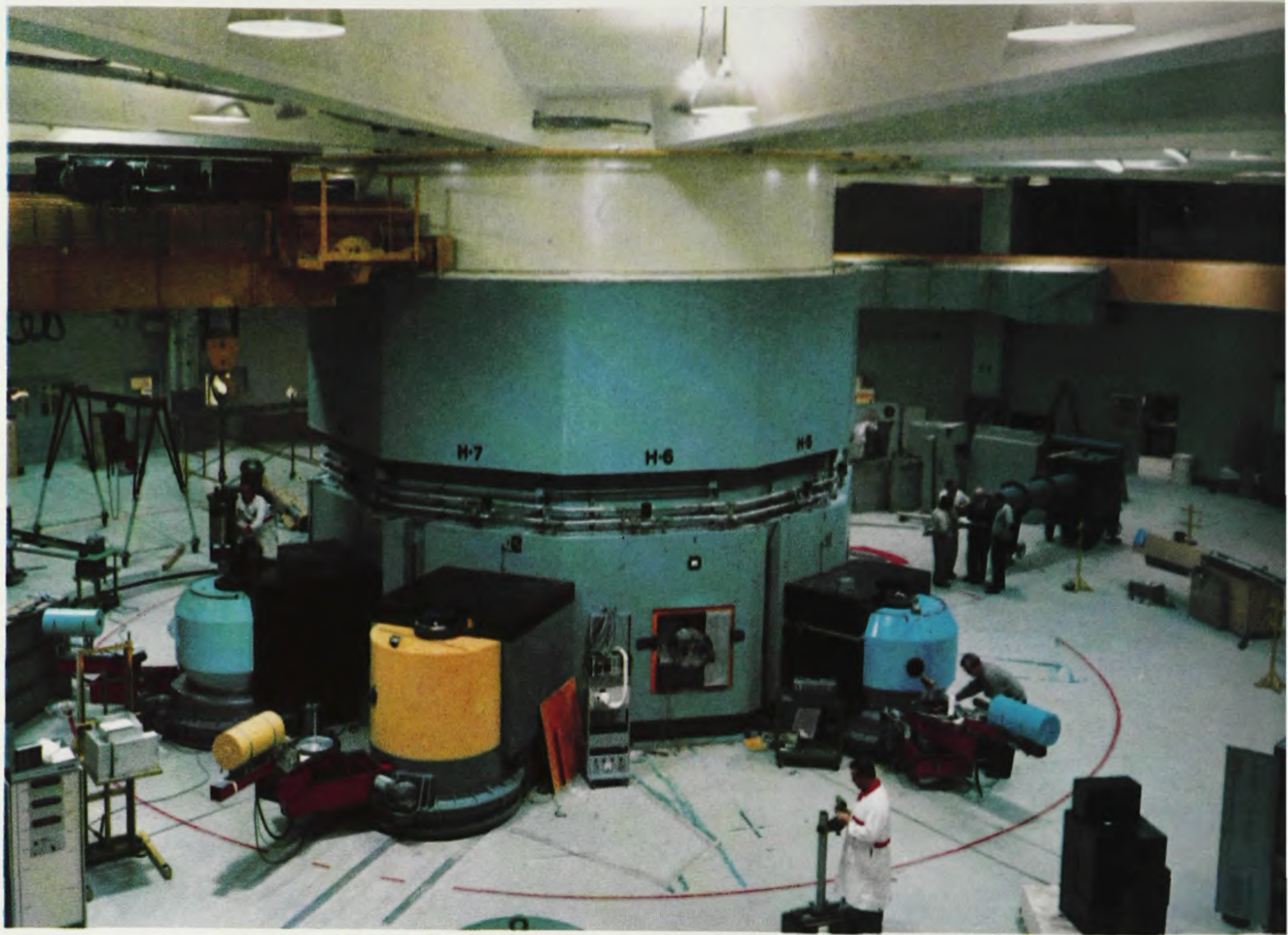

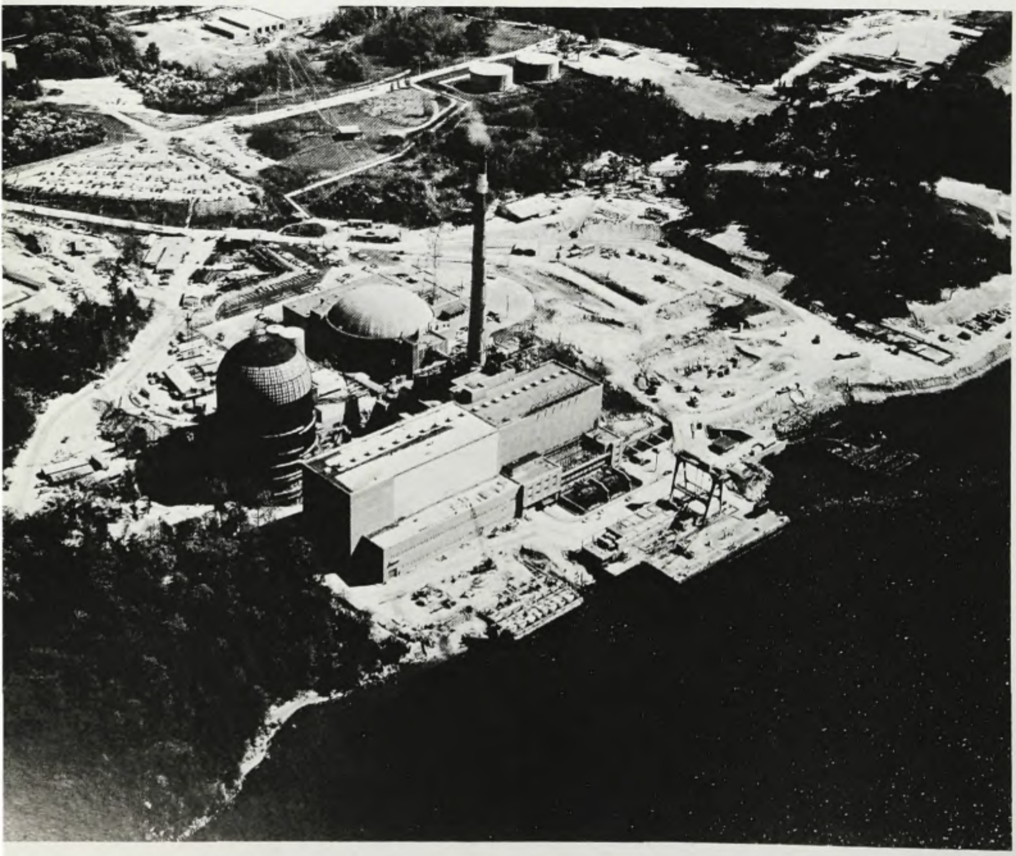

REACTORS for research and commerce. Above: The Brookhaven National Laboratory high-flux beam research reactor, which supplies a maximum neutron flux of 1.6×10^{15} neutrons cm^{-2} sec^{-1}. Picture shows three neutron spectrometers and a dual-beam port. Left: Consolidated Edison's nuclear power station at Indian Point, N. Y. Unit no. 1 (265 000 kW) has operated since 1962. Unit no. 2 (873 000 kW) will be finished in 1970 and a third unit is planned.

NUCLEAR RESEARCH AS A SOURCE OF TECHNOLOGY

What is the value to the economy of research in pure physics? The study of the nucleus is one example of pure research that has paid dividends in the production of electrical power, new materials and techniques.

WILLIAM W. HAVENS JR

RECENTLY THE VALUE of pure research to the US nation has come into question. Although the federal government has steadily increased its support of pure research since the Second World War, attempts to determine the value of pure-research activities to the national economy have been inconclusive. Project Hindsight concluded that very little basic research carried on in university laboratories had contributed to the development of weapons systems since the war and implied that consequently there was little point in the Defense Department's continued support of pure research in universities. On the other hand, those individuals who support increased funding of pure research by the federal government point out that the nation's most rapidly growing industries are those that have invested most heavily in research, with the implied conclusion that an investment in pure research will result in an expanded national economy.

As the nuclear industry is one of the few that originated in the laboratory and has developed into a large independent industry, it appears desirable to examine it to determine the factors involved in its development to the present state, where it contributes to the economic growth of the nation, and to determine the roles that basic and applied research have played in this history.

Power, processes and products

The nuclear industry has clearly come of age, and the technology already developed is self-supporting. Born in the laboratory, nurtured in infancy by the Manhattan Project, and supported and developed in its childhood and adolescence by the Atomic Energy Commission, the nuclear industry has now matured to the stage where it can stand alone without subsidy from society. The statement that nuclear energy has come of age can be made because there is now a truly impressive commitment from public-utilities companies to the large-scale generation of electrical energy from nuclear sources. Nuclear-power generators can probably be classified as one of the most rapidly expanding industries in the US. During 1967 various utilities organizations announced plans to install 29 nuclear power reactors in their systems. These reactors have a combined generating capacity of 24 287 megawatts and bring to 67 the total number of central-station nuclear reactors in operation, under construction and planned in the US as of 29 December 1967. These new reactors bring the total US nuclear-plant capacity to approximately 42 750 megawatts. Thus nuclear energy is directly affecting nearly every individual in the US by reducing his power bills through the efficient application of principles of nuclear energy.

Not generally recognized, however, is that large-scale production of nuclear energy is not the only advancement nuclear-physics research has contributed to our society. It would be difficult to list the number of processes and products that employ nuclear techniques in their development as nearly all technological systems now utilize nuclear know-how. Take, for example, nuclear tracers, used in an increasing number of fields. The efficiency of weed killers was vastly improved because radioactive tracers were able to determine exactly how quickly and to what extent specific chemicals were absorbed by plants. Lubrication studies use tracers to determine how much, and how far, material from one sliding component traverses into another sliding component. The medical profession uses radioactive materials in both diagnostic and treatment procedures. The use of radioactive techniques in chemical analysis is widespread. Some of the most sensitive chemical analyses use nuclear techniques, thus enabling solid-state physicists to obtain purer

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materials. Nuclear techniques are also widely used in locating oil deposits. For example, the density of rock strata thousands of meters below the surface of the earth can be determined quite accurately by measuring the gamma rays scattered by the strata. And, recently, the bronze Greek Horse owned by the Metropolitan Museum of Art was discovered to be a forgery by irradiating the statue with gamma rays from Ir^{192}. The report of the Atomic Energy Commission to Congress and its report on Fundamental Nuclear Research for 1966 give a very large number of examples of how nuclear techniques have been applied to almost all branches of science and technology.

When did nuclear physics start?

In our attempt to determine the roles of pure and applied research in the development of the nuclear industry we would be wise to define our terms. The definition is difficult, however, as pure and applied research cannot be clearly separated; what constitutes pure and what constitutes applied research depends to a large extent on the environment in which the research is done, on the motivations of the researcher and on the organization supporting the research. I think we get some idea of the difference between pure and applied research by tracing the history of the nuclear industry.

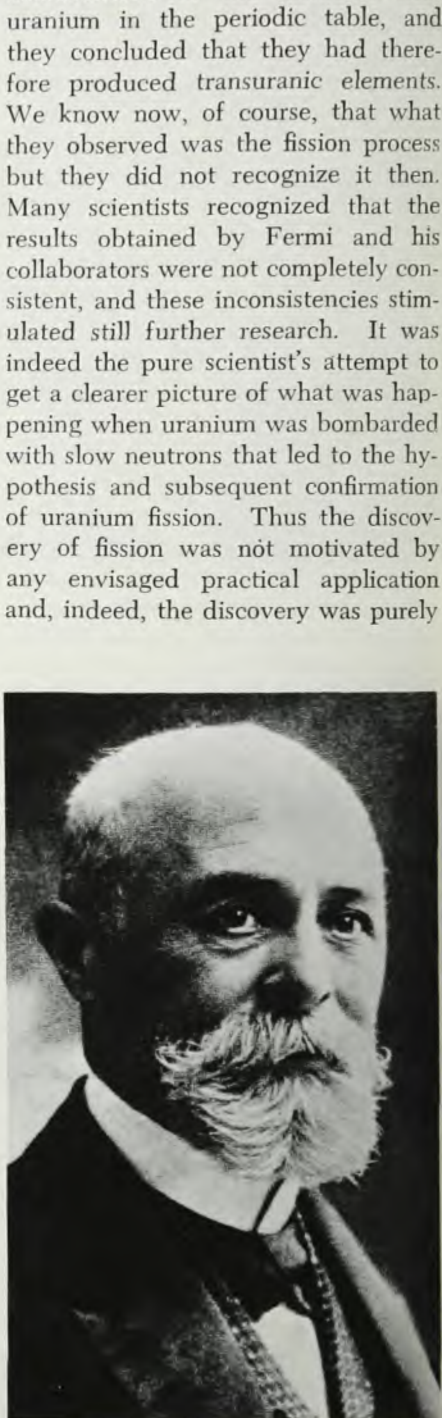
Let us begin by examining the discovery of the fission process. We must go back to the beginnings of nuclear physics and the discovery of radioactivity by Henri Becquerel in 1898. Becquerel's discovery indicated that there should be a great deal of energy in uranium ores because the rays emitted from these ores penetrated the black-paper covering of photographic plates. The brilliant work of the Curies in isolating the element radium from large amounts of uranium ore must certainly be relegated to the area of pure research because very little practical application of this discovery could be envisaged at that time.

Francis Aston's study of the masses of the various elements, together with Albert Einstein's special theory of relativity, indicated that a great deal of energy resides in the nucleus; a plot of the binding energy per nucleon in the nucleus against the mass number of the nucleus showed that those elements near iron in the periodic table are most tightly bound while those at both the low and high mass-number ends of the table are more loosely bound. Thus if it were possible either to combine several light elements to form intermediate-mass elements, or to split heavy elements into intermediate-mass elements, nuclear energy could be released. It was thus quite obvious to nuclear physicists even before the discovery of the neutron in 1932 that it was possible to obtain large amounts of energy from nuclear reactions. But, of course, no one at that time knew how to effect this energy release. Even the famous and visionary Ernest Rutherford said in 1933: "The energy produced by breaking down the atom is a very poor kind of thing. Anyone who expects a source of power from the transformation of these atoms is talking moonshine."

Light and heavy nuclei

Modern nuclear physics may be said to have begun with the discovery of the neutron, as it was only with the discovery of this particle that it became clear that atomic nuclei were divisible into yet smaller units, neutrons and protons. Suppose we look at nuclear physics in the early 1930's from the points of view of both the pure-research physicist and the applied-research physicist. The way to approach the problem of freeing the energy in the nucleus is to study very light nuclei because they have the fewest component particles; it appears much easier to establish the relationship between these few components than in the heavy nuclei, where the component number is very much larger. Therefore, in the eyes of the pure scientist, it is much more fruitful to examine the details of the energy-level structures of light nuclei. To the applied physicist, whose goal is to obtain energy from a nuclear system, it also appears more fruitful to investigate the light nuclei. In view of this situation—where it appeared that information about light-nuclei systems could lead to fusion of several light nuclei—I therefore believe that a research director looking for potential energy sources would have directed his staff to begin work on light nuclei rather than heavy ones.

In pure research, it is man's eternal curiosity that stimulates him to investigate one particular phenomenon; Enrico Fermi in Rome had noticed that induced radioactivity was markedly increased by embedding his neutron sources in paraffin. After several experiments, he concluded that slow neutrons were much more effective in inducing radioactivity than fast neutrons. Fermi and his group then attempted to create new elements by bombarding uranium with slow neutrons. The radioactivity they observed from this procedure was not characteristic of the elements near uranium in the periodic table, and they concluded that they had therefore produced transuranic elements. We know now, of course, that what they observed was the fission process but they did not recognize it then. Many scientists recognized that the results obtained by Fermi and his collaborators were not completely consistent, and these inconsistencies stimulated still further research. It was indeed the pure scientist's attempt to get a clearer picture of what was happening when uranium was bombarded with slow neutrons that led to the hypothesis and subsequent confirmation of uranium fission. Thus the discovery of fission was not motivated by any envisaged practical application and, indeed, the discovery was purely



HENRI BECQUEREL (1852–1908), who discovered radioactivity in 1898 during work on optics. (Burndy Library)

accidental. It is worth noting that fission would probably not have been discovered had the criteria of the "most efficient" use of research funds for practical uses been applied to Fermi and his group at the University of Rome.

The Manhattan Project

After fission was discovered and the number of neutrons released in the process measured, it was quite clear that uranium fission was a mechanism that would permit the large-scale release of nuclear energy, and therefore it could be utilized both for military and civilian purposes. Dean George Pegram of Columbia University wrote in 1939 to Admiral Bolton of the Bureau of Ships specifically requesting support for research in uranium. He wrote that recent experimental results in the study of uranium led him to believe that there was a strong possibility of developing an explosive that would be the most powerful ever imagined and that, moreover, it could also be used for propelling submarines.

Probably very little further work would have been done of the uranium project by pure scientists at that time. However, uranium fission was discovered on the eve of World War II and the possibility of developing a super explosive that could end the war caused some farsighted people in the US Government to invest heavily in the development of this project. A mere six years elapsed between the discovery of nuclear fission and its demonstrable military and political applications.

There is no doubt that the Manhattan Project was one of the largest and most brilliant efforts in the field of applied research. The object of the Project was clear—obtain an atomic bomb in the fastest possible time. Money was a minor consideration; time was of the essence. Very few discoveries of fundamental importance were made during the course of the Manhattan Project, although many discoveries later resulted in products in the civilian economy. For example the fluorocarbon compounds were developed for gaskets and pump oil in the diffusion method of separating U^{235}. The gas used in this process was uranium hexafluoride, and the free fluorine in this compound could displace hydrogen in any of the hydrocarbon materials. Fluorocarbons are best known today to the general public under the trade names "Teflon" and "PTFE" (for polytetrafluorethylene).

We can conclude that the pure-science work on the uranium project was concluded in 1941 and that the Manhattan Project was a development rather than a research project. After a demonstration of the military use of atomic energy many scientists on the Manhattan Project believed that the next step was the formation of a civilian nuclear-energy program. One might reasonably ask: Why did it take approximately 20 years to develop economic nuclear power when apparently all the tools and much of the information required to develop this power was available in 1945? The answer lies in the economics of nuclear energy, an area that had not been considered important in the development of the bomb. What is the value of an atomic bomb? For the military purpose of ending a war, it is obviously worth a great deal. But no monetary value can be placed on its worth.

FIFTH ANNIVERSARY celebration, December 1947, at the now demolished West Stand at the University of Chicago. Left to right: Robert Bacher, Farrington Daniels, Walter Zinn, Enrico Fermi, R. M. Hutchins. (Argonne National Laboratory.)

A universal panacea

The next phase in the development of nuclear energy was again military, being the development of a power plant for submarine propulsion. Here again the economic value of a submarine that can circle the world without surfacing is difficult to assess in monetary terms. Therefore national-defense needs rather than civilan-power needs originally dictated the atomic-energy program. However, as military atomic energy was further developed, some of the resultant technology could be applied to the civilian economy.

In 1955 at a conference in Geneva a great deal of information on atomic energy was released. In the US up to that time there was no real economic drive to develop economical methods for producing atomic energy on a competitive basis with ordinary-fuel energy sources. The US appeared to have fossil-fuel reserves in abundance and there appeared to be no real necessity for developing atomic energy. The Geneva Conference on Atoms for Peace was launched with great fanfare and excellent press coverage. Newspaper articles represented atomic energy as a panacea for all social ills: There would be cheap electric power; the oceans would be purified and pumped over mountains to irrigate deserts; with very cheap electric power a large fraction of the unarable land would become agriculturally productive, thus ending food shortages; there would be no reason for nations to go to war since all would have plenty. And thus the development of atomic energy was envisaged as leading to paradise on earth.

Changing economics

However, the field of atomic energy had not been economically appraised in any realistic manner. Atomic energy was so linked to the military establishment that it was extremely difficult to obtain data that would allow realistic evaluation of the economic aspects of nuclear power.

Probably the greatest benefit the world enjoyed as a direct result of the Atoms for Peace Conference in Geneva was the advertisements for atomic energy. Evidence of this is seen in the cost curves for the production of electricity from fossil fuels; the curves took a nose dive following the conference in 1955. The publicity that atomic energy received stimulated those people using fossil fuels to develop more economic uses of these fuels, so afraid were they of the competing atomic fuel. This development may account for the present low cost of electric power as compared with other commodities.

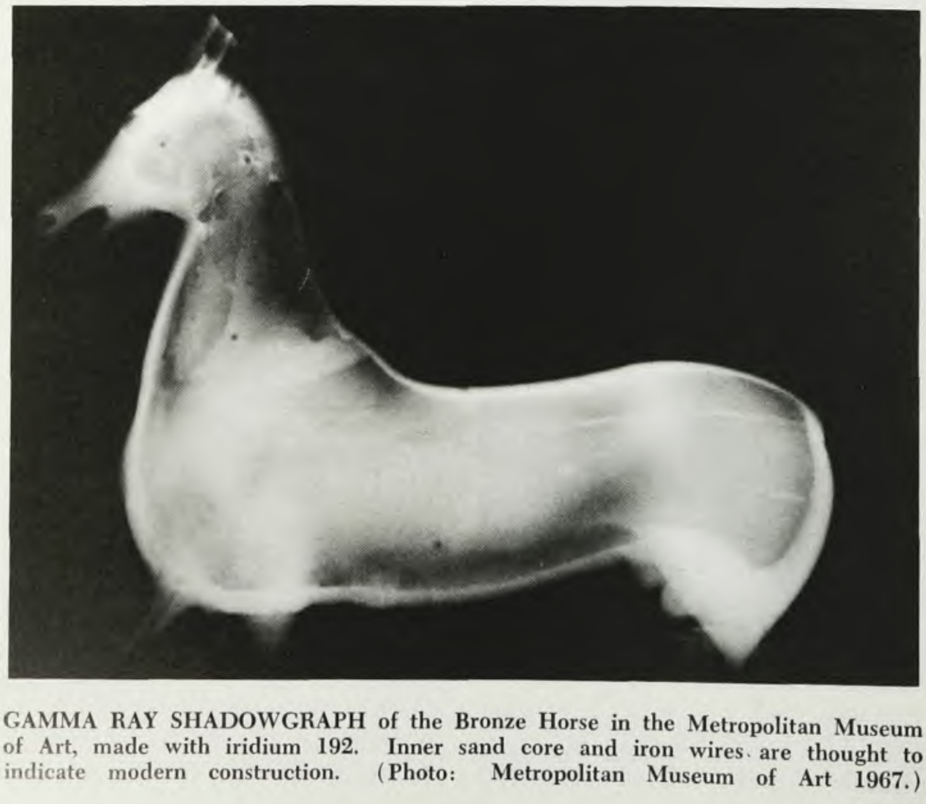
From 1955 to 1959 the economic value of atomic energy was more realistically assessed. Much to our surprise the power from atomic energy could not compete at that time with the power yielded by fossil fuels. This realization precipitated a decline in the nuclear-energy industry, which hit bottom about 1959. J. A. Lane concluded at that time[1] that nuclear energy could not compete successfully with fossil-fuel power; in 1966 he wrote[2] that nuclear energy was by then definitely economical. The figures he gave to illustrate the economic feasibility of nuclear power are \$0.003–0.004 per kilowatt hour, considerably above the estimated cost of \$0.00276–0.00279 per kilowatt hour for the proposed 1000 megawatt high-temperature, gas-cooled reactor whose economic costs were briefly summarized in 1967.[3]

One might ask what dramatic breakthrough in technology suddenly made nuclear energy feasible. The answer is that no single development, idea or person made nuclear energy economically competitive. It was rather the widespread collective efforts of a large number of people working in universities, national laboratories and industry.

Progress towards viability

Now that we have briefly traced the history of the nuclear industry from the original discovery of the nucleus as an energy source in 1898, through the discovery of fission in 1939, to its economic viability in 1964 I do not know what point in time we should choose to examine the role that basic and applied research have played in the development of this industry. Certainly 1898 is too early because the nucleus was a complete mystery then. On the other hand, practically all the basic research needed to justify development of a nuclear-energy program had been completed by 1941. Certainly before 1939 all the work done to obtain information for development of the nuclear industry was in the area of pure research, and without this pure research the industry would not exist today. Perhaps the latest time to start the clock is with the discovery of fission in 1939 because this discovery revealed the mechanism by which large-scale production of nuclear energy could be achieved. Using this time scale we find that the largest fraction of the work done up to 1941 was in pure research, and from 1941 onward the largest fraction of the effort can be attributed to applied research. Remember that there was an emergency wartime situation in 1941 and nobody examined carefully the total amount of money that was spent on the development of the atomic bomb. The efficacy of nuclear energy was demonstrated in 1945 for military purposes, but even as late as 1958 nuclear energy could not successfully compete in the civilian market. Therefore I think the minimal time we can give for the development of economic nuclear energy is 25 years, of which two were devoted primarily to pure research and 23 to development.

If, however, we start with the original discovery of radioactivity, we must conclude that the total time required to develop economic nuclear energy was 66 years, of which 43 were devoted to research and 23 to development. Recalling that nuclear energy had all possible encouragement and advertising, that an enormous number of people were confident that it eventually would be developed, and that a large fraction of the money was spent in the development of nuclear energy for military purposes, we can see that judging the value of pure research on the basis of a 20-year history is not a very good basis for judgment. It is unusual for dramatic dis-



GAMMA RAY SHADOWGRAPH of the Bronze Horse in the Metropolitan Museum of Art, made with iridium 192. Inner sand core and iron wires are thought to indicate modern construction. (Photo: Metropolitan Museum of Art 1967.)

WHOLE BODY SCAN of a patient with lung and thyroid cancer. Iodine 131 distribution, 72 hours after an intake of one millicurie, shows localization of cancer. (Photo: US Atomic Energy Commission.)

coveries like fission to come out of the laboratory. Most of the discoveries that affect the civilian economy are small improvements in existing systems and are hardly noticeable to the layman because he really does not fully understand how many of the systems work.

Should we continue research?

The general population of the earth has invested in the research and development of nuclear energy for 66 years. Perhaps we have obtained all of the useful information we can about the nucleus and this field is essentially mined out. There would then be no point in investing further in this area because we could not reasonably expect any further return. I would not raise this point unless I thought it could be refuted without difficulty; nuclear physics has much to offer in the future. I pointed out that if the research director for the nation had appraised the nuclear-energy system in the early 1930's, he would have concluded that it was much more profitable to develop a system for nuclear fusion than to study heavy nuclei. A fairly extensive research and development program on the controlled-thermonuclear process has existed in the US since the late 1940's. This project probably received a large amount of support because the value of thermonuclear reactions in hydrogen bombs has been so well demonstrated, but the connection between a thermonuclear bomb and a controlled thermonuclear reaction is quite different from that between the fission bomb and the controlled release of nuclear energy from fission.

Although at present the exact configuration that will be used to release thermonuclear energy on a large scale cannot be described, great progress has been made in the study of this process. I am convinced that eventually there will be large-scale controlled thermonuclear reactors for the production of electrical power similar to the large-scale controlled fission reactors.

If both fission and fusion reactors are developed to their fullest, what practical motivation can there be for continuing research in nuclear physics? Fundamental physics tells us that most of the energy in the nucleus is not released in either a fission or fusion process. In both the fission and fusion reactors less than 0.1% of the mass of uranium in the fission reactor and hydrogen in the fusion reactor is converted to energy. At the present time neither I nor, I believe, anybody else, knows the total fraction of the mass of the nucleus that can be transformed into energy on a large scale. However, in 1938 no one knew how to transform nuclear energy into electrical energy on a large scale either. A major discovery in pure research changed that situation completely.

Unexpected applications

The following development that grew out of a problem in pure research in the nuclear-energy field demonstrates one of the possible applications of pure research to industry. The idea originated in a project to obtain a detector sensitive to specific charged particles emitted in nuclear reactions. R. L. Fleischer, P. B. Price and R. M. Walker pointed out that almost all insulating solids record tracks of nuclear charged particles, and they developed a technique for etching the tracks of charged particles in solids.[4] By varying the type of incident particle, the energy of the charged particle and the solid on which the charged particle impinges, they are able to vary the size of the tunnel that the particle creates in the solid. Studies of charged-particle tracks led to the development of a new filter that has been found useful in biological studies. Holes varying from 500 nanometers to many microns in diameter are easily obtainable. They found that polycarbonate plastic is a convenient material in which to produce holes of 1 micron to 15 or 20 microns—a size range that includes typical biological-cell dimensions. Such filters are thus appropriate for the separation of cells of differing sizes, for example to separate free-floating cancer cells from normal blood cells. Normal cells pass through the filter while the larger cancer cells are separated out. Exactly how this technique will develop is at present uncertain. But this recent discovery illustrates how a detector, developed for one experiment in pure research, can be applied to areas where no one dreamed of an application before some physicist used his fertile imagination.

At the present time nuclear forces are not fully understood, and consequently new techniques must be developed to examine them in greater detail. Nuclear physicists will attempt to stretch existing technology to improve the experimental results. This stretching of the existing technology leads to new discoveries, and the application of basic research results leads in turn to new technology.

The conclusion, therefore, is that both pure and applied research must be generously supported if we are to have new technologies that will benefit mankind.

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