waste problem for the Greenwood Energy Center, as indicated by the comments in Sec. 3.8 on Radioactive Materials Inventory.

2. Fuel Consumption and Fuel Waste

The reactor core for the 1000 MW(e) Grenwood Plant is to consist of 205 fuel assemblies, of which 68 are to be replaced each year. Each fuel assembly weights 1550 lbs., consists of 208 zircalloy-clad fuel rods, and contains about 463 kgm. of uranium. The U-235 content of the fuel rods vary somewhat, but for the purposes of discussion here, we shall take the enrichment to be about 3% by weight. Thus very roughly, the weight of U-235 in one assembly is about 14 Kgm, for this weight in the 68 assemblies then is 957 kgm, or roughly 1 ton. During the 3 years that these assemblies are in the reactor core, the approximately 1 ton of U-235 is burned up. We can verify this by the following estimate. The energy released by burning 1 gm of U-235 is roughly 1 MWD (megawatt day). The thermal efficiency of a nuclear power plant is about 1/3, so that to generate 1000 MW(e) of electricity we will need to burn about 3000 MWD/day, or about 3Kg of U-235 every day. Consequently, in U-235 consumption amounts to about 365(3) Kgm, which is roughly 1 ton of U-235. The fission waste products for the year's operation will also amount to about 1 ton. As noted in the Environmental Report, the 68 fuel assemblies needed every year can be brought in with 6 truck shipments.

For comparison, consider the problem for a 1000 MW(e) coal plant. The heat of combustion of bituminous coal is about 14,000 Btu/lb, or about 28 million Btu/ton. This amounts to about 1/3 MWD/ton. Hence the coal tonnage requirement for one year amounts to

$$\frac{365\ (3000)}{1/3} \cong 3 \text{ million tons of coal/year}$$

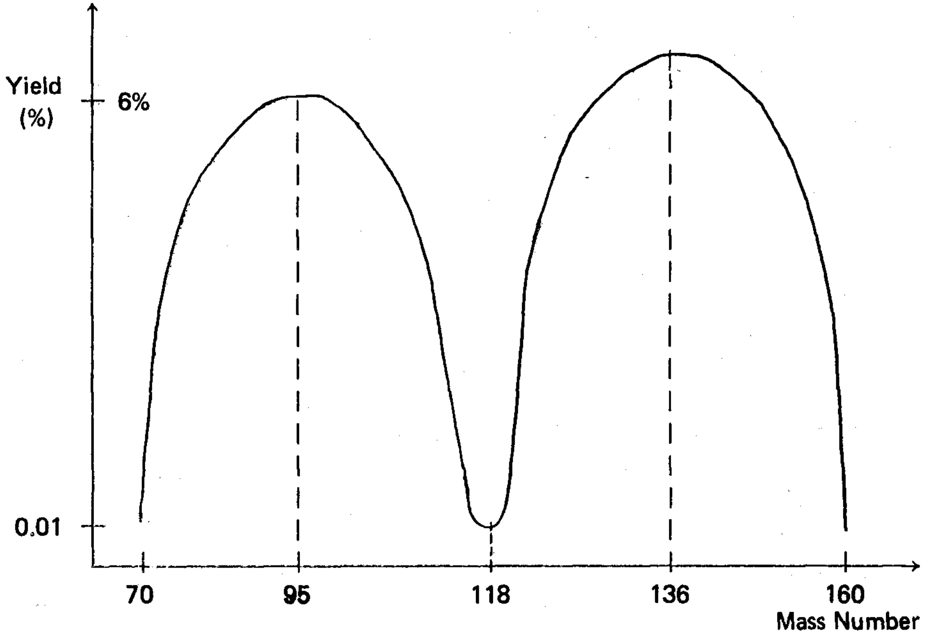
To supply this coal, 100 car train loads of coal will be needed every day. Furthermore, the ashes will amount to about 300,000 tons, so that 33 freight cars will be needed every day to haul away this amount. The rest, that is 2.7 million tons, will be exhausted into the atmosphere and in the process the atmospheric oxygen will be used up. If this process were to continue until all of our fossil fuel reserves are burned, the atmospheric content of oxygen would drop, with corresponding decrease in the ozone content. We need to remind ourselves that the primordial atmosphere-600 million years ago-had too little oxygen to shield living organisms from the solar ultra-violet radiation. We also need to keep in mind that the SST (super sonic transport) program in this country was stopped because of the dangers of depleting ozone from the atmosphere.

Returning to the problem of the spent fuel waste products, the statement is often made that the radioactive wastes from 1 ton of spent fuel can be reduced to about 2 cubic feet of solid matter. The 1 ton of fission products mentioned earlier comes from the 68 fuel assemblies that contain about 34 tons of fuel. The volume of waste products that need to be disposed of then, amounts to about 68 cubic feet per year.

3. Fission Products and Yields

We need to remind ourselves that the bulk of the 1 ton fission product waste materials is not radioactive, even before it leaves the nuclear power plant site, where it is kept for several months. To see this we need to examine the fission products and the yields of the major ones.

The yields of the fission products are given by a double-humped curve, extending from nuclear mass numbers of about 70 up to above 160, as follows:



The minimum occurs at mass number of about 118, for which the yield is only about 0.01%. The peaks occur at about 96 and 136, for which the yields are about 6%. There are thus two islands of nuclear masses, referred to as the light and heavy fission fragments respectively. Typical of the light fission fragments are Sr-90 and Kr-85. The most frequently heavy fission fragments are Cs-137 and I-131. The light fission fragments with yields greater than 1% are shown in the accompanying table.

LIGHT FISSION FRAGMENTS

Mass Nº	Stable End Prod.	Longest Lived Precursor	Half-Life	Yield (%)
84	Kr	Br	30m	1.1
85	Rb	Kr	10.3yr	1.5
86	Kr	-	-	2.1
87	Sr	Rb	52 x 10^9 yr	2.7
88	Sr	Kr	2.8hr	3.7
89	y	Sr	50.6d	4.8
90	Zr	Sr	29yr	5.9
91	Zr	Y	59d	5.9
92	Zr	Y	3.53hr	6.1
93	Nb	Zr	9.5 x 10^5 yr	6.5
94	Zr	-	-	6.5
95	Mo	Zr	65d	6.4
96	Zr	-	-	6.4
97	Mo	Zr	17hr	6.2
98	Mo	Nb	51.5m	5.9
99	Ru	Tc	0.21 x 10^6 yr	6.1
100	Mo	-	-	6.5
101	Ru	Tc	14m	5.0
102	Ru	Tc	5s	4.2
103	Rh	Ru	40d	2.9
104	Ru	-	-	1.8

Thus in this group, we note that the stable isotopes Kr-86, Zr-94, Zr-96, Mo-100, and Ru-104, are produced directly, accounting for about 23% of this group. The radioisotopes of half-lives greater than 1 year are Kr-85, Rb-87, Sr-90, Zr-93 and Tc-99, which account for about 23%. A little over 50% of the products have half-lives of 1 year or less.

The next table (Page 86) shows products and yields (greater than 1%) for the heavy fragments. Those with half-lives longer than 1 year are I-129, Cs-135, Cs-137, and Pm-147. The combined yield of these radioisotopes is about 16%.

The third table (page 87) gives the fission fragments that are often listed as the principal fission product radioisotopes in radioactive wastes.

We note that the so-called fission product wastes contain the precious metals like ruthenium and rhodium and also the rare-earths such as lanthanum, cerium, praseodynium, neodynium, and samarium. Both ruthenium and rhodium are hard acid resistant metals, similar in chemical properties to platinum. The rare-earths have striking luminescent and magnetic properties. For example, it will be recalled neodynium is an important laser material. The rare-earths are also being investigated for solid-state magnetic devices.

4. Spent Fuel Elements

Most of the fission products produced during power plant operation stay in the fuel rods.

The first step in waste handling, after removal from the reactor, is storage for several months under 15 to 20 feet of water in a pool near the power plant site. During this period short-lived isotopes decay.

The fuel assemblies are then transported in heavily shielded shipping containers, called casks, to a fuel reprocessing plant. These casks are designed to insure that transportation accidents will not cause any significant release of radioactivity. According to AEC regulations, the casks must be able to withstand a 30 foot drop test onto a flat unyielding surface, a 40-inch drop onto a six-inch diameter post, a fire of 1475°F for 30 minutes, and submersion in three feet of water for 8 hours.

HEAVY FISSION FRAGMENTS

Mass Nº	Stable End Prod.	Longest Lived Precursor	T½	Yield(%)
129	Xe	I	1.6×10^6yr	1.0
130	Te	-	-	2.0
131	Xe	I	8.05d	2.9
132	Xe	I	2.3hr	4.4
133	Cs	Xe	5.27d	6.5
134	Xe	I	52.5m	7.6
135	Ba	Cs	2.0×10^6yr	6.2
136	Xe	-	-	6.3
	Xe	I	86s	3.1
137	Ba	Cs	30yr	5.9
138	Ba	Cs	32.2m	5.8
139	La	Ba	83m	6.0
140	Ce	Ba	12.8d	6.3
141	Pr	Ce	32.5d	6.0
142	Ce	La	1.4hr	6.2
143	Nd	Pr	13.7d	6.2
144	Nd	Ce	285d	6.1
145	Nd	Pr	5.9hr	4.2
146	Nd	Pr	24m	3.3
147	Sm	Pm	2.6yr	2.6
148	Nd	-	-	1.8
149	Sm	Pm	53hr	1.3

PRINCIPLE FISSION-PRODUCT RADIOISOTOPE IN RADIOACTIVE WASTE

Radioisotope	At. Nº	Half-Life	Yield (%)
Kr-85	36	9.4yr	0.3
Sr-89	38	54d	4.8
Sr-90	38	25yr	5.9
Zr-95	40	65d	6.4
Nb-95	41	35d	6.4
Tc-99	43	5 x 10^5 yr	6.1
Ru-103	44	39.8d	2.9
Rh-103	45	57m	2.9
Ru-106	44	lyr	0.38
Rh-106	45	300	0.38
Te-129	52	72m	1.0
I-129	53	1.7 x 10^7 yr	1.0
I-131	54	5.3d	2.9
Cs-137	55	33yr	5.9
Ba-140	56	12.8d	6.3
La-140	57	40hr	6.3
Ce-141	58	32.5d	6.0
Ce-144	58	590d	6.1
Pr-144	59	17m	6.1
Pm-147	61	2.26yr	2.6

At a typical reprocessing plant, remote control manipulators disassemble the fuel assemblies and shear the individual metallic fuel rods into short pieces. The fuel pellets are leached out of the cladding by nitric acid. The solution containing the dissolved fuel goes through a chemical process which separates more than 99.9% of the fission products from the U, Np, and Pu. The solution of high level fission products may then be concentrated and finally solidified into a sand-like glassy material. Each metric ton of fuel processed will produce about 2 cubic feet of high level waste. Such high level wastes, according to one proposal, are to be buried in deep salt mines.

5. *How Soluble is Soluble?*

Engineers and scientists often get mired in a jungle of semantics because words have different meanings to different people. A part of the controversy concerning the disposal of radioactive wastes stems from the fact that the word "soluble" means one thing to the non-technical intervenors, but something quite different to the technically trained.

To an average private citizen, salt is soluble but glass is **not** soluble. Thus a layman, if questioned in court or a public hearing, would be able to say unhesitatingly that glass is not soluble. An engineer, on the other hand, knowing more about the properties of glass, would not be able to be so positive and therefore if faced with the question would answer that glass is soluble. Thus a seeming contridiction arises because what an engineer said in court to be **soluble** may be the same as a layman's use of the word **insoluble.**

The point is that the radioactive glass is **insoluble** by conventional laymen's standards.

The radioactive glass a placed in a stainless steel container, which again, by conventional layme's standards is non-corroding. But by engineering standards, stainless steel corrodes at a very slow rate. To be safe, engineers are concerned about these exceedingly slow rates of solution and corrosion.

Leaching rates of glass are extremely small. According to laboratory tests, the rate was of the order of 10^{-7} to 10^{-6} gm glass/cm^2/day. In a field experiment samples containing U were left in the swamp for 3 years, about 1 to 2 mCi leached out, equivalent to leaching rate of about 5×10^{-10} gm glass/cm^2/day.

6. Power From Radioisotopes

The radioactive waste products such as Sr-90 and Pu-238, can be used as power supplies for remote communication systems. For such applications, the radioactive decay energy is converted to electrical energy by either the electron-voltaic effect or the thermoelectric effect. Weather stations run by radioisotope energy have been set in the inaccessible artic regions. The recent January 1974 issue of Nuclear News notes some notable successes of SNAP-27 radioisotope power generator, run on Pu-238. The 63.5w power supply has been running for 4 years on the lunar surface. The 30 watt SNAP-27 system in Pionneer-10 provided the power needed to transmit the close-up pictures of the Jovian surface. For Pioneer-10 solar cells could not be used, as was done for the flights to Mars and Venus, because Jupiter is too far from the sun.

REFERENCES

1 - RISING dangers of atomic wastes. U. S. News and World Report, 1973.
2 - HODGES, L. *Environmental pollution.* S. n. t.
3a - FOX, C. H. *Radioactive wastes.* Washington, D. C., USAEC, s. d.
3b - HOGERTON, J. F. *Atomic fuel.* Washington, D. C., USAEC, s. d.
3c - GSCHNEIDER JR., K. A. *Rare earths: the fraternal fifteen.* Washington, D. C., USAEC, s. d.
3d - CORLISS, W. R. & MEAD, R. L. *Power from radioisotopes.* Washington, D.C., USAEC, 1971.
4 - TEACHER'S guide for the environmental impact of electrical power generation: nuclear and fossil. Harrisburg, Pennsylvania Dep. Education, Nov. 1973. (WASH-1262).
5 - ENVIRONMENTAL impact of electrical power generation: nuclear and fossil. Harrisburg, Pennsylvania Dep. Education, 1973. (WASH-1261).
6 - AMERICAN NUCLEAR SOCIETY, Hinsdale, Ill. *Nuclear power and the environmental: questions and answers.* Hinsdale, Ill., s. d.
7 - MAWSON, C. A. *Management of radioactive wastes.* Princeton, N. J., Van Nostrand, 1965.
8 - BLOMEKE, J. O. et alii. Managing radioactive wastes. *Physics to-day,* New York, **26** (8):36-42, 1973.
9 - HAMMOND, R. P. Nuclear power risks. *Am. Scient.,* New Haven, **62**:155, Mar./Apr. 1974.

CHAPTER XI

Statistical Fluctuation of Death Rates: Nuclear and Leukemia

> ". . .In counting scintillations from a constanst source, the variations of the number in a given time were occasionally so marked that it is difficult at first sight to credit that they are mere examples of random distributions and are not necessarily to be ascribed to the inefficiency of the counter". From Rutherford, Chadwick, and Ellis, **Radiations from Radioactive Substances,** p. 171, Revised Edition, 1951.

1. Comments

The main objective of the discussion to follow is to show how the statistical methods needed to interpret fluctuations in radioactive decay can be used to analyze fluctuations in human death rates. The motivation for this stems from the fact that recently an MD from Petoskey, Michigan, a city near the Big Rock nuclear plant, is creating quite a stir by circulating a paper on "A Report on Selected Charlevoix County Statistics for the Alliquippa Hearings, July 31, 1972". A part of the results in this report was reported in the **Ann Arbor News,** Saturday, July 14, which quoted E. J. Sternglass. According to the latter, the Petoskey MD reported, among other things, that cancer leukemia deaths in Charlevoix increased 31% and 150% respectively. Comments about the paper including an aerial view of the Big Rock plant, appeared in the **Nuclear News.** Furthermore copies of the report apparently have been sent to two Michigan U. S. Congressmen, Senator Price of Illinois, and also to the Chairman of the Atomic Energy Commission, but addressed to the Pentagon.

Certainly the sincerity of the MD's concern is above question, but incorrect conclusions appear to have been drawn because of inadequate statistical analysis. The point that cannot be overemphasized is that death roles from such as cancer and leukemia in a small population sample as Charlevoix County can fluctuate widely, for the reason that death rates from these causes are very small. Statistical analysis is essential and it turns out that the statistical methods applicable to the study of "rare" events in human population is also just the method to analyze fluctuations in radioactive decay. The problem for radioactivity "deaths" was first analysed back in 1910 by Rutherford and Geiger, assisted by the Mathematician Bateman.

Consequently, it will be helpful to consider first the historic 1910 experiment by Rutherford and Geiger, and then see what can be done to analyse human population events. To make the mathematical parallelism clear, we will use the word population to describe either a nuclear or human sample, and the word death, to apply to nuclear deaths (radioactive decay) as well as to human deaths.

2. Rutherford, Geiger, Bateman Experiment

This experiment is discussed in Rutherford, Chadwick, and Ellis, p. 172, in R. B. Lindsay, **Introduction to Physical Statistics.** Also references to more recent investigations are given in Evans, **The Atomic Nucleus,** p. 777.

According to the paper by Rutherford, Geiger, and Bateman, a continuous record of alpha-particle scintillations produced by a film of Po (Polonium, Z-84) was made for 326 minutes. They recorded 10,097 counts (nuclear deaths!) during this interval. To analyze the results, they subdivided the interval week 1/8 minute sub-intervals, and found the counts during a particular 1/8 minute could vary from 0 to as high as 14, despite the fact that the average number of scintillations was 3.87. They then recorded the number of subintervals during which a particular number of counts were recorded. The results were as follows:

Table I

Counts	0	1	2	3	4	5	6	7
Subinterval	57	203	383	525	532	408	273	139
Counts	8	9	10	11	12	13	14	
Subinterval	145	27	10		0	1	1	

Thus, for example, during 57 subintervals, no count was registered, for 203 subintervals there was 1 count, etc. The average number was 3.87 per 1/8 minute interval, but we notice that during many intervals the recorded counts were 3 or even 4 times as large as the average value.

These results were analysed by using the Poisson distribution function

$$L_x = n \frac{m^x}{x!} e^{-m} \tag{1.1}$$

in which L_x is the number of intervals during which x scintillations were recorded, n is the number of time intervals, and m is the average number of scintillations, or as pointed out earlier, records of nuclear deaths.

Before going on, let us first see how the above result is obtained.

3. Poison Distribution

The steps leading to the Bateman Eq. (1.1) are given in Evans, p. 747. We start with

$$P_x = \frac{Z!}{x!\,(Z-x)!} P^x (1-P)^{Z-x}$$

in which

Z, population (sample size), nuclear or human
X, number of deaths, nuclear or human
p, probability of individual death, nuclear or human
Px, probability that x deaths will occur in the population

The population Z is in general a large number. Rutherford and Geiger did not indicate the size of the example they used, but this can be estimated easily by the following analysis. The number of counts on the average was slated to be about 4 in 1/8 minute, or about 32 counts/minute. This means that the nuclear death rate is 32/minute, i. e.,

$$\frac{dZ}{dt} = -32/\text{minute}$$

But according to the law of radioactive decay

$$\frac{dZ}{cM} = -\lambda Z$$

so that knowing the value of the left-hand side of the equation, we can compute Z, if λ is known. This quality, of course, is the decay constant and is related to the radioactive half-life by

$$\lambda = \frac{\ell n\ 2}{T_{\frac{1}{2}}}$$

The source used by Rutherford and Geiger was probably Po-210, whose half-life is about 138 days. Therefore

$$\lambda = \frac{\ell n\ 2}{T_{\frac{1}{2}}} = \frac{0.693}{138\ (24)\ (60)}$$

and from

$$\lambda Z = 32$$

we obtain

$$Z = \frac{32}{\lambda} = \frac{32\ (138)\ (24)\ (60)}{\ell n\ 2} \cong 9 \times 10^6$$

The very large value of Z justifies the use of the so-called Stirling approximation, namely

$$Z! \cong Z^{z + \frac{1}{2}}\sqrt{2\pi}\, e^{-Z}$$

(See, for example, W. Kaplan, **Adv. Calculus**, p. 453)

Hence

$$\frac{Z!}{(Z-x)!} = \frac{Z^{Z+\frac{1}{2}}\sqrt{2\pi}\,\ell^{-Z}}{(Z-x)^{Z-x+\frac{1}{2}}\sqrt{2\pi}\,\ell^{-(Z-x)}}$$

$$= \frac{Z^x}{(1 - {}^x/_Z)^{Z-x+\frac{1}{2}}\,\ell^x}$$

The limiting value of the denominator, for a large value of Z, is 1, as can be seen by the following analysis. Consider

$$\ell n\left[1 - {}^x/_Z\right]^{Z-x+\frac{1}{2}} = (Z - x + \tfrac{1}{2})\,\ell n\,(1 - {}^x/_Z)$$

$$= (Z - x + \tfrac{1}{2})\left[- {}^x/_Z + \qquad\right]$$

which in the limit of large Z is just-X.

$$(1 - {}^x/_Z)^{Z-x+\frac{1}{2}}\,\ell^x = 1$$

Furthermore

$$(1 - p)^{Z - x} \cong (\ell^{-p})^{Z - x} \cong \ell^{-pZ}$$

sothat

$$P_x = \frac{Z^x}{X!} p^x \ell^{-pZ} = \frac{(pZ)^x}{X!} \ell^{-pt} = \frac{m^x}{X!} \ell^{-m}$$

in which we have put $m = pZ$ for the average number of deaths for the population sample.

The average of "nuclear deaths" in the Rutherford Geiger experiment was about 3.87. The total number of 1/8 minute intervals was 2608, so that the expected number of intervals, for X nuclear deaths to occur is

$$L_x = 2608 P_x = 2608 \frac{(3.87)^x}{X!} e^{-3.87}$$

The following table gives a comparison of the observed and calculated values:

Table II

Scintillations	Obs	Calc.
0	57	54
1	203	210
2	383	407
3	525	525
4	532	508
5	408	394
6	273	254
7	139	140
8	45	68
9	27	29
10	10	11
11	4	4
12	0	1
13	1	1
14	1	1

The agreement is excellent. However, they observed that the agreement is less satisfactory if the subinterval was taken to be 1/4 minute, with half as many subintervals. Thus, to have good agreement, a large number of time intervals is essential.

IV. Leukemia Deaths in Charlevoix County

Let us now consider the application of the above statistical relations to a human population, namely the 16,000 or so of Charlevoix County. We need, however, to note that the agreement between observed statistics and calculated values cannot be expected to be as good as for the Rutherford Geiger experiment. For this there were 2,608 time intervals. The time interval used to analyze vital statistcs is generally one year, so that to get comparable agreement...between observation and calculated results... we would need statistics for 2,608 years. Another factor that could contribute to discrepancy between theory and experiment would be the population, which for Charlevoix County is only 16,000, compared to the nuclear population of about 10 million.

With these reservations in mind, let us now examine the leukemia statistcs. The following compilation was made hurriedly one Saturday afternoon in the Public Health library, so that there could be some errors. But the agreement is surprisingly good. For comparison, as a central group, the combined leukemia statistics for Luce and Mackinac Counties are listed, the reason being that the combined population (6,789 + 9,660 = 16,449) is very close to that of Charlevoix County (16,541). These two counties are in the upper Peninsula, to the north and northeast, and so away from the direction of prevailing winds, which is to the southeast.

Table III

Leukemia Deaths

Year	Charlevoix	Luce & Mackinac
	(16,541)	(16,449)
1950	1	1
1951	0	1
1952	0	2
1953	1	0
1954	0	0
1955	1	0
1956	0	3
1957	0	0
1958	2	1
1959	3	1
1960	0	2
1961	2	0
1962	1	0
1963	1	0
1964	0	1
1965	0	1
1966	2	2
1967	4	2
1968	0	1
1969	0	1
Total	18	19
Average	0.95/year	0.9/year

The Big Rock plant went into operation in 1962, so that the concern is primarily with the number of deaths from this date on. We notice that there were as many as 3 deaths in 1956 in Luce and Mackinac, and also in Charlevoix County in 1959, three years before the plant started. There were 4 cases in 1967, and we need to consider whether this number is outside of statistical expectations.

The statistics of Table III gives the lollowing result:

Leukemia Deaths	**Frequency**	
	Charlevoix	Luce &Mackinac
0	10 (7.74)	(7 (8.13)
1	5 (7.35)	8 (7.32)
2	3 (3.48)	4 (3.51)
3	1 (1.08)	1 (1.05)
4	1 (0.26)	0 (0.24)

The numbers in brackets are the calculated values. Interesting result is that 3 deaths in one year is to be expected about once in 20 years. However, the rate of 4 deaths per year is to be expected only about once in 100 years. Consequently, the 4 deaths in 1967 may possibly be outside of statistical fluctuation.

But even if the leukemia death rate of 4 for one year could be shown to be real, it would be difficult, if not impossible, to attribute it to nuclear power plant radioactive emissions. One reason is that the natural radiation level is substantially higher than plant emission levels. There is a cement factory close by, so that this could be the cause, but again this would be extremely difficult to show. The more nearly reasonable cause could be social factors. One is that there is an excellent clinic in Petoskey. This tends to attract patients and could have an apparent increase in leukemia cases because of the better clinical detection capabilities. Also the population age composition needs to be taken into account; the Charlevoix area is a resort area, and many go there to retire. It is known that in certain Florida counties the cancer and leukemia death rates are several times that of the national average. Cancer and leukemia are in a sense a rich man's disease, and so if this rate is high in Charlevoix, it could be an indication of the resident's financial status.

CHAPTER XII

Discussion: Benefits and Risks

> "The technological approach taken by the atomic power industry has been the most cautious in engineering history. It has been customary, heretofore, in other technologies, to proceed with applications first, safety being secondary, and to await an empirical balance between safety constraints and social value. Examples of this are present in the history of the automobile, air transport, and, of most recent public concern, the use of insecticides. The novel approach of the atomic industry in attempting to establish public safety prior to the construction and operation of atomic power plants is a direct consequence of the fact that the public interest has been the principal objective, rather than the immediate economic gain of the few. It has been assumed by the atomic industry that long term economic gains will follow demonstrated social values".

1. Shape of Things to Come

Not long ago, I attended a meeting of the Technical Advisory Council and the top management group of one of the major U. S. corporations. The meeting was called to discuss and to prepare the corporation for technical and social developments that might be coming in 20, 30, or even 50 years. The meeting opened with very brief comments from the vice-president, namely on the coming energy crisis-this subject was not yet being stressed by the media as it is today-and the rise of consumer legislations. The two-day meeting ended with the last speaker passing out a pamphlet on **Let the Seller Beware** and showing a film strip on consumer legislations and limited liabilities.

It was an eye-opening experience to me, because through the years, like many others, I had come to picture corporations and industrial organizations as profit-mongering ogres. This meeting made me realize that perhaps there is another side to the story. The second information that I got was the profound changes in social acceptance, such as for cars. It appears that near the turn of the century, when the horseless carriage was invented, some of the pedstrians were **frightened** by the monster, so that in England an ordinance was passed requiring such vehicles to be preceded by a man on foot carrying a lantern.

What I wondered about was that the record of the car industry would have been had the national leaders, state authorities, and even international organizations had met to discuss the economic, political, social, and environmental implications of the new technology and had carefully laid out plans for its development. Perhaps the groups could have asked and evaluated the impact of mining of the raw materials, like iron ore, and drilling of oil on the environement. Perhaps they could have asked themselves the question of the legitimate uses of the new technology and of the effect of building roads and speedways through metropolitan areas. And perhaps they could have been concerned about the toxicity of engine fumes and the problems of the disposition of old cars.

In contrast to the haphazard developments in the car industry, the nuclear technology has been from the very beginning concerned with the problems of safety, environmental impact, etc. For example, the report WASH–740 referred to frequently by the critics of nuclear power was undertaken by the AEC. The problem of bio-concentration, which the environmentalists have seized upon as an issue, was identified through an AEC program that was started in the early 1950's. The critics like Gofman and Tamplin have made much to do about skin tumors produced by radiation. But as noted earlier, the picture was taken from a book by Zirkle, which documents the research that was started under the Manhattan Project. Gofman and Tamplin's book was published 20 years later, in 1971.

Despite these precautionary actions, the AEC and other organizations related to the nuclear technology have come under critical attacks. There are no doubt a number of contributing factors, but one may be that the public feels uneasy about the licensing procedures for power reactors. As shown in the AEC pamphlet on **Atomic Power Safety**, one step in the licensing procedure calls for a public hearing, which citizens may attend to give testimony. Perhaps this step occurs too late; we shall return to this point later. Another source of distrust may stem from what might be called a cultural lag. The modus operandi of nuclear technology are those of spaceship economics; public thinking is still in terms of cowboy economics.

One inescapable implication of spaceship economics, it seems to me, is the concept of benefits and risks. In cowboy economics, which is based on infinite reservoir of resources and in infinite sink for waste products, risks do not have to be taken into account. For spaceship economics, both the resources and risks are finite, so that risks have to be evaluated carefully to maximize the benefits. Some may find this concept of benefits and risks repugnant, but it is an inescapable one, and my feeling is that we will be hearing more and more about it in the years to come. Not long ago I happened to mention this to a colleague in the humanities. I was then accused of condoning megacide, but my answer was that megacide is preferable to gigacide, and in the case of nuclear power, that we're talking about kilocide.

This subject of benefits and risks is dealt with in such papers as "Radiation in Perspective" by C. Starr (Nuclear Safety 5, 325 (1964), "Social Benefits versus Technological Risk" by C. Starr in Science 165 1232 (19 Sept. 1969), and "Nuclear Energy: Benefits versus Risk" by W. H. Jordan (Physics Today, P.32-38 (May 1970) .

We shall review some of the comments appearing in these papers and, then, propose a suitable plan of action.

2. USAEC Report WASH-740 (March 1957)

This report, referred to frequently by both proponents and critics of nuclear power, suggests that in the event of a major accident of a large nuclear power plant, there could be damages up to about $7B in addition to about 3,000 deaths. The maximum credible accident is taken to be one in which 50% of the radioactive inventory of a 500 MW(t) nuclear powerplant is released. The estimated radioactivity of such a power plant is about 400 Megacuries. A sobering fact we need to keep in mind is that nuclear power plants under construction today or in the planning stage are in the 1000 MW(e) range. The thermal efficiency is about 1/3, so that for modern power plants, the thermal ratings will be closer to 3000 MW(t) and not just 500 MW(t). In addition the value of the estimated damage is based on the 1957 dollar.

There are several points that the critics do not point out. The fact that this is a USAEC report is often not mentioned. Another is that the report is best described by the subtitle in italics "A Study of Possible Consequences if Certain Assumed Accidents, Theoretically Possible but Highly Improbable, Were to Occur in Large Nuclear Power Plants". What the critics fail to mention is that the report estimates the probability of the occurrence of a catastrophic accident to be somewhere between 100,000 and 10^9 per reactor year. The small probability stems from the fact that for the worst imaginable accident to occur, a complex series of improbable adverse circumstances must occur simultaneously. This probability has been likened to the probability that a large jet plane, say a B-747, would crash into the center of a fully packed football stadium.

The following analysis given by Starr is instructive. He supposes that the stadium is about 100 yards in radius. There are about 100 stadiums in the United States so that relative probability of a plane crashing into the stadium area to any other part of the United States is given by the ratio of the two areas, namely

$$\frac{100\,(300)^2}{3.6 \times 10^6\,(5280)^2} = 9 \times 10^{-8}$$

in which 3.6 million square miles is the land area of the United States. In one year, there are on the average about 3.5 crashes on scheduled airlines, so that the probability of a plance crashing into any one of the 100 stadiums in any one year is about 320×10^{-9}, or 320 chances in a billion (320 times in a billion years). But stadiums are empty the bulk of the time. If we assume that they are occupied 4 hours a week, every week of the year, then the probability falls to 2×10^{-9}. The probability is very small and perhaps this is the reason for our intuitive feeling of being **safe** from commercial airline crashes while watching football games Saturday afternoon.

This example give us, then, a rough semi-quantitative feeling for the concept of safeness. It appears then that hazards of the order of a few times in a billion per year is **quite** safe. Riding in a private car is less safe, because according to statistics, the chances of death from a car accident while riding is about one per million hours. If a person spends two hours every day in a private car then his chances of meeting accidental death is 730×10^{-6}/year, or roughly 10^{-3}/year.

3. Windscale Accident

This accident, although considered by many to be the worst nuclear accident to date, does not seem to be anywhere close to the maximum credible accident postulated in the WASH-740 report. The accident occurred in October, 1957; the chances of a similar accident occurring is close to zero, and in Michigan, it would be safe to say that it would never occur. In the first place, the Windscale pile (England) was an air-cooled graphite reactor; at present there is no plan to build reactors of this type. The second reason is that the Windscale pile did not have the domeshaped spherical containment vessel; the accident was such that the radioactivity would have been contained if such a vessel had been present. It will be recalled that all power reactors under construction in Michigan are to have the huge, spherical containment vessel.

Published reports state that the Windscale accident released the following amounts of radioactive materials:

I - 131	20,000 Ci
Co - 137	600
Sr - 89	80
Sr - 90	9

There, however, seems to be a typographical error, because the data is not internally consistent. Using the information given in the Radiological Health Handbook, the following results are obtained:

	Ci	gm/Ci	gm	Millimoles	Fission yield (%)
I - 131	20,000	8.06×10^{-6}	0.16	1.25	2.93
Cs - 137	600	1.32×10^{-2}	6.12	45	6.15
Sr - 89	80	3.44×10^{-5}	0.00275	0.034	4.79
Sr - 90	9	6.96×10^{-3}	0.063	0.07	5.77

The Cs-137 release of 45 millimoles is very large in comparison to, say, I-131; the known fission yields would have suggested that the amount of Cs-137 would be about 2 to 3 times that of I-131. The discrepancy can be removed by interchanging Cs-137 and Sr-89 radioactive releases. Thus.

Released Radioactivity

	cm/Ci	Ci	gm	millimole	Fission Yield (%)
I - 131	8.06×10^{-6}	20,000	0.16	1.25	2.93
Cs - 137	1.02×10^{-2}	600	0.82	6.0	6.15
Sr - 89	3.44×10^{-5}	80	0.021	0.21	4.79
Sr - 90	6.96×10^{-3}	9	0.063	0.71	5.77

This assignment of radioactivity gives more nearly consistent results. For example, the Cs-137/I-131 ratio is about 5, compared to the 2.1 ratio expected from fission yield data. One point to notice that the amount of Sr released seems to be small in comparison to Cs-137; if the data is correct, the difference could be attributed to the boiling points. Cs boils at 670°C, compared to 1150°C for Sr. For iodine, the boiling point is about 183°C. Thus Sr is the least volatile, I is the most volatile, so that in recent years, there has been less concern for Sr but more for I.

Another point to speculate about is the comparison of this accident with the postulated possibility of WASH-740. The power of the Windscale pile seems to be uncertain, but it probably was in the 10 MW(t) range. Hence if we were to use a factor of 50, the radioactive release could have been in the Megacurie range, which is about 1% of the postulated value.

4. Price-Anderson Act

Some critics assert that this Act is an indication of insurance companies' lack of confidence in the power reactor safeguards. What the critics fail to mention is that insurance companies do not underwrite risks where actuarial data do not exist. One of the most recent well-reported cases is that of the astronaut, John Glenn. At the time of the first orbital flight, in Feb. 1962, the media reported that no insurance company would issue a policy.

The article by Chauncey Starr gives a defense for the Price-Anderson Act. The article states that it is not unusual for the Federal Government to provide insurance when private insurance companies cannot provide the necessary protection. He quotes from the "Federal Disaster Insurance" Staff Study, Report of the Committee on Banking and Currency, U. S. Senate, Jan. 1956, pages 251 to 252:

> "The Congress has already enacted into law several programs incorporating the insurance method or a related indemnity method with the payment of fees or charges. These include such programs as
>
> 1. Crop insurance
> 2. Bank deposit insurance
> 3. Savings and loan account insurance
> 4. Housing mortgage insurance (FHA and VA)
> 5. Maritime vessel mortgage insurance
> 6. Maritime cargo wartime insurance
> 7. Aviation wartime insurance
> 8. Veteran's life insurance
> 9. Unemployment insurance
> 10. Old-age and survivor's insurance
> 11. Government employees' insurance
> 12. Export-Import bank tangible guaranty program
> 13. Mutual Security Act investment guaranty program
> 14. V-loans guaranteed by Federal Government agencies and
> 15. War damage insurance
>
> It can be readily seen that the insurance device has already gained wide use in Federal programs. Several of these programs were inaugurated by Federal legislations at a time when persons in private business cast strong doubts in their workability; but as operating experience pregressed, the confidence of private businessmen in the program grew so that now many of them have become part and parcel of everday business transaction stoutly defended by some of the same groups that were first hesitant about their praticality".

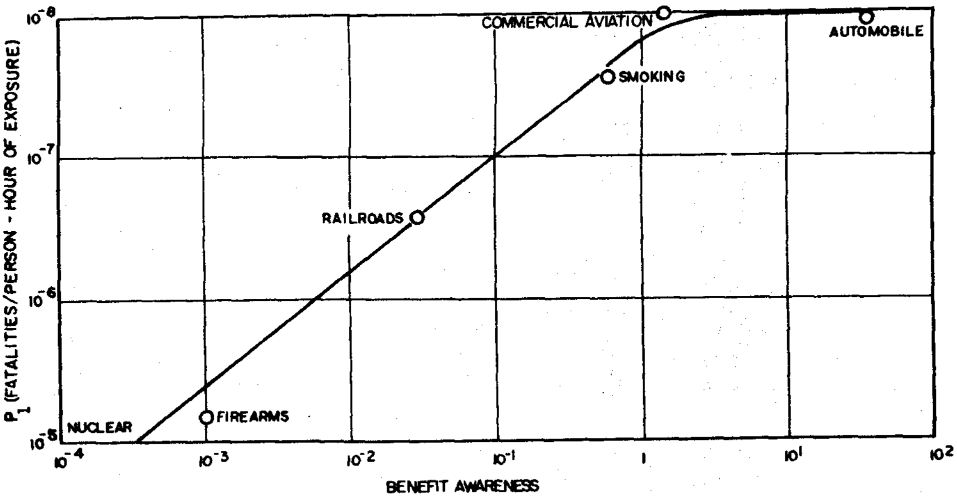
The critics of nuclear power assert that the Price-Anderson Act encourages electric utilities to take unwarranted risks. Maybe, but the deterrent is that an accident will cripple the entire nuclear industry. It is difficult to see why a company would take the risk.

5. Technological Risks

That for every benefit there are risks (including monetary costs) is as universal as the second law of thermodynamics. This law, well know in physics, states the physical processes occuring in nature are irreversible, so that in the process of obtaining useful (beneficial) work, certain fraction of the intake heat is unavoidably wasted(unless the lower working temperature is zero degree absolute). As we have already noted, for both fossil and nuclear power plants, the thermal efficiency is about 1/3, so that 2/3 of the input energy is wasted. We should note, however, that hydroelectric plants are close to 100% efficient, because they are not heat engines. A short time ago we happened to stop at the TVA Norris Dam, and as I came out of the men's room, I told my wife that I didn't mind using the electric hand-dryer, because there is very little wasted heat energy. But for a hand-dryer in Ann Arbor, for example, only 1/3 of the energy burned at the power plant is available for end use; 2/3 of the energy is wasted. Even plants, as we have seen, produce "thermal pollution".

What we might call the low of benefits and risks is but a *societal generalization* of the Second Law of Thermodynamics. For any benefit, we need to pay in costs or risks. As we have seen, energy-wise, Al production is an extremely costly, i.e. about the equivalent of 15 tons of coal is consumed to produce one tone of Al. The energy cost of producing Si is even greater, despite its abundance. Thus there is the inevitable cost in energy, to be able to convert solar energy into electric power. We have heard about the marvels of modern medicine; but here the risks are quite high. I've known a research pharmacologist who would not let his wife take pills during pregnancy; he was too aware of the high risks.

In the article by Starr, there is an interesting plot showing how awareness leads to acceptance of higher risks. The plot is as follows:



Perhaps this plot should not be taken too literally. But we need to remind ourselves that the public, because of massive advertising, is often unaware of the risks involved in obtaining the benefits.

6. Planning for the Future

Possibly a crucial point to be kept in mind is that an individual is willing to accept relatively high risks for voluntary activities but will demand low risks for involuntary activities. Thus, as Starr points out, an individual may be willing to assume the risks of flying private planes, undergoing surgery, climbing mountains, etc. and yet be unwilling to acept the involuntary risks of nuclear power plants, no matter how small. Perhaps the following comments by Starr are pertinent:

> "Involuntary activities differ in that the criterion and options are determined not by the individuals affected but by a controlling body. Such control may be in the

> hands of a government agency, a political entity, a leadership group, an assembly of authorities or "opinion makers", or a combination of such bodies. Because of the complexity of large societies, only the control group is likely to be fully aware of all the criteria and options involved in the decision process. Further the time required for feedback of the experience that results from the controlling decision is likely to be very long. The feedback of cumulative individual experience into societal communication channels is a slow process, as is the process of altering the planning of the control group".

The hope of the AEC in developing the nuclear industry, it seems, was that there will be a well-informed public to steer the direction of the "control group", which we small take to be the electric utilities. The public could have availed themselves of the problems identified by the AEC programs of 20 to 30 years standing. Putnam's book on **Energy in the Future** was sponsored by the AEC some 30 years ago. The problem of bioconcentration was identified about 20 years ago. And even the WASH-740 report is now 14 years old. Furthermore, it should be pointed out that these are not highly mathematical and technical reports; they are descriptive and qualitative. The comments that the critics are making today in 1973 are often taken verbatim from the early reports. Thus it is quite clear that the public as a whole cannot be depended upon to exert intelligent control over the control groups. And as Starr states, "...society has generally clothed many of its controlling groups in an almost impenetrable mantle of authority and of imputed wisdom".

The solution to the problem may be to organize various **control groups** to study the problem of the impact of a technology from a broader base. In a recent article "Forensic Science-A Proposal", in the March issue of the Bulletin of the Atomic Scientists, Donald P. Gessaman and Dean E. Abrahamson proposed organizing forensic science groups, consisting of economists, lawyers, physicians, etc. Perhaps such groups can assess the technical requirements of our society and be able to make recommendations more nearly acceptable to the public.

As for my part, I have been toying with the idea of generating a study group in our own Nuclear Engineering Department, in colaboration with other disciplines, such as Natural Resources, to examine the energy requirements of say Southeast Michigan, hopefuly interesting members of the state legislature.

In this connection, perhaps we need to remind ourselves of the words by Glenn T. Seaborg, appearing in Newsweek, Jan. 4, 1971. He said

> "In our highly technological society, where we face many problems as a result of excessive and poorly planned uses of science and technology, it is understandable that nuclear energy should come under attack as part of the public's disillusionment with science and technology. These issues-including the effect of nuclear energy on the environment-should be vigorously debated. In the case of nuclear power, I believe that when all sides are heard and all the facts presented, the public will agree that the advantages outweight any problems. In fact, the development of nuclear power may prove to be a turning point in the way we plan and develop most of our future technologies".

The least we can do is to give his ideas a try.

REFERENCES

1 - HOGERTON, J. F. *Atomic power safety.* Washington, D. C., USAEC, 1964.
2 - STARR, C. Radiation in perspective. *Nucl. Saf.,* Washington, D. C., 5:325-35, 1964.
3 - ———. Social benefits versus technological risk. *Science,* New York, 165:1232-8, 1969.
4 - JORDAN, W. H. Nuclear energy: benefits versus risks. *Physics to-day,* New York, 23 (5):32-8, 1970.
5 - GEESAMAN, D. P. & ABRAHAMSON, D. E. Forensic science: a proposal. *Bull. atom. Scient.,* Chicago, 29 (3):17-24, 1973.
6 - HAMMOND, R. P. Nuclear power risks. *Am. Scient.,* New Haven, 62:155, Mar./Apr. 1974.

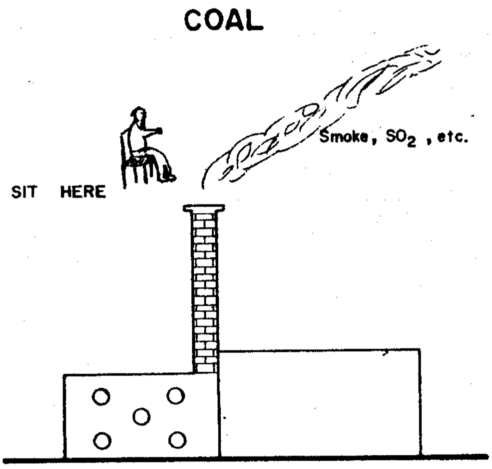
CHAPTER XIII

Coal vs Nuclear Power Plants

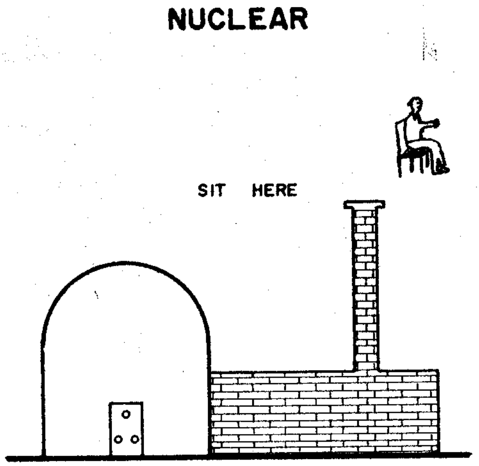
1. Comments

The paper by D. J. Rose, **Nuclear Electric Power** (Science 184, 351 (19 April 1974) raises some interesting points about nuclear power plants compared to coal plants. Some of Rose's conclusions are based on a paper by L. B. Lave and L. C. Freeburg, **Health Effects of Electricity Generation from Coal, Oil and Nuclear Fuel,** (Nuclear Safety 14, 409 (Sept.-Oct., 1973)).

To get a graphic picture of the relative merits (or risks), consider the following:



COAL TURBINE BLDG



NUCLEAR FUEL (SEALED)

The economics of the two types of power plants need to be discussed; but there are comments in Rose's paper so we shall not discuss them here. In addition to the economic cost, the **cost** stemming from public risks needs to be evaluated. As for the risks stemming from mining, Love and Freeburg indicate that uranium mining is much safer.

What we might consider carefully, however, is the health risks to the public resulting from electric power generation. And to make the problem as concrete as possible, we shall consider the health risk to an individual sitting on the rim of the stacks for one hour. The question is: Which will present the greater risk to a person, the effluents from the stack of a coal plant, or the effluents from a nuclear plant?

Before we get into the details, let us first make a few observations.

(1) Stacks. The stacks serve two very different purposes. For the coal plant, it is essential for the generation of electric power; for the nuclear plant, it is not. For the coal plant, the stack is connected to the furnace, in which coal is burned. For the nuclear plant, on the other hand, the stack is not connected to the reactor core in which the nuclear fuel is burned; the stack is

for ventillation purposes.

This fact would tend to suggest that the nuclear power plant stack would be safer.

(2) Effluents. For the coal plant, about 90% of the burned fuel comes up the stack; for the nuclear plant, a very small fraction comes up.

So again qualitatively we might begin to see that the nuclear plant stack is safer to sit on.

Let us put these ideas into more quantitative terms. For the coal plant let us focus our attention on the SO_2 effluent, and compare its personal health risk to the risk from radioactive effluents. To make a quantitative evaluation, consider the following table.

(1000 MW(e) Plant)

Coal	Nuclear
1. Fuel 3,000,000 Tons/YR	1 Ton
2. Ash 300,000 Tons	1 Ton
3. Gas Effluent	
SO_2 3.06×10^8 lbs	
Particulates 9.9×10^6 lbs	Radioactivity (Kr-85, Xe-133)
Ra-226 0.0172 Ci	BWR 1.6×10^4 Ci
Ra-228 0.0108 Ci	
Oxygen — depleted	
CO_2 CO	
4. Standard SO_2 80 μgm/m^3	3×10^5 pCi/m^3

The risks from breathing the air depends clearly upon the pollutant concentration. According to EPA and AEC standards, SO_2 concentration of 80 μ gm/m^3 and Kr-Xe gas concentrations giving 3×10^5 p Ci/m^3 are considered to be safe enough.

The SO_2 standards are based on observations. In London, a rise in the daily death rate of 20% or more has been detected for SO_2 concentrations of 0.5 ppm lasting for a **full day**. Daily mean concentrations of 0.2 ppm lasting for 3 or 4 days has led to increased mortality in Rotterdam. In New York, there have been increased hospital admisions when the SO_2 concentrations were around 0.25 ppm. The concentration 0.2 ppm is about 240 μ gm/m^3, or about 3 times the EPA standard.

For the radiation standard, the basis is quite different and there is no evidence that radioactive viable gases giving the activity, has ever produced ill health effects. The standards for radioactive materials in air are set in such a way that a person breathing that air continuously for **one year** will not absorb more than 5 rads of radiation in one year for occupational exposure and not more than 0.5 rad for an individual of the public-at-large. There is evidence that large doses of radiation (defined as 50 rads or more) are harmful, and there are scattered peices of evidence suggesting that small doses might be beneficial. The standard of 5 rad/year is essentially an extrapolation from high dose effects. The assumption is made that 50 rads delivered over a span of 10 years has the same effect as 50 rads delivered in an instant.

In other words, it is assumed that there are no repair mechanisms; this of course is not necessarily true, because the existence of chromosome repair mechanisms for certain cases have been demonstrated in the laboratory.

To calculate the pollutant concentration, the air flow rate is needed. A reasonable number for this is about 200,000 ft^3/min. for both coal and nuclear plants. Since

$$1 \text{ ft}^3 = 0.0283 \text{ m}^3$$

the above flow rate amounts to about 100 m^3/sec. Also, for the SO_2 release rate, we have

$$3.06 \times 10^8 \text{ ebs/yr} = 4{,}500 \text{ gm/sec}$$

giving then the concentration of 45gm/cm^3, which is roughly 500,000 times the allowed standards. Let us call this quantity the personal health risk index; this is the ratio of the actual pollutant concentration to the allowable concentration

For the radioactive releases we have

$$1.6 \times 10^4 \text{ Ci/yr} = 5 \times 10^{-4} \text{ Ci/sec.}$$

which gives

$$\frac{5 \times 10^{-4} \text{ Ci/sec}}{100 \text{ m}^3\text{/sec}} = 5 \times 10^{-6} \text{ Ci/m}^3$$

The standard is

$$3 \times 10^5 \text{ p Ci/m}^3 = 3 \times 10^{-7} \text{ Ci/m}^3$$

so that the personal health risk index is

$$\frac{5 \times 10^{-6}}{3 \times 10^{-7}} = 17.$$

As stressed already, SO_2 concentrations of 80 μgm/m^3 lasting for a few days are known to produce ill health effects. In contrast, there is no known effects arising from a person living one year in an atmosphere containing

$$3 \times 10^5 \text{ p Ci/m}^3 \text{ of Kr-85 and Xe-133.}$$

This is a striking example of the conservatism-the margin of safety-built into radiation standards.

CHAPTER XIV

Atmospheric Transport Mechanisms

1. Comments

Concern is often expressed about the invisible radiations from nuclear power plant stacks. The purpose of this chapter is to give some insight to the mechanisms that bring about atmospheric dilution of radioactive effluents.

2. Lapse Rate

This is the technical term used for the rate of atmospheric temperature drop with height and determines to a large extent whether the released warm air, containing the pollutants will rise or fall. In the troposphere, which is the part of the atmosphere nearest to ground, the temperature drops steadily with altitude to about-50 to-80°C at a rate of about 6,5°C/km(about-19°F/mi). This is referred to as the **lapse rate** of the troposphere.

The **adiabatic lapse rate** is the rate of temperature change with altitude, if the released warm air is allowed to expand adiabatically. The importance of this quantity is almost obvious. If the temperature of the released air is higher than the surroundings, the density is less and therefore will continue to rise. The ascent time is short so that we can assume the expansion is adiabatic. The adiabatic lapse rate is about 9.8°C/Km, which is obtained as follows. From the ideal gas law, we have

$$PV = n\,RT$$

From the hidrostatic equation

$$\frac{\partial P}{\partial h} = g\rho = -g_n M/V$$

in which M is the mean molecular which, for the mean molecular which, for the atmosphere is about 28.97 gm/gm mole. For adiabatic expansion

$$PV^{\gamma} = P_o V_o^{\gamma} \quad \frac{T}{T_o} = (\frac{P}{P_o})^{R/C_p}$$

where

$\gamma = Cp/Cv$

$\gamma = 1.40$ (AIR)

$C_p = 3{,}5\ R$ (AIR)

Then the lapse rate is given by

$$\frac{\partial T}{\partial h} = \frac{\partial T}{\partial P}\frac{\partial P}{\partial h}$$

and since

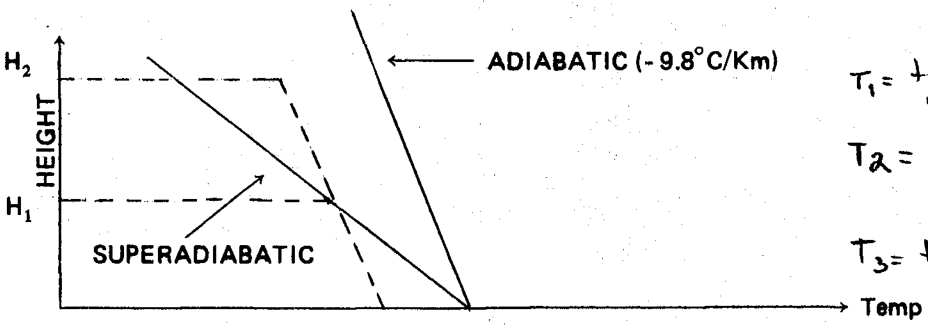
$$\frac{\partial T}{\partial P} = T_o \left(\frac{R}{C_p}\right) \frac{P^{R/C_p - 1}}{P_o^{R/C_p}} \frac{V}{nC_p}$$

we obtain

$$\frac{\partial T}{\partial h} = \left(-\,gn\,\frac{M}{V}\right) \frac{V}{nC_p} = -\frac{gM}{C_p}$$

which gives the quoted value of -9.8°C/Km.

The actual atmospheric lapse rate depends upon weather conditions. On sunny days, the ground temperature rises, and the lapse becomes numerically large, i.e. it becomes super adiabatic. The effect of this situation upon a released mass of air can be seen from the following diagrams



T_1 = temperatura inicial do ar liberado

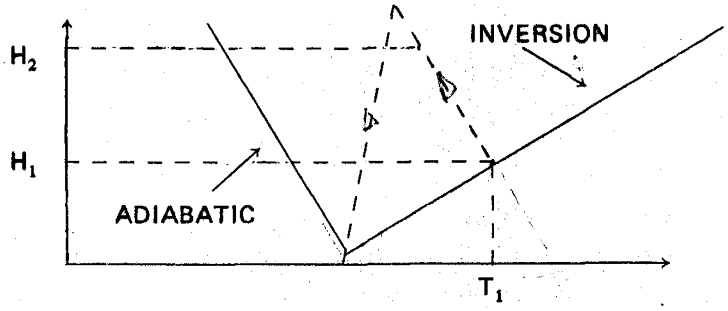
T_2 = temp. final (H_2) do ar liberado

T_3 = temperatura da atmosfera circundante.

Suppose the parcel of air is released at height H_1 at temperature T_1. As it rises, its temperature drops, along the dotted line, parallel to the adiabatic lapse rate. Its temperature is warner relative to its surroundings, the density is less, so that it will be accelerated upward. This then would be favorable for the dispersal of air pollutants.

Note that the meteorologist's way of plotting lapse rate is somewhat confusing. The lapse rate, by definition is given by $\partial T/\partial h$ i.e. the temperature is the dependent variable and the altitude is the independent variable.

The opposite extreme case is inversion, for which the lapse rate is positive. This could be caused by warm air over cold air, or at night, when the ground temperature drops by radiating the absorbed heat into the surrounding atmosphere. The situation is as follows:



When the parcel of air rises to H_2 the buoyant force becomes zero.

2. Continuous Release

For a continuous point source the downwind concentration of radioactive materials is taken to be given by

$$\chi_{(x,y)} = \frac{Q}{2\pi\sigma_y\sigma_Z\bar{\mu}} \exp\left[-\left(\frac{h^2}{2\sigma_Z^2} + \frac{y^2}{2\sigma_y^2}\right)\right]$$

where

χ - downwind concentration

Ci/m^3 at (x, y, z)

Q=source strength

σ_y, σ_z=crosswind and vertical plume standard deviation (m)

μ=mean wind speed (m/sec)

h=effective stack height

Consider then the release from the stack considered earlier at a point 5 to 10 miles downwind. The annual release is about 1.6×10^4 Ci so that this gives

$$Q = 1.6 \times 10^4 \text{ Ci/yr} = 5 \times 10^{-4} \text{ Ci/sec}$$

The standard deviations, σ_y and σ_z depend upon weather conditions (See Eisenbud, pp. 97 and 98). At 5 miles, σ_y varies between 200 m and 1Km, Let us assume the average value of about 500 m. Also assume about 2 Km for σ_z. The mean wind speed in Michigan is about 15 mi/hr. or about 6.7 m/sec. The concentration turns out to be about which is an extremely small number.

CHAPTER XV.

Pathways of I-131 to Man

1. The Environmental Problem

One of the concerns of nuclear power is the radioactive I-131, which could escape into the atmosphere and add to human radiation dosage. The problem arises because iodine is essential for life but its concentration is extremely low. The amount of iodine in the human body is about 0.03 gms for a standard man (70 Kgms), giving a concentration of about 43 ppm by weight. In the environment, the iodine concentration is frequently very low and hence often needs to be augemented in our diet. The abundance of iodine in the earth's crust is only about 0.3 ppm and ranks #63 among the elements. For comparison, not that thorium, uranium, silver, and gold rank #39 (12 ppm), #50 (4 ppm), #67 (0.1 ppm), and #71 (0.005 ppm) respectively. Tables 1, 2, and 3 give the abundance of elements in the earth's crust, in sea water, and in standard man respectively.

Consider then the following situation:

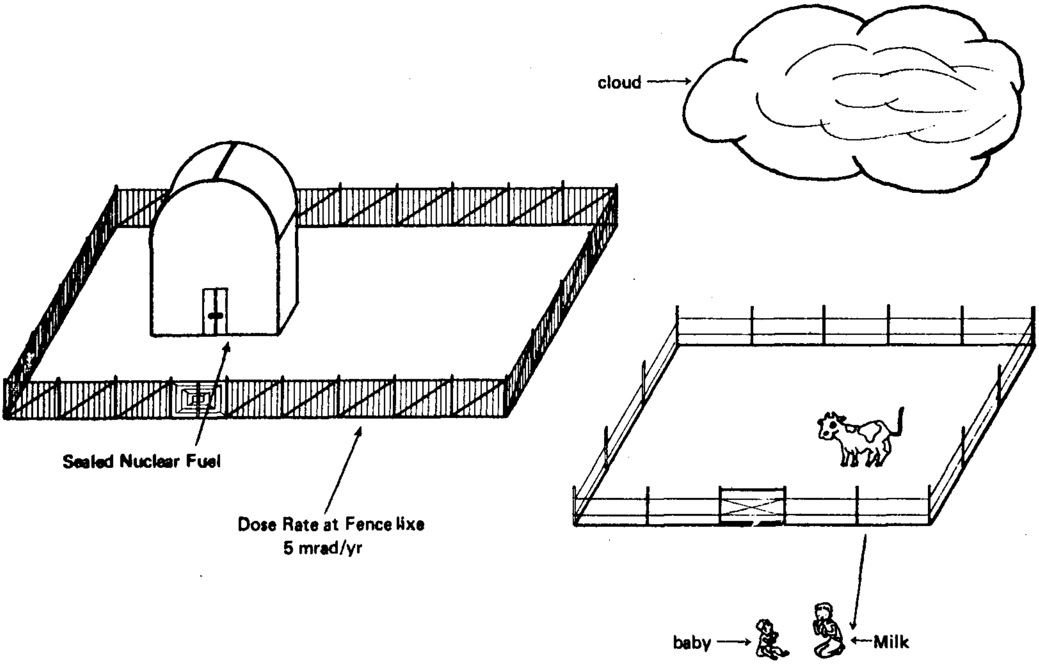


Table I

Average Amounts of the Elements in the Earth's Crust*

In Grams Per Metric Ton or Parts Per Million

Element	Quantity	Element	Quantity	Element	Quantity
O	466,000	N	46	Br	1.6
Si	277,200	Ce	46	Ho	1.2
Al	81.300	Sn	40	Eu	1.1
Fe	50.000	Y	28	Sb	1?
Ca	36,300	Nd	24	Tb	0.9
Na	28,300	Nb	24	Lu	0.8
K	25,900	Co	23	Tl	0.6
Mg	20,900	La	18	Hg	0.5
Ti	4.400	Pb	16	I	0.3
H	1,400	Ga	15	Bi	0.2
P	1,180	Mo	15	Tm	0.2
Mn	1,000	Th	12	Cd	0.15
S	520	Cs	7	Ag	0.1
C	320	Ge	7	In	0.1
Cl	314	Sm	6.5	Se	0.09
Rb	310	Gd	6.4	Ar	0.04
F	300	Be	6	Pd	0.01
Sr	300	Pr	5.5	Pt	0.005
Ba	250	Sc	5	Au	0.005
Zr	220	As	5	He	0.003
Cr	200	Hf	4.5	Te	0.002?
V	150	Dy	4.5	Rh	0.001
Zn	132	U	4	Re	0.001
Ni	80	B	3	Ir	0.001
Cu	70	Yb	2.7	Os	0.001?
W	69	Er	2.5	Ru	0.001?
Li	65	Ta	2.1		

---

* From: "Principles of Geochemistry", B. Mason, John Wiley & Sons, 1952.

Table 2

Elements in Solution in Sea Water (Except Dissolved Gases)[1,2]

Element	mg/kg Cl = 19.00%	Total in oceans (tons)	Natural activities		
			Nuclide	Total (tons)	Curies
Chlorine	18,980	2.66×10^{16}			
Sodium	10,561	1.48×10^{16}			
Magnesium	1,272	1.78×10^{15}			
Sulfur	884	1.23×10^{15}			
Calcium	400	5.6×10^{14}			
Potassium	380	5.3×10^{14}	K^{40}	6.8×10^{10}	4.6×10^{11}
Bromine	65	9.1×10^{13}			
Carbon	28	3.9×10^{13}	C^{14}		2.7×10^{8}
Strontium	13	1.8×10^{13}			
Boron	4.6	6.4×10^{12}			
Silicon	0.02 -4.0	$0.028\text{-}5.6 \times 10^{12}$			
Fluorine	1.4	2×10^{12}			
Nitrogen (comp.).	0.01 -0.7	$0.14\text{-}9.8 \times 10^{11}$			
Aluminium	0.5	7×10^{11}			
Rubidium	0.2	2.8×10^{11}	Rb^{87}	1.18×10^{11}	8.4×10^{9}
Lithium	0.1	1.4×10^{11}			
Phosphorus	0.001-0.1	$0.014\text{-}1.4 \times 10^{11}$			
Barium	0.05	7×10^{10}			
Iodine	0.05	7×10^{10}			
Arsenic	0.01 -0.02	$1.4\text{-}2.8 \times 10^{10}$			
Iron	0.002-0.02	$0.28\text{-}2.8 \times 10^{10}$			
Manganese	0.001-0.01	$0.14\text{-}1.4 \times 10^{10}$			
Copper	0.001-0.01	$0.14\text{-}1.4 \times 10^{10}$			
Zinc	0.005	7×10^{9}			
Lead	0.004	5.6×10^{9}			
Selenium	0.004	5.6×10^{9}			
Cesium	0.002	2.8×10^{9}			
Uranium	0.0015	2.1×10^{9}	U^{238}	2.8×10^{9}	3.8×10^{9}
Molybdenum	0.0005	7×10^{8}	U^{235}	2.1×10^{7}	1.1×10^{8}
Thorium	$<$ 0.0005	$<7 \times 10^{8}$	Th^{232}	1.4×10^{7}	8×10^{6}
Cerium	0.0004	5.6×10^{9}			
Silver	0.0003	4.2×10^{8}			
Vanadium	0.0003	4.2×10^{8}			
Lanthanum	0.0003	4.2×10^{8}			
Yttrium	0.0003	4.2×10^{8}			
Nickel	0.0001	1.4×10^{7}			
Scandium	0.00004	5.6×10^{7}			
Mercury	0.00003	4.2×10^{7}			
Gold	0.000006	8.4×10^{6}			
Radium	$0.2\text{-}3 \times 10^{-10}$	28 -420	Ra^{226}	4.2×10^{2}	1.1×10^{9}

---

[1] Sverdrup, H. U., M. W. Johnson, and R. H. Fleming, OCEANS (1942).

[2] Revelle, R., T. R. Folsom, E. D. Goldberg and J. D. Isaacs (1955).

Table 3

Report of Committee Two

Element distribution in total body of the standard man
(Average chemical composition of the adult human body)

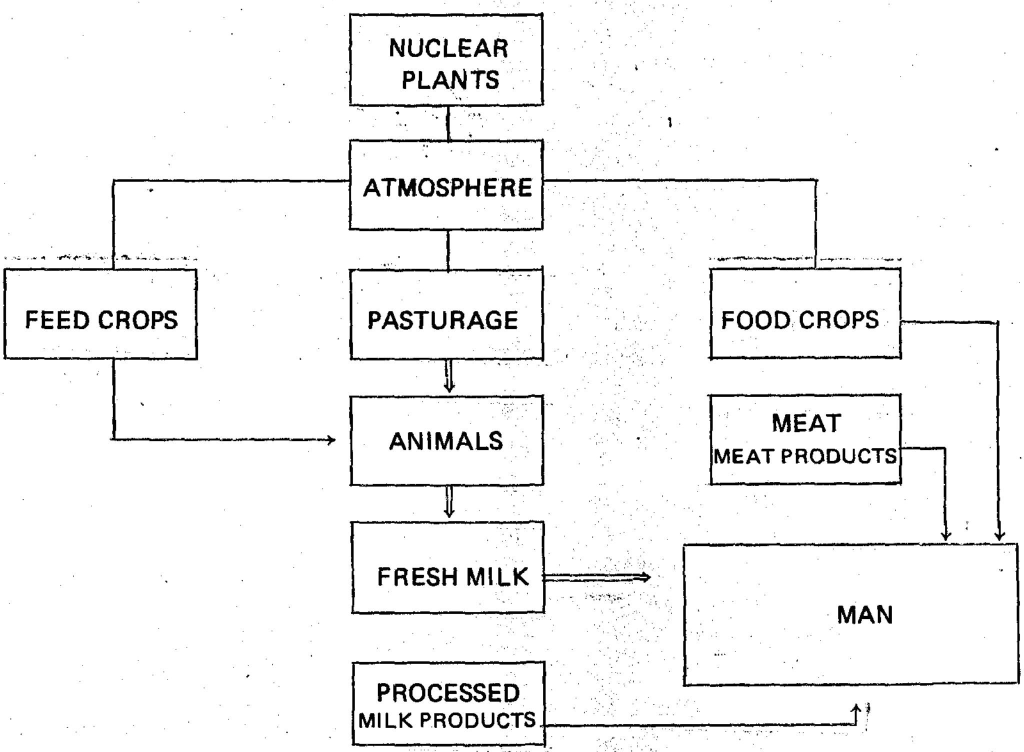
Element		Per cent by weight	Approximate amount in 70 kg man (g)
Oxygen	(O)	65.0	45,500
Carbon	(C)	18.0	12,600
Hydrogen	(H)	10.0	7000
Nitrogen	(N)	3.0	2100
Calcium	(Ca)	1.5	1050
Phosphorus	(P)	1.0	700
Sulfur	(S)	0.25	175
Potassium	(K)	0.2	140
Sodium	(Na)	0.15	105
Chlorine	(Cl)	0.15	105
Magnesium	(Mg)	0.05	35
Iron	(Fe)	0.0057	4
Zinc	(Zn)	0.0033	2.3
Rubidium	(Rb)	0.0017	1.2
Strontium	(Sr)	2×10^{-4}	0.14
Copper	(Cu)	1.4×10^{-4}	0.1
Aluminium	(Al)	1.4×10^{-4}	0.1
Lead	(Pb)	1.1×10^{-4}	0.08
Tin	(Sn)	4.3×10^{-5}	0.03
Iodine	(I)	4.3×10^{-5}	0.03
Cadmium	(Cd)	4.3×10^{-5}	0.03
Manganese	(Mn)	3×10^{-5}	0.02
Barium	(Ba)	2.3×10^{-5}	0.016
Arsenic	(As)	$<1.4 \times 10^{-4}$	<0.1
Antimony	(Sb)	$<1.3 \times 10^{-4}$	<0.09
Lanthanum	(La)	$< 7 \times 10^{-5}$	<0.05
Niobium	(Nb)	$< 7 \times 10^{-5}$	<0.05
Titanium	(Ti)	$<2.1 \times 10^{-5}$	<0.015
Nickel	(Ni)	$<1.4 \times 10^{-5}$	<0.01
Boron	(B)	$<1.4 \times 10^{-5}$	<0.01
Chromium	(Cr)	$<8.6 \times 10^{-6}$	<0.006
Ruthenium	(Ru)	$<8.6 \times 10^{-6}$	<0.006
Thallium	(Tl)	$<8.6 \times 10^{-6}$	<0.006
Zirconium	(Zr)	$<8.6 \times 10^{-6}$	<0.006
Molybdenum	(Mo)	$< 7 \times 10^{-6}$	<0.005
Cobalt	(Co)	$<4.3 \times 10^{-6}$	<0.003
Beryllium	(Be)	$< 3 \times 10^{-6}$	<0.002
Gold	(Au)	$<1.4 \times 10^{-6}$	<0.001
Silver	(Ag)	$<1.4 \times 10^{-6}$	<0.001
Lithium	(Li)	$<1.3 \times 10^{-6}$	$<9 \times 10^{-4}$
Bismuth	(Bi)	$<4.3 \times 10^{-7}$	$<3 \times 10^{-4}$
Vanadium	(V)	$<1.4 \times 10^{-7}$	$<10^{-4}$
Uranium	(U)	3×10^{-8}	2×10^{-5}
Cesium	(Cs)	$<1.4 \times 10^{-8}$	$<10^{-5}$
Gallium	(Ga)	$< 3 \times 10^{-9}$	$<2 \times 10^{-6}$
Radium	(Ra)	1.4×10^{-13}	10^{-10}

The nuclear fuel is sealed in fuel rods, but through several mechanisms, a portion of the I-131 in the reactor core will escape to the outside. The ventillation stack exhausts some of the radioactive materials, like I-131, that have escaped into the turbine building and other structures. The radioactive I-131 is dispersed in the air, but as it spreads, part of it settles to the ground. Suppose a part of it is desposited in farm land, say a pasture. Cows grazing on this pasture will reconcentrate the radioactive I-131, because iodine is an essential mineral. A portion of this reconcentrated I-131 will appear in the milk they give. If a child drinks this milk, the radioactive iodine could again be further reconcentrated.

The question is "what concentration of I-131 in the milk will be safe enough for the child to drink and what must be the I-131 releases at the stack to be below this safe-enough limit? " A related question, of course, is "how does this calculated 'safe-enough' release compare to the amounts actually released from nuclear power plants? "

2. Biological Pathways

The above pictorial diagram is very clumsy so that it is customary to discuss the various pathways of radio-nuclide to man by means of the following diagram:

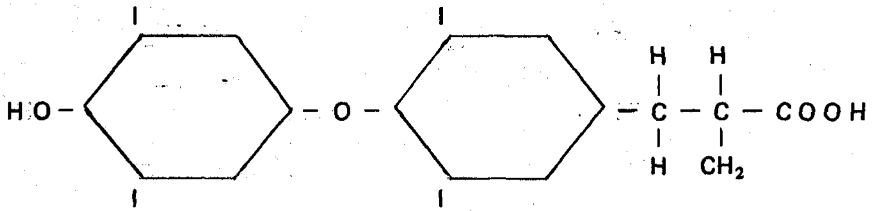


Of the various possible pathways, the pasture-cow-milk-child one is considered to be the most critical, so that we shall analyze it in detail. We also need to notice that the above diagram does not include the effects of external radiation, such as the gamma rays from the radioactive cloud passing by overhead, or being immersed in a radioactive atmosphere.

3. Iodine Metabolism

As indicated earlier, the average amount of iodine in the human body is about 0.03 gm, or about 30 mgm. The iodine concentration is about 0.35 mg/gm thyroid. The thyroid of an adult is taken to be 20 gm, giving 7 mg for iodine in the thyroid glands. For a year-old baby, the thyroid gland is only about 2 gms, but the total iodine uptake is about the same, so that if the iodine is radioactive, the activity will be 10 times greater for such children.

Iodine is needed for thryoxine for which the chemical formula is $C_{15} H_{11} I_4 NO_4$ and the structural formula is



Note that this is an amino acid and is one of the hydrolytic products of proteins. However, it is **not an essential** amino acid (5,6).

4. Radiation Effects and Standards

Young children treated with x-rays in the neck region for enlarged thymus or for other benign head and neck conditions, have had a significantly higher incidence of tumors, including thyroid carcinoma, than have children in control groups. Radiation doses to the thyroid found to be associated with thyroid carcinoma under these conditions, range upwards from about 150,000 mrads. Experience with exposure of the thyroid to large doses of radiation from I-131 for therapeutic reasons is extensive but is almost entirely confined to adults. The report of the panel of experts of the NAS-NRC committees states that, although therapeutic doses of I-131 to the thyroid have been in the range of a few thousand rads upward, I-131 has not been identified in a causative way with the development of thyroid cancer in humans, except in one doubtful case. X-ray doses to the thyroid appear to be from 5 to 15 times as effective in producing biological changes as I-131.

Let us translate these into equivalent internal doses of I-131. The standards set by the ICRP (International Committee on Radiation Protection) for I-131 are

Occupational Exposure	700 μ Ci/tyroid/yr
Public-at-Large Exposure	70 μ Ci/tyroid/yr
Child	7 μ Ci/tyroid/yr

The number 700 pCi results in radiation dose of about 30 rads to the thyroid. The I-131 equivalent of x-ray dose of 150 rads then is 3500 pCi, and 5 to 15 times this last amount are 17,500 pCi and 52,500 pCi respectively. To appreciate a little more fully the degree of safety built into the radiation standards, we shouldnotethat the **medical** standards are about:

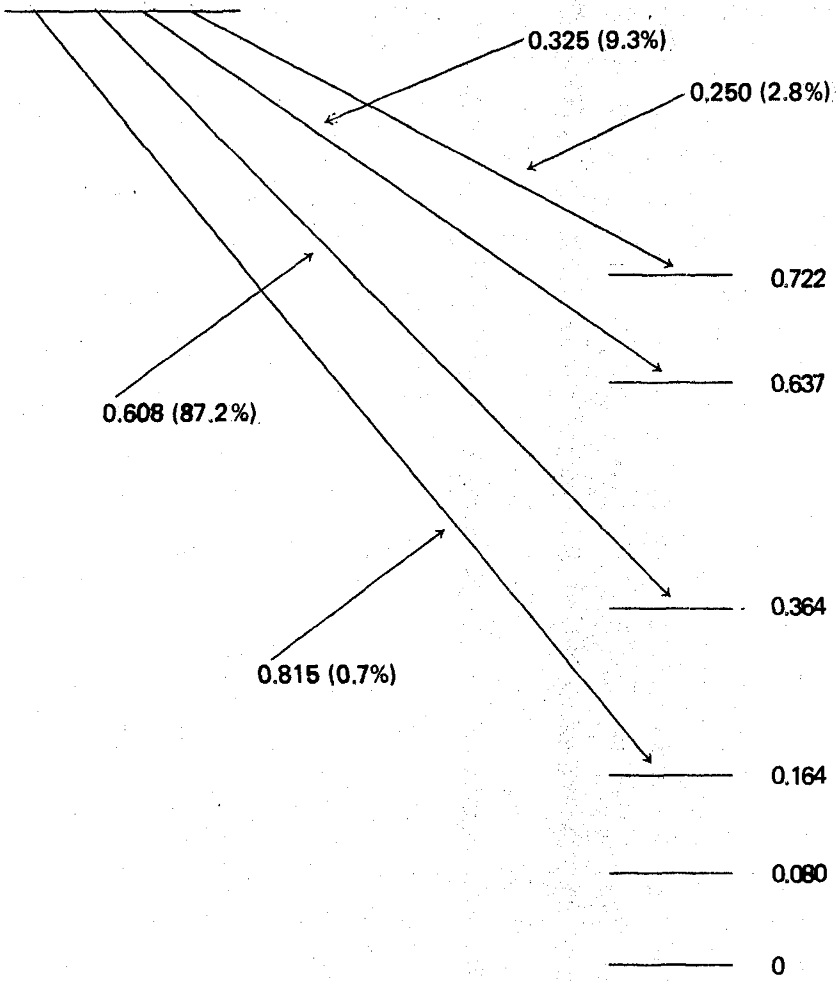
Diagnosis	2,000,000pCi
Therapy	1,000,000,000pCi

But how do these numbers compare with the I-131 releases from nuclear power plants? An excellent discussion of this is given in the paper(7) by Stigall, Fowler, and Krieger, who studied the I-131 releases from the boiling water reactor, Dresden Unit 1 (200 MW(e)). According to their measurements, the radioactivity of I-131 accounts for about 72 ppb (parts per billion) of the total radioactivity released from the stack. The total release, which is mostly noble gases, results in radiation of about 5 mrad/yr at the power plant fence line. Hence the contribution from I-131 is about 72(5) = 360 pCi/yr.

5. Physics of I-131

This is one of the fission products. The precursor that has been identified is Sb-131 and the decay sequence leading ultimately to stable Xe-131 is roughly as follows:

The decay scheme of I-131 to Xe-131 is somewhat complex.



The numbers 0.608 (87.2%), for example mean that the maximum energy of the beta particle is 0.608 MeV and the decay from I-131 to Xe-131 takes place through this transition about 87.2% of the time. The maximum energies averaged over all beta transitions then is:

$$\begin{aligned}(0.815)\ (.007) &= 0.0057\\ (0.608)\ (.872) &= 0.53\\ (\ .335)\ (.093) &= 0.031\\ (\ .25\ )\ (.028) &= \underline{0.007}\\ & \quad\ 0.573\ \text{MeV}\end{aligned}$$

This is the maximum beta particle energy. In beta decay, the electron energy varies continuously from 0 to Truax, and the average energy is frequently taken to be about 0.4 of the maximum value. Then

$$(0.4)\ \ (0.573) = 0.23\ \text{MeV}$$

This is the amount of energy desposited in the tissue if one I-131 were to undergo decay. Then for 1 curie of I-131 in one gram of tissue we would have, since

$$1\ \text{Ci} = 3.7 \times 10^{10}\ \text{disintegration/sec.}$$

$$\begin{aligned}&3.7 \times 10^{10}\ (0.23)\ (1.6 \times 10^{-6})\ \text{erg/sec/gm tissue}\\ &= (3.7)\ (0.23)\ (1.6) \times 10^{4}\ \text{erg/sec/gm tissue}\\ &= 136\ \text{rad/sec/Ci}\end{aligned}$$

Another question is "how much I-131 is produced in a nuclear power plant? " To answer this question, one convenient number to remember is that a 1000 MW(e) nuclear power plant "burns" roughly 1 tonnes of U-235 per year. When U-235 undergoes fission, both light and heavy fission fragments are produced, and about 2.9% of the heavy fission fragments result in I-131. The rate of U-235 undergoing fission per second is then

$$\frac{10^{6}}{235}\ \frac{6 \times 10^{23}}{31 \times 10^{6}}$$

Each fission leads to one heavy fragment, and 2.9% of these are I-131. Hence

$$\frac{1}{235\ (31)}\ (6 \times 10^{23})\ (.029)\ \frac{131}{6 \times 10^{23}}$$

$$= \frac{(0.029)\ (131)}{235\ (31)}\ \ 0.00052\ \text{gm I - 131/sec}$$

This last number can be converted into curies by noting that the specific activity of I-131 is

$$1.24 \times 10^{5}\ \text{Ci/gm I-131}$$

Then

$$0.00052\ \text{gm I-131/sec} = 64.5\ \text{Ci I-131/sec}$$

From this quantity we can estimate the I-131 inventory in the core of a reactor that has been running for a period long in comparison to the radioactive half-life of 8.05 days. The net rate of I-131 increase is given by

$$\frac{dN}{dI} = \lambda N + P$$

in which λN is the radioactive decay decrease rate and P is the production rate. Solving the differential equation we find

$$N = \frac{P}{\lambda}(1 - \ell^{-\lambda t})$$

so that the I-131 inventory is about

$$P/\lambda$$

in which is 64 Ci/sec as estimated and λ is the decay constant, given by

$$\lambda = \frac{1n2}{T\tfrac{1}{2}} \cong 10^{-6}/\text{sec.}$$

$$\therefore N = \frac{P}{\lambda} \sim 64 \times 10^6 \text{ Ci I-131}$$

We can compare these quantitative with the numbers quoted by Stigall et al for the 200 MW(e) Dresden 1 plant. They give 15 Ci/sec for the production rate and 15 MCi for equilibrium inventory.

6. I-131 Discharge

The following numbers give some indication of the amount of radioactive iodine-131 that escapes from a nuclear power plant. The numbers are actually for the Dresden plant.

I-131	
Inventory	15,100,000 Ci
Production rate	15 Ci/sec
In primary coolant	0.418 Ci
Stack discharge	0.000,000,84 Ci/sec
Noble gas discharge rate	0.0116 Ci/sec

The following numbers were reported for the environmental concentration of I-131

Cattle thyroids*	0.45p Ci/gm
Milk	
Measured**	0.67p Ci/liter
Estimated	1.09p Ci/liter
Calculated	0.038p Ci/liter

* Average of three cattle thyroids from a farm 2.3 Km east of the plant.

** Dairy farm 3.4 Km west of the Dresden stack.

7. Radioactivity Standards for Milk

We notice that the above values for I-131 concentration in milk is very small in comparison to the FRC (Federal Radiation Council) standard of 100 pCi/liter of milk. To appreciate the margin of safety in this standard, we shall retrace the calculations to see how they are set.

(a) Occupational Exposure. For workers in nuclear facilities (nuclear power plants, nuclear accelerators, etc.), radiation dose of 0.6 rem/week to the skin and thyroid is considered safe enough. Even if exposed continuously at this rate, the dose in one year would amount to 30 rads/year. As indicated earlier, x-ray induced thyroid carcinoma stems from radiation doses of 150 rads and upward.

To calculate the amount of I-131 what will deposit 0.6 rad/week in the human adult thyroid, we need

(1) Disintegration energy, 0.23 MeV
(2) Adult thyroid mass, 20 grams,
(3) 1 Ci = 3.7×10^{10} disintegration/sec
(4) 1 rad = 100 erg/gm thyroid
(5) 1 MeV = 1.6×10^{-6} erg
(6) 1 week = 6.05×10^5 sec
(7) T = 8.05 days
(8) T = 138 days in thyroid
(9) T_{eff} = 7.6 days

The disintegration energy from 1 Ci of I-131 then is

$$3.7 \times 10^{10}\ (0.23)(1.6 \times 10^{-6}) = 1.36 \times 10^4 \text{ ergs/sec}$$
$$= 8.2 \times 10^9 \text{ ergs/wk}$$

Suppose that the amount of I-131 in the thyroid is 10^{-6} Ci. The dose rate (per gram thyroid) then is

$$\frac{10^{-6}}{20}\ (8.2 \times 10^9) \text{ ergs/wk/gm thyroid}$$

$$= 410 \text{ ergs/gm thyroid/wk}$$

$$= 4.1/\text{rad/wk}$$

Thus to meet the 0.6 rem/wk standard, the so-called body burden of I-131 of a worker **continuously** taking in the radioactive material should not be more than 0.14 μCi, or 140,000 pCi/thyroid.

For a worker speding only a part of his time in a nuclear facility, the maximum permissible burden is taken to be 700,000 pCi/thyroid.

drinks, but the principal source is the pasturage it consumes. Fortunately for humans, much of the I-131 is accumulated in the cow's thyroid, and only about 10% appears in milk.

Studies indicate that 1 pCi/m^2 of pasture will result in about 0.1 pCi/liter of milk. Hence to meet the FRC standard of 100 pCi/liter, the pasture contamination should not exceed 1000 pCi/m^2.

9. Atmospheric I-131 Concentration

Pasture contamination results from the settling of I-131 in the air above it. The deposition rate is given by

$$XVg$$

in which

X - concentration in air
Vg - deposition velocity

However, the deposition rate is opposed by the dissappearing rate, part of which comes from radioactive decay (8 days) and others by being washed off, etc. The **effective** half-life of I-131 on the pasture is then taken to be about 5 days. Then the I-131 loss rate from the pasture surface is given by

$$\lambda P$$

in which P is the pasture I-131 surface density and

$$\lambda = \frac{0.693}{\text{Teff}} = \frac{0.693}{5\,(8.64 \times 10^4)} = 1.6 \times 10^{-6}/\text{sec}$$

Then

$$\begin{aligned} XVg = \lambda P &= (1.6 \times 10^{-6}/\text{sec})\,(1000\ \text{pCi/m}^2) \\ &= 1.6 \times 10^{-3}\ \text{pCi/m}^2/\text{sec} \end{aligned}$$

Measurements indicate that the deposition velocity is about 1 cm/sec. or about 0.01 m/sec. Then.

$$\chi = \frac{1.6 \times 10^{-3}}{0.01}\ \text{pCi/m}^3$$

$$= 0.16\ \text{pCi/m}^3$$

$$= 1.6 \times 10^{-13}\ \text{Ci/m}^3$$

In passing it should be noted that this is a very small amount of I-131. The specific activity of I-131 is

$$1.24 \times 10^5\ \text{Ci/gm}$$

so that

$$\chi = 1.6 \times 10^{-13} \text{ Ci/m}^3$$

$$= \frac{1.6 \times 10^{-13}}{1.24 \times 10^5} = 1.3 \times 10^{-18} \text{ gm I-131/m}^3$$

The smallness of the I-131 concentration can perhaps be appreciated by comparison with the noble **rare** gases in the atmosphere. The rare gases are He, Ne, A, Kr, Xe, and Rn. The last is the radioactive gas radon, which occurs naturally. Its concentration inside buildings, where the concentration is highest, is about 0.5 pCi/liter, or about 500 pCi/m^3. In London, on clear days, the radon concentration has been shown to be 2000 pCi/m^3; the high concentration is due to burning of coal. In an open field, away from coal-burning plants, the radon activity is typically in the range from 100 to 500 pCi/m^3.

The composition of the atmosphere is roughly as follows:

N_2	78.03
O_2	20.99
A	0.94
CO_2	0.03
M_2	0.01
Ne	0.0012
He	0.004
Kr	0.000,001
Xe	0.000,000,08
Rn	0.000,000,000,000,06

Thus the I-131 concentration that would give the maximum permissible concentration in children is about one-millionth of the very rare radioactive gas radon.

10. I-131 From Power Plant Stacks

From the Pasquill-Sutton equation, which is most frequently used to estimate downwind radioactivity concentration, the ground level concentration is maximum at

$$X_{max} = \left(\frac{h}{C_z}\right) \frac{2}{2-y}$$

where the concentration is given by

⑥

$$X_{max} = \frac{2q_o}{\pi e \rho h^2} \frac{Cz}{Cy}$$

If we put

$$Cz = Cy \qquad n = 0.25$$

we find that

$$q_o = 3.3 \times 10^{-12} h^2 \text{ Ci/sec.}$$

for the rate at which I-131 could be released. Wind direction varies, that the above value can be increased by a factor of 20.

Then

$$q_c = 6.6 \times 10^{-11}\ h^2\ \text{Ci/sec.}$$

If the stack height is 50m, then

$$q_c = (6.6)\ (25) \times 10^{-9} + 165 \times 10^{-9}\ \text{Ci/sec.}$$

$$= 165{,}000\ \text{pCi/sec.}$$

REFERENCES

1 - BOLZ, R. A. Y. *Handbook of tables for applied engineering science.* S. l., Ohio, Chemical Rubber, 1970.

2 - NATIONAL ACADEMY OF SCIENCES, National Research Council, Washington, D. C. *The effects of atomic radiation on oceanography and fisheries.* Washington, D. C., 1957. (Publ. 551).

3 - INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Stockolm. *Report of commitee II on permissible dose for internal radiation.* London, Pergamon Press, 1959. (Publication, 2).

4 - FEDERAL RADIATION COUNCIL, Washington, D. C. *Background material for the development of radiation protection standards.* Washington, D. C., July 1964. (Report 5).

5 - NOLLER, C. R. *Chemistry of organic compounds.* S. n. t.

6 - ARNOW, L. E. *Introduction to physiological and pathological chemistry.* S. n. t.

7 - STIGAL, G. E. et alii. ^{131}I discharges from an operating boiling water reactor nuclear power station. *Hlth Phys.*, New York, 20:593-9, 1971.

8 - BURNETT, T. J. A derivation of the "Factors of 700" for ^{131}I. *Hlth Phys.*, New York, 18:73-5, 1970.

9 - HULL, A. P. Invited comments on a derivation of the "factor of 700" for ^{131}I. *Hlth Phys.*, New York, 19:698, 1970.

10 - GEORGE, K. D. ^{131}I "reconcentration factor". *Hlth Phys.*, New York, 19:699, 1970.

11 - CHAMBERLAIN, A. C. & CHADWUICK, R. C. Deposition of airborne radioiodine vapor. *Nucleonics,* New York, 11-(8):22-5, 1953.