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NUCLEAR POWER REACTORS

Chapter 1

NUCLEAR POWER PROSPECTS *

There seems to have been general agreement among those attending the International Conference on the Peaceful Uses of Atomic Energy in August 1955 that world requirements for energy are going to increase as fast during the next fifty years as they have during the last, if not faster, and that nuclear energy, representing a new source of power, will be developed and harnessed to assume a significant role in meeting these world energy requirements.

There is also general agreement that the most important peaceful role of nuclear energy will be that of a source of heat for generating steam to drive conventional turbogenerators. The nuclear reactor—the machine for converting nuclear energy to heat—is therefore the heart of the application of atomic energy to power production, and the development of the reactor is the subject of this volume. The problems of developing practical power reactors have received and are receiving a great deal of attention throughout the world. This effort was reported at Geneva by many workers, and the present volume attempts to include or refer to the more significant of their papers.

To a large extent the publicity given the atom, based on its importance in international affairs, has tended to slight the many and very difficult problems of developing economic power reactors; such publicity has also tended to overstress the immediate, and perhaps ultimate, role of the atom in national and international economics.

The development of atomic power reactors is in a very early stage, and while its prospects have been given a great deal of publicity as a practical source of power, virtually no electric power has yet been produced by nuclear fission. Furthermore, because of the magnitude of the technical and economic problems yet to be solved, it is unlikely that any significant amount of power will be produced from this source within the next four or five years.

World power requirements. The United Nations organization has reported on world use of large quantities of energy derived from various sources, and

* Chapter 1 was prepared by the volume editor and is generally based on the Geneva Conference papers listed at the end of the chapter.

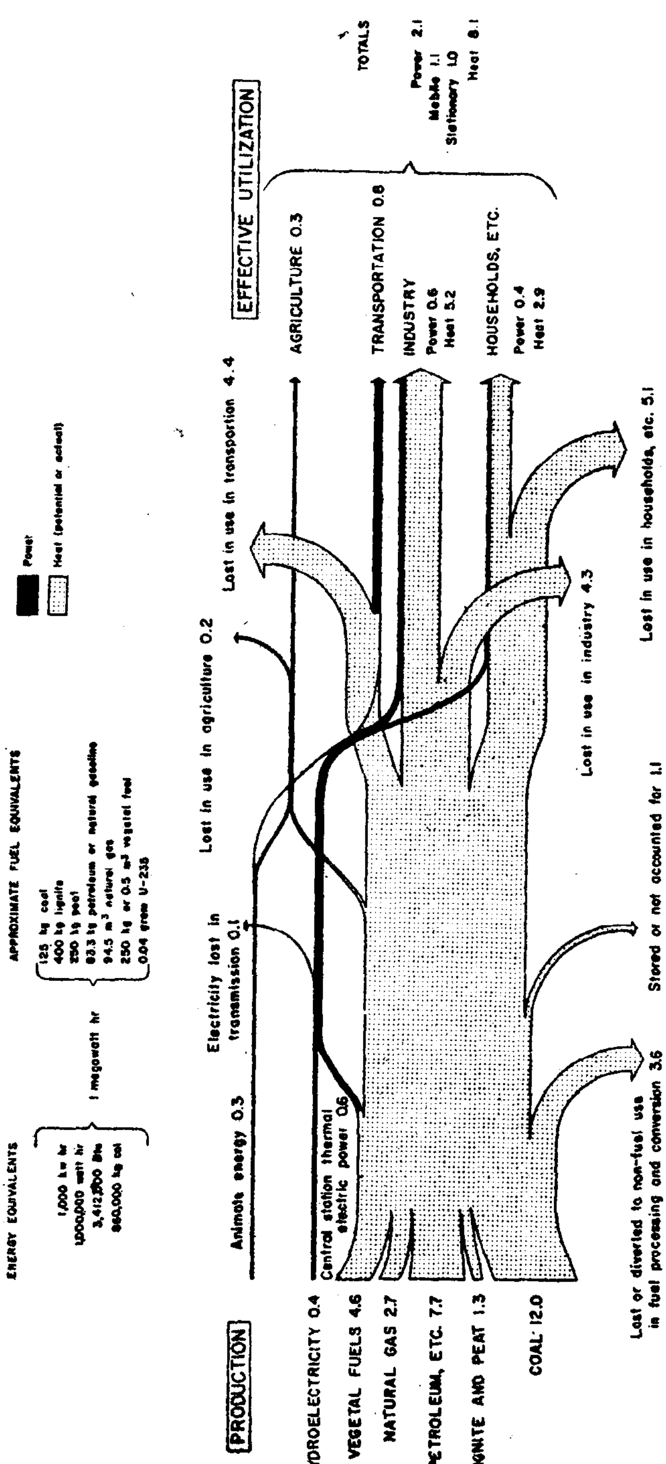

FIG. 1.1. Origin and utilization of the world's energy in 1952. Figures in thousand million megawatt hours electricity equivalent.

for various purposes, as shown[1] in Fig. 1.1 The data shown here reflect all sources and uses of energy, not just for power alone.

The world's requirement for energy has increased from about 1000 million megawatt hours equivalent of electricity in 1860 to more than 23,000 million MW hr equivalent of electricity in 1953, as shown[1] in Fig. 1.2. This requirement is expected to increase at the rate of 4% to 6% per annum, from a total of 10.2 million MW hr of electricity equivalent in 1952 to 27 million MW hr of electricity equivalent in 1975, and 84 million MW hr of electricity equivalent in the year 2000.

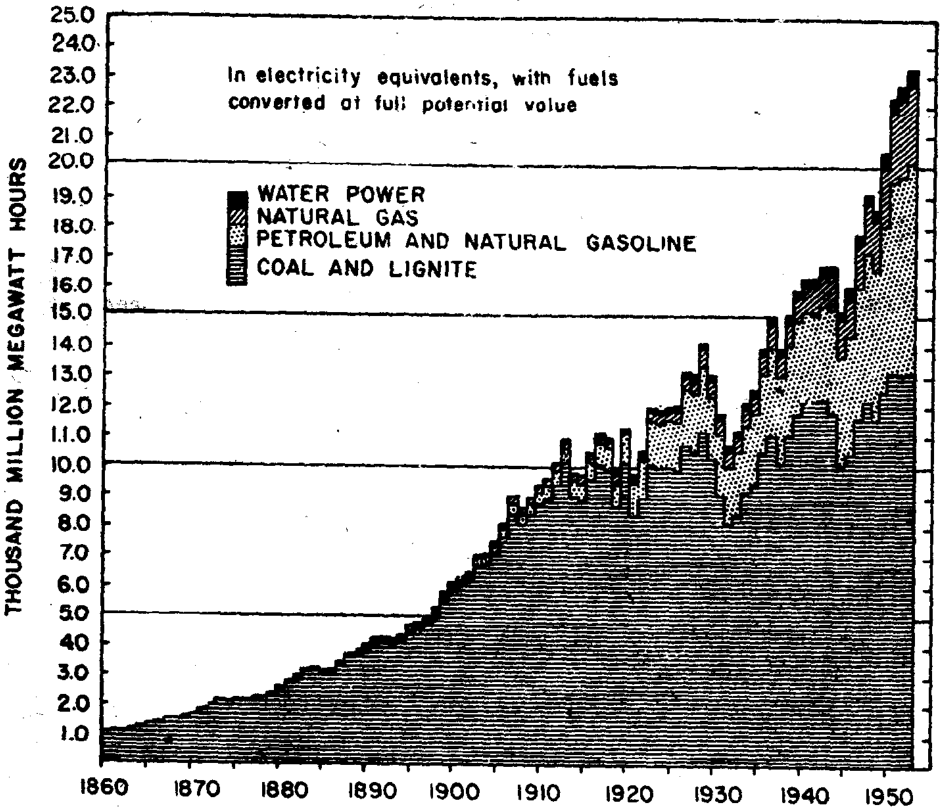

FIG. 1.2. World production of commercial sources of energy, 1860–1953.

A corresponding increase, though perhaps smaller because of improvements in efficiency of utilization, would be reflected in the production of energy, so that while "the requirements of useful energy may be three times as large in 1975 as they were in 1952, and eight times as large in the year 2000 as they were in 1952, fuel supplies will probably need to increase at a rate of only about 3½% per annum to keep pace with requirements."[1]

[1] Numbers refer to the list of references at the end of the chapter.

All countries anticipate an increasingly large demand for energy from all sources, and many of these were reported at Geneva. As Mr. G. H. Daniel of the British Ministry of Fuel and Power pointed out [2] in his discussion, "The Energy Requirements of the United Kingdom," the growth in demand for electricity is rapidly outstripping that which can be economically furnished by coal and other available sources, so that the discovery and development of nuclear power "is timely, if not providential." As further noted by Mr. Daniel, growing difficulties of extracting coal and the prospect of ultimate depletion of oil reserves make it necessary for the British to find means by which nuclear power can be harnessed as a source of energy.

In Canada it is envisioned that economic nuclear power from 100,000-kw or larger stations may be required in the late 1960's or early 1970's in specific areas in which the demand for power is rapidly outstripping available resources. J. Davis of the Canadian Department of Trade and Commerce, reporting on forecasts of regional power requirements in Canada, notes [3] that such large nuclear plants will be economic only for base load use, and the consequent tendency will be to defer their construction until "substantial improvements in design paid for by others" will have been realized. He also notes the possible use of 2000- to 3000-kw nuclear plants in far northern areas in which they would furnish power more economically than diesel engines, and the adaptation of nuclear plants of intermediate size to specific requirements of individual industries, such as the pulp and paper industry.

Nuclear energy is an extremely concentrated form of energy and thus is very mobile. This mobility of nuclear fuels, compared with that of conventional sources of energy, will be a factor in hastening the development of atomic power production, according to Walker L. Cisler,[4] in spite of the obvious problems confronting it. He believes it will take two to three "generations" of reactors to develop sufficient technical proficiency to produce power at a cost low enough to be competitive, and that it may be fifty years before nuclear energy can contribute significantly to meeting new fuel requirements in any part of the world. He points out that lack of technical development and capital, as well as social and economic considerations, may retard the development of atomic power in countries in which it might compete economically with conventional power at an early stage.

The role of nuclear power. Although it is agreed that atomic energy is most apt to find practical applications in the generation of electric power, it is difficult to predict the exact role that nuclear power will play. While many predictions are available,[4,5,6,7] it appears only safe at this stage of development to describe the limiting effects that nuclear energy may have on an over-all economy, as Mr. Philip Sporn has done [8] in discussing the role of nuclear energy in the United States. He does, however, say firmly that "the addition of nuclear power to the energy supply of the United States will assure the continuation of the availability of ample supplies of energy . . . without any fear that at some stage when the supply of fossil fuels begins to diminish, a material disruption in economic development will result from the unavailability of an adequate supply of energy."

The role that nuclear power will play in meeting world power needs will depend on many factors. The principal factor will probably be the ability of man to cooperate in the labors of harnessing its benign uses in the face of its so obviously and devastatingly malevolent ones. Other major factors governing the ultimate role of nuclear power are its economic development and the availability of sufficient amounts of nuclear fuel.

Development of economic nuclear power. Although this volume is largely devoted to technological descriptions of the various types of power-producing reactors, something should be said here about the size of the market for nuclear power. This appears to depend largely on reducing its cost to a point at which it is competitive with conventional power. In the United States, where the cost of conventional power is relatively low, it would seem that a longer period would be required. However, other important factors are involved, such as national prestige, special regional requirements, size limitations, and so on.

In discussing[8] the economic potential of nuclear energy, Dr. Karl M. Mayer provides a regional analysis of the United States market for nuclear energy, based upon economic considerations only. He states, "If nuclear power could be generated for 7 mills per kw hr in 1955, and if advantage were taken of every economic opportunity to install a nuclear power plant, then by 1975 one could expect about 100×10^9 kw hr, or about 6% of the United States electric power output, to be generated by nuclear reactors. If the cost of generation could be reduced by one mill, to six mills per kw hr, then the market potential for nuclear energy in the power industry would double."

The United States government has adopted a program of subsidizing the development of several different reactor types and sizes through laboratory work and experimental reactor projects, as described by U. M. Staebler.[9] A major objective of the program has been to stimulate the ingenuity and imagination of American industry and thereby hasten the day when reactor power plant development will be taken over by industry.

The original emphasis of the program—to a large extent that described at Geneva—was on the reduction of cost or investment in the reactor plant. The importance of reactor plant system costs, including especially the fuel costs, is now being recognized, and increasingly larger efforts are being devoted to finding ways of lowering these operating costs. The significance of some of these over-all system cost factors, including the credits for plutonium produced, is noted by J. A. Jukes of the United Kingdom Atomic Energy Authority[10] and in other discussions, some of which are included in Chapter 2 of this volume.

Not only is it important to consider the costs of the various elements of the over-all nuclear plant, but special care must be taken to select a reasonable and consistent method of determining the elements of power costs, if realistic comparisons are to be made of nuclear and conventional power costs.[11,12]

Although many feel that the most important applications of atomic power will be in small power plants (less than 75,000 kw of electricity) in isolated or near-isolated areas of the world, this application received no special attention at Geneva. Representatives of several countries outlined their projected power requirements, but failed in most cases to state cost ranges which might exist and the economic conditions likely to be imposed. Mr. Samuel B. Morris noted[13] that in the United States the increasing price and the shortage of diesel oils underline the importance of intensifying development work on these small reactors. However, it has also been noted in highly developed countries that increasingly larger uses of electric energy have encouraged the creation of large power networks connected with large power stations.

Availability of nuclear fuels.* There appears to be plenty of source materials—uranium and thorium—available in the earth's crust to satisfy the requirements of a large number of power-producing reactors. Jesse C. Johnson states[14] that "the world's energy resources in the form of nuclear fuels far exceed those of all other types of fuel. There are adequate resources of uranium and thorium for a long-range expanding world power program." He estimates that between 1 and 2 million tons of uranium reserves exist in the producing nations of the West which can be extracted "at an average cost of about $10 a pound for U_3O_8 in a high-grade concentrate." An additional several million tons of uranium can be obtained in both the intermediate cost range—$10 to $30 per pound of oxide—and the cost range of $30 to $50 per pound of oxide, at present considered high, if the costs of extraction can be justified.

Dr. J. V. Dunworth estimates[15] the quantities of thorium which may be required both for inventory and for the annual make-up in operating plants. Inventory requirements, although small, are large in comparison to those for annual make-up. The quantities of thorium required will remain small for some years, because thorium cannot be used without large and unavailable quantities of fissionable materials such as uranium 235 and 233.

References for Chapter 1

1. Geneva Conference Paper 902, "World Energy Requirements in 1975 and 2000," prepared by the United Nations.
2. Geneva Conference Paper 388, "The Energy Requirements of the United Kingdom" by G. H. Daniel of the United Kingdom.

* For a more complete discussion of the raw materials situation, see *Exploration for Nuclear Raw Materials*, edited by R. D. Nininger, D Van Nostrand Company, Inc., Princeton, N. J., 1956.

3. Geneva Conference Paper 3, "Electric Power in Canada: Regional Forecasts in Relation to Nuclear Power Possibilities" by J. Davis of Canada.
4. Geneva Conference Paper 863, "The Role Which Nuclear Energy Can Play as an Energy Source in the Next Twenty-five to Fifty Years" by Walker L. Cisler of the United States.
5. Geneva Conference Paper 389, "The Contribution of Nuclear Power to United Kingdom and World Energy Resources up to 1975" by J. D. Cockcroft of the United Kingdom.
6. Geneva Conference Paper 475, "The Economic Potential of Nuclear Energy" by K. M. Mayer of the United States.
7. Geneva Conference Paper 11, "An Economic Forecast of the Role of Nuclear Power in Canada" by J. Davis and W. B. Lewis of Canada.
8. Geneva Conference Paper 468, "The Role of Energy and the Role of Nuclear Energy in the United States" by Philip Sporn of the United States.
9. Geneva Conference Paper 816, "Objectives and Summary of USAEC Civilian Power Reactor Program" by U. M. Staebler of the United States.
10. Geneva Conference Paper 390, "The Cost of Power and the Value of Plutonium from Early Nuclear Power Stations" by J. A. Jukes of the United Kingdom.
11. Geneva Conference Paper 477, "Capital Investment Required for Nuclear Energy" by W. K. Davis of the United States.
12. Geneva Conference Paper 476, "Economics of Nuclear Power" by J. A. Lane of the United States.
13. Geneva Conference Paper 849, "Need in the United States for Small Power Reactors" by S. B. Morris of the United States.
14. Geneva Conference Paper 470, "Nuclear Fuel for the World Power Program" by J. C. Johnson of the United States.
15. Geneva Conference Paper 867, "The Possible Role of Thorium in Nuclear Energy" by J. V. Dunworth of the United Kingdom.

Chapter 2

NUCLEAR FUEL CYCLES AND REACTOR TYPES *

Developing nuclear power and developing power from fossil hydrocarbon fuel have in common a variety of possible fuels, a variety of devices in which they can be burned, and a variety of uses to which the energy can be put. In the case of nuclear fuels, both the raw materials, thorium and uranium, will be used; questions of relative advantage will be settled by experience. Because the nuclear fuels are so much less bulky than fossil fuels, it is unlikely in the long run that one fuel will prevail over another simply because of local availability. In the initial period, since a start must be made somewhere, it is worthwhile to compare the two nuclear raw materials. This comparison will be based on the nuclear characteristics and on the implied engineering characteristics of systems based on uranium and on thorium.

For countries which possess no diffusion plant facilities for re-enriching slightly used fuel, the problem of which system to start with is automatically answered: natural uranium must be the raw material. But this is a temporary situation. The plutonium produced in the natural-uranium reactor will be burned in enriched-fuel reactors, and it soon becomes a question whether to use the excess neutrons to manufacture U-233 or to manufacture more Pu-239.

The total amount of thorium in the lithosphere seems to be three times as great as the total amount of uranium.[1] Thorium exists only in the +4 valence state; almost all of its salts are insoluble. Uranium is ordinarily oxidized to the generally more soluble U^{6+}. As a result, relatively little of the earth's thorium has been leached out of the original igneous rocks, while larger amounts of U^{6+} have been washed out of these rocks. Thus, although there may be more thorium on earth, there is some informed opinion that workable deposits of thorium may be less common than workable deposits of uranium.

The average thorium content of the lithosphere is estimated to be 10 grams

* The section "Additional Comments on the Plutonium-Uranium Cycle" is taken from Geneva Conference Paper 403, "Fuel Cycles and Types of Reactors" by J. V. Dunworth of the United Kingdom. All other material in this chapter is from Paper 862, "Survey of Fuel Cycles and Reactor Types" by A. M. Weinberg of the United States.

per ton. The electrical energy content of 10 grams of thorium at 25% thermal efficiency, and assuming complete burning, is about 60,000 kw hr. If the allowable fuel cost, exclusive of chemical processing, is 1 mill per kw hr, then the thorium in each ton of rock would be worth $60, while the uranium is worth $20!

Nuclear Considerations

Neutron economy—i.e., conversion efficiency from one fissionable isotope into another—is important for both the highly enriched breeders and the slightly enriched or unenriched converters. The importance of neutron economy in the breeders is obvious. In the converters, especially the heterogeneous converters, the main economic question centers around fuel burn-up: How long can the fuel element run without requiring reprocessing? It is usually considered that economy requires 0.3% of all the atoms in the fuel element to be burned before reprocessing; this amounts to a fuel cost of about 1 mill per kw hr if fabricated fuel costs $25 per kg. As the reactor converts one kind of fissionable material into another, its reactivity may rise or fall depending on a sensitive balance between the nuclear properties of the various fissionable isotopes and the fission product poisons.

Number of neutrons produced in neutron reactions. The most important nuclear quantities in determining the long-term usefulness of a nuclear fuel are ν, the number of neutrons per fission, and η, the number of neutrons produced per neutron absorbed. The values of ν, η, and α (the ratio of capture to fission) at thermal energy and high energies for the fissionable isotopes are summarized in Table 2.1. It is seen that the non-fission capture probability decreases as energy increases, but that it does not become extremely small in

TABLE 2.1. VALUES OF ν, η, AND α *

Quantity	U-233	U-235	Pu-239
ν	2.54	2.46	2.88
η (thermal)	2.31	2.08	2.03
$\alpha = \sigma_c/\sigma_f = (\nu/\eta) - 1$ (thermal)	0.098	0.184	0.42
α (100 ev)		~0.52	~0.72
α (1000 ev)		~0.48	~0.60
α (10,000 ev)		~0.35	~0.43
α (100,000 ev)		~0.13	~0.18
α (500,000 ev)		$\lesssim$0.1	$\lesssim$0.1

* The values of α are taken from boron filter measurements done at Knolls Atomic Power Laboratory, with theoretical interpolation 10^4 and 2×10^5 ev.

either U-235 or Pu until about 5×10^{6} volts. At this energy ν and η are almost equal.

Of the fissionable isotopes, Pu is seen to have the highest ν but the lowest thermal η, U-233 a lower ν but the highest thermal η. Since the theoretical breeding gain is $\eta - 2$, the table shows that the U-233–Th cycle is the better possibility for thermal breeding, while the Pu-239–U cycle is the better possibility for fast neutron breeding. Relatively little neutron economy advantage is to be gained in going to a fast breeder in the U-233–Th cycle; much more is gained in the Pu-239–U cycle.

What has been said so far ignores the possibility of fast fission contributions in U-238 and Th-232. The fast effect in the U-238 system with fission neutrons is estimated to be about five times as large as in the thorium system. In a heterogeneous, very closely packed lattice of natural or slightly enriched uranium it is estimated that this might increase by as much as 10% the effective number of neutrons produced per Pu-239 or U-235 atom destroyed; in the corresponding U-233–Th system this would be only about 2%. Thus for very closely packed heterogeneous systems the neutron economy of the Pu-239–U-238 system may be about as good as in the U-233–Th system.

The situation is less clear in the resonance region. It is seen there that the η(Pu-239) drops disastrously immediately above thermal energy, and that even as high as 100 kev it is still significantly below the very fast neutron value of $\sim$2.88. Less is known about U-233; the initial measurements show η(233) to be pretty constant immediately above thermal energy.

The energy referred to is of course the neutron energy; in a thermal, moderated reactor this would mean essentially the temperature of the moderator. In a reactor like the Pressurized Water Reactor or the Aqueous Homogeneous Reactor in which the moderator runs at 250°C, the value of η(Pu-239) will have dropped well below 2; thus even with a high fast effect the likelihood of achieving a self-sustaining breeding cycle in such a system appears remote. Of course this might be improved, at the expense of engineering complication, by separating the moderator and cooling water. If the moderator were kept cool, the neutron temperature might be low enough to allow a relatively high η in the U-238–Pu system.

Fission Product Poisoning

The economics of all power-breeder reactors is very strongly influenced by the frequency of chemical recycling. In heterogeneous reactors this may well be determined by radiation damage to fuel elements. Should fuel elements be developed which can sustain very high burn-ups, then the limiting factor becomes the neutron loss to the fission products and to the higher isotopes. The fission product losses in the resonance, fast, and thermal regions and to the higher isotopes like Pa-233 or Pu-240 will be discussed separately.

Resonance region. E. P. Wigner has made the following estimate of the poisoning due to fission products in the resonance region. On the assumption that the reduced neutron width is proportional to the level spacing, it is possible to arrive at a definite expression for the average absorption cross section of a nucleus in the non-thermal region. If we measure the energy E, the radiation width Γ_r, and the level distance D in electron volts, the average capture cross section in barns becomes:

$$\sigma = \frac{1800f}{\sqrt{E}} \frac{\Gamma_r}{\Gamma_r + 4.4 \times 10^{-4} fD\sqrt{E}} \left(1 + \frac{A^{2/3}E}{10^7}\right) \tag{1}$$

where f is the ratio between reduced neutron width $\Gamma_n/\sqrt{E}$ and level spacing; i.e., $\Gamma_n/(D\sqrt{E}) = 4.4 \times 10^{-4} f$, and A is the mass number. The $A^{2/3}$ term in (1) takes care, approximately, of the higher angular momenta. A similar formula should hold for the fission cross section with the fission width Γ_f replacing Γ_r.

Recent data [2] show that for nuclei in the light fragment group, f lies between .05 and 0.2; for the heavy fragments f is about twice as large, although the fluctuations in f are quite irregular. The radiation width is about 0.15 volt for the light fission fragments, about 0.1 volt for the heavy ones. These values are still uncertain by at least 50%; nevertheless they may be used to indicate the general character of the fission product poisoning.

According to (1) the *average* cross section is first proportional to $1/\sqrt{E}$ and should, in this region, have nearly the same value for every element. At a higher energy, when the second term in the denominator becomes larger than the first, the cross section should decrease as $1/E$; finally at very high energy (1 Mev) the average absorption cross section approaches the constant value

$$\sigma \sim 0.4A^{2/3}\Gamma_r/D \tag{2}$$

The fission width is considerably greater than the radiation width; for this reason the fission cross section does not show the same strong $1/E$ high-resonance region dependence.

The $1/E$ dependence of the fission product absorption sets in where Γ_r and the neutron width, $\Gamma_n = 4.4 \times 10^{-4} fD\sqrt{E}$, become equal. For the light fragments (for which $D \sim 100$ ev) this would occur at about 400 ev, while for the heavy fragments ($D \sim 10$ ev) this occurs around 3000 ev. Of course these values are very rough, especially since many of the fission products are magic or near-magic nuclei; for these D is larger, and the $1/E$ region sets in at even lower values. Nevertheless, this crude calculation indicates that fission product poisoning in a resonance reactor is less important above a few kilovolts than below this energy.

Unfortunately the available information on η in this low-resonance region is not very encouraging. Experiments summarized in Table 2.1 show that η in Pu-239 probably does not exceed 2 at around 10 kilovolts and is significantly less than 2 below 10 kilovolts.

Calculations of the average cross sections of light ($A = 100$) and heavy ($A = 140$) fission products, based on (1) are summarized in Table 2.2. The column labeled $\bar{\sigma}_f$ (U-235) is an average value of the fission cross section of U-235 at the indicated energy. The last column is the ratio of the sum of light and heavy fission product cross sections computed by (1) to the fission cross section of U-235. It is this ratio which is a measure of the seriousness of the fission product poisoning in a resonance reactor.

TABLE 2.2. AVERAGE RESONANCE CAPTURE CROSS SECTIONS

E (ev)	$\bar{\sigma}_a$ ($A = 100$) (barns)	$\bar{\sigma}_a$ ($A = 140$) (barns)	$\bar{\sigma}_f$ (U-235) (barns)	$\dfrac{[\bar{\sigma}_a(A = 100) + \bar{\sigma}_a(A = 140)]}{\bar{\sigma}_f\,(\text{U-235})}$
10^2	20	60	25	3.2
10^3	3.7	14	7	2.6
10^4	0.5	2.6	3.8	0.8
10^5	0.07	0.4	1.8	0.26
10^6	0.019	0.14	1.3	0.12

Parameters: For $A = 100$: $f = 0.17$, $\Gamma_r = 0.15$ ev, $D = 100$ ev.
For $A = 140$: $f = 0.4$, $\Gamma_r = 0.10$ ev, $D = 10$ ev.

The resonance poisoning according to Table 2.2 is very serious below 10 kev. For example, at 10 kev if 10% of the fuel is burned, the fission products poison cross section would amount to 8% of the fuel cross section. Thus the outlook for a high burn-up resonance reactor, to say nothing of a resonance breeder, is fairly poor unless the fission products are removed rapidly or the spectrum is kept high.

The situation is better above 10 kev: here the $1/E$, rather than $1/\sqrt{E}$, fission product cross section variation is well established, while the fission cross section falls much more slowly. Thus at 10^5 ev the fission product poisons are only one-third as important as they are at 10^4 ev.

It should be stressed that the above estimates are based on average parameters in which there is considerable uncertainty. For example, the data are also consistent with a value of f for the light fragments only one-half the value used here. This would make the light fragment poisoning less important, but since the heavy fragments cause most of the poisoning anyhow, this does not change our general conclusions.

Fast region. In the very fast region the asymptotic formula (2) gives for the light fission product absorption cross sections about 12 mb and about