A Future With Fusion

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The world's energy resources are facing depletion. The resources which are presently used in energy production are nonrenewable and therefore, are increasing in price as they become more scarce. As a result of the increasing expense, these materials are becoming economically less attractive. This necessitates a change in technology which will enable energy production from alternative resources. Nuclear fusion is currently undergoing research as a possible solution to the world's growing demand for electricity. In order to determine if fusion power is feasible, the economic efficiency as well as the technical efficiency must be compared with that of conventional resources. This comparison will involve such factors as spillover costs, construction and fuel costs, thermal efficiencies and availability.

As our nation faces population growth and rapid technological advancement, we also experience an increasing demand for electricity, necessitating the development of alternative resources. Since 1973, electricity consumption has increased at the same rate as U.S. economic growth.(14) The economic well being of the nation is often measured by the gross national product (GNP). The real GNP is the total market value, neglecting inflation or deflation, of all final goods and services produced in the economy in one year. The GNP must be corrected for inflation because inflation otherwise creates in an artificial rise in the GNP. A rise in the real GNP may occur from increased input of labor or increased productivity of labor. Increased input of labor may result from population growth. As the population grows, there is a greater demand for products and services and a need for additional labor. Enhanced productivity arises primarily from technological progress. Since the demand for electricity derives from the demand for goods and services which depends on its use, a rising real GNP may also indicate a growing need for electricity.

In order to meet the growing demand for electricity, the production methods must be technically efficient as well as economically efficient. The maximum efficiency may be described obtaining a given amount of output from the smallest amount of input possible. In terms of energy production, this involves obtaining the maximum amount of energy from any given resource. Economically, the goal is to employ a least-cost combination of resources to attain the final product. Demand for energy is a major problem among U.S. industries. Therefore, economic efficiency as well as availability may be extremely dependent upon the technical efficiency of energy production. For instance, more effective methods of energy production lead to lower manufacturing costs for industries. The lower production costs would, in turn, result in lower product prices and greater satisfaction of demand.

Our present methods of electricity generation involve primarily coal fired and nuclear fission plants. Although oil and gas have been used, they do not provide a significant portion of electricity production. Most oil plants have been converted to coal as a result of increased fuel prices. Gas turbines, although relatively inexpensive to install, have such low thermal efficiencies that high fuel costs result in high operation costs.(11) Therefore gas turbines are primarily used for peak loads.

The operation of a coal fired plant begins with coal being conveyed through feeders to the pulverizers. The pulverized coal is then transported to the burners through a system of fuel and air conveying lines. The burner mixes the pulverized coal with air at the furnace for efficient combustion. Heat from the process is extracted in the boiler and used to produce steam. The steam passes through a superheater which heats the steam to a temperature as high as possible. The pressure from the steam turns the turbines which, in turn, turn the generator.

Nuclear fission power also makes use of steam to generate electricity. However, the heat source is quite different from that of a coal fired plant. The fuel for a nuclear rector must be a fissionable element. When a fissile atom gains a neutron, it becomes unstable and splits into two or more products. This division results in vast amounts of kinetic energy. As the fission products are slowed down within the fuel matrix, the kinetic energy is converted to heat.

While fission releases heat by splitting atoms, fusion energy is released by the union of atoms. Although research has led to the development of several methods of fusion containment, magnetic confinement devices have undergone the most research. The magnetic confinement reactors use magnetic fields to contain the fusioning plasma. The plasma is a gas which has been heated high enough to completely ionize the gas. This is necessary to overcome the repulsive forces which, at low temperatures, will not undergo fusion. The fuel for this reactor is deuterium and tritium. The product of the D-T reaction is a high energy neutron and an alpha particle. The neutrons slow down and deposit their energy in a reactor blanket. The blanket region is composed of lithium and serves to convert neutron energy into heat. The heat produced can be used for conventional steam power generation. Furthermore, the lithium provides a medium for the production of tritium (2) as shown in the following equation:

$$ {}_{3}^{6}Li + {}_{0}^{1}n \rightarrow {}_{2}^{4}He + {}_{1}^{3}H $$

Spillover costs are vital in determining if a given resource is feasible. The production of electricity using coal, nuclear fission, and nuclear fusion results in external costs which are borne to the entire society as well as the immediate buyer and seller. The use of coal to produce electricity creates numerous environmental hazards. Coal mining reduces and eliminates other resources, which then increases the real cost of energy production. As water flows through coal seams, it may extract acidic materials from the coal and pollute streams or other water supplies.

Burning high-sulfur coal produces atmospheric pollution and acid rain which are further responsible for contamination of ground water as well as deterioration of man-made structures.(19) This damaging process begins when a photon of sunlight strikes a molecule of ozone (O_3). The molecule splits into an oxygen molecule (O_2) and a highly reactive oxygen atom which in turn readily combines with H_2O to form two hydroxyl radicals (OH). These hydroxyl radicals may react with nitrogen dioxide (NO_2) to form nitric acid (HNO_3), and sulfur dioxide to form sulfuric acid (H_2SO_4). As the acid products enter lakes, streams, etc., the pH is lowered. The lower pH, in turn, damages aquatic life. Plankton and crustaceans may disappear, fish cease to reproduce, and new algae appear.(16)

The acidic materials resulting from coal fired plants may be responsible for the destruction of forests. The aluminum released from soil minerals by acid may also compete with calcium for binding sites on fine roots, reducing a tree's supply of calcium and slowing its growth. The soil itself may lose nutrients when calcium, magnesium and potassium are leached away by acid rain. High levels of nitrate from nitric acid deposition can injure fungi that live in the roots of conifers which help such trees ward off disease and extract water and minerals.

All fossil fuels release CO_2 when burned. The level at which they are now burned is causing a 3% per decade rise in CO_2 in the atmosphere.(15) Short wave radiation from the sun continues to reach the earth's surface at its usual rate. However, after it is transformed into heat on the earth's surface, a fraction of the re-radiated infrared energy is absorbed by carbon dioxide in the atmosphere rather than escaping directly into space, thereby increasing the average temperature on earth. As levels of CO_2 rise, an increasing portion of the sun's heat will be trapped in the atmosphere, at some point, causing serious environmental effects. Increasing the temperature by only a few degrees could bring about major climatic changes, including the melting of polar ice caps and substantial flooding of lowlands.

The use of coal in the production of electricity also involves certain health risks. Coal imposes higher death rates and workdays lost per unit of electricity than other alternatives. It is estimated that a single 1000 megawatt coal plant may cause up to 75,000 cases of respiratory diseases per year, twice that many asthma attacks and ten times that many aggravated heart and lung diseases.(10)

Nuclear fission is also responsible for producing environmental costs. The rejection of heat to cooling water or air is a source of thermal pollution. The release of heat into surrounding areas may be altering the environment to a degree which could be hazardous to wildlife. Furthermore, the dangers of radiation exposure are a major concern among those in the industry. The danger of radioactivity is that it can cause cancer, genetic defects, and other physical disorders over the years. For example, hundreds of uranium miners have developed lung cancer as a result of being exposed to high levels of radon gas. Moreover, thousands of people have been exposed to uranium sludge piles left from mining operations.

The possibility of a nuclear accident also adds to the cost of producing electricity with a fission reactor. The 1979 nuclear accident at Three Mile Island was estimated to have cost 7 billion dollars.(9) The extent of the damage resulting from radiation emissions is a controversial issue. Many nuclear activists claim that the radiation released from the Three Mile Island accident may have a profound effect on the environment. Furthermore, they suggest that many side effects from radiation exposure may not be evident for years or even generations later. However, those actively involved in the industry claim that the amount of escaping nuclear debris was surprisingly insignificant.

Nuclear waste disposal must also be included as part of the costs of nuclear electricity generation. A typical 1000 megawatt reactor, operating at 80% capacity generates between 30 and 40 tons of radioactive waste per year.(10) Although the nuclear industry has been producing radioactive waste for many years, no permanent solution for disposal has been developed. It is a remarkable product because the radioactive waste has a lifetime of millions of years, and continues to emit radiation at sufficient levels to heat the waste to hundreds of degrees in temperature. At present, some nuclear facilities store spent fuel rods in storage pools at the power plant. However, as more nuclear waste is produced, the plant is eventually faced with the expense of constructing additional pools or transporting waste to other facilities. Transporting radioactive waste involves further risks. Vehicles carrying low-level wastedrums have incurred accidents which have led to ruptured drums, scattering radioactive materials over the highway. Several methods of waste disposal have been employed, however, most have proven unsuccessful. For example, tanks at the Hanford, Washington storage reservation are corroding and leaking. Furthermore, earthen trenches where plutonium has been deposited have become so overfilled that scientists are concerned about the possibility of a chain reaction. Migration of high level waste in the soil may also be a potential hazard, where as waste may eventually reach the water table. Disposal of nuclear waste in the ocean is another alternative which has failed. Between 1946 and 1970, more than 47,000 concrete lined steel cans of radioactive waste were dumped into the Pacific Ocean. Many of the cans have cracked or imploded due to water pressure.(3) The disposal of radioactive waste has become a great expense for the nuclear industry as well as society.

Nuclear fusion may provide a solution for a number of problems associated with nuclear fission power. A nuclear fusion reactor may also produce spillover costs; however, these costs are considerably less than those for conventional operations. The deuterium used in the fusion reactor is harmless, in the radioactive sense.(7) Only tritium is unstable and as a result, most ordinary materials which would be used as reactor components become radioactive under neutron bombardment. On the other hand, tritium has an half-life of only 12 years and is stable enough to be used up as a fuel element yielding stable $^{4}_{2}He$ or it can be stored until it decays to a harmless radiation level. Furthermore, unlike uranium ore, which must be milled, enriched or reprocessed, fusion fuels pose no environmental hazards. Deuterium and tritium are produced in the reactor.(18) In fusion reactors, the danger of accidents similar to those of fission reactors is nonexistent. The core of a fusion reactor is an extremely hot plasma. If an accident were to occur in the containment vessel, and the gas were to escape, it would cool down instantly when it touched the solid walls. Even a complete loss of coolant accident could not cause the equivalent of a meltdown. The amount of fuel gas in the reactor is so small (at a pressure of approximately a ten thousandth of an atmosphere) that the total heat content is not so large that it is difficult to design secure vessel walls; that is very difficult with a fission reactor.(9)

The depletion of scarce resources is also an important consideration in the economic comparison of coal, fission, and fusion. As the amount of a given resource diminishes, the price will increase, making it economically more attractive to use an alternative resource. Coal and uranium being exhaustable resources, will eventually become so expensive that they will claim an even larger portion of national output, thus making it impossible for economic growth to continue. This may be illustrated through graphical interpretation as shown in Figure 1. In Figure 1, we assume that the demand (D) is constant, while supply (S) increases. The equilibrium price is represented by the intersection of the supply and demand curves. This point represents the price at which the quantity supplied by the producers and the quantity demanded by the consumers are equal. As the quantity available increases, the supply curve moves from S_2 to S_1. As the supply curve moves to the right, the equilibrium price decreases.

It is possible to estimate the total amount of reserves and the length of time remaining before all remaining reserves are exhausted by the use of a logistic equation. The equation:

$$P_t = [p_o/r]e^{rn} \qquad [1.1]$$

where p_o is the initial production, r represents the rate of change of production, n is the number of years from 0 to t, and e is the base of the natural logarithms, may be used to calculate the cumulative production at the present time.(10) For example, to calculate the cumulative production of coal from the year 1973 to 1987, the initial production for 1973, 2308 x 10^6 tons(1) and the rate of production, 3%,(20) are incorporated into the equation such that:

$$P_t = [2308 \times 10^6/0.03]2.718282^{(0.03)(14)}$$

$$P_t = 117.090 \times 10^9 \text{ tons of coal}$$

Furthermore, the cumulative reserves for the year 1987 may be calculated with the following equation:

$$R_t = D_t - P_t \qquad [1.2]$$

where R_t is cumulative reserves, D_t cumulative discoveries, and P_t cumulative production. Therefore, if the cumulative discoveries through 1987 equal 1.64 x 10^{13} tons,(5) the reserves for the year 1987 are:

$$R_t = 1.64 \times 10^{13} - 117.09 \times 10^9$$

$$R_t = 1.625 \times 10^{13} \text{ tons}$$

From the estimate of present reserves, we may also determine how long the reserves will last. The equation:

$$n = 1/r \ln [Rr/p_o + 1] \qquad [1.3]$$

uses the estimate of present reserves, R, the initial production, p_o, and the growth rate of production, r, to estimate the life of a resource. Hence, the estimated number of years remaining for the life of coal in 1987 is:

$$n = 1/0.03 \ln [(16.25)(0.03)/0.005071 + 1]$$
$$n = 152.54 \text{ years}$$

This method may also be employed to estimate the life of uranium resources. If the initial production, p_o, for 1973 is 51.4×10^6 lbs,(1) and the growth rate of production, r, is approximately 2.5%,(20) then the cumulative production in 1987 is:

$$P_t = [51.4/0.025]2.718282^{(0.025)(14)}$$
$$P_t = 2.918 \times 10^9 \text{ lbs}$$

Given the cumulative discoveries for 1987, 6.20×10^{12} lbs,(5) the amount of uranium reserves may be derived:

$$R_t = 6.20 \times 10^{12} - 2.918 \times 10^{9}$$

$$R_t = 6.2 \times 10^{12} \text{ lbs}$$

Now the life time of the uranium reserves may be calculated:

$$n = 1/0.025 \ln [(6200)(0.025)/0.173 + 1]$$

$$n = 271.96 \text{ years}$$

The length of time available before all remaining reserves are exhausted depends on the growth rate of production.
For example, if in 1995, the growth rate of production of uranium were to rise to 4%, cumulative discoveries remained unchanged, and the production for that year were 1.76×10^{8} lbs, the life of uranium resources would then equal:

$$n = 1/0.04 \ln [(6200)(0.04)/0.176 + 1]$$

$$n = 181.28 \text{ years}$$

The depletion of scarce resources may also be illustrated graphically. Figure 2 depicts the example in which the remaining coal reserves were calculated using equations [1.1], [1.2], and [1.3]. The growth rate of production for coal is 3%, while discoveries remain constant. The cumulative reserves curve shows the 153 years remaining in the life of this resource. Figure 3 illustrates the movement of the cumulative reserves curve where the growth rate of production is increased to 5%. By increasing the growth rate of production, we have decreased the life of the resource to 102 years. Figures 4 and 5 describe a similar situation for uranium. At a growth rate of production of 2.5%, the curve shows 272 years remaining in the life of uranium. However, as the growth rate of production increases to 4%, as shown in Figure 5, the life of uranium decreases to 181 years.

Figure 6 represents the resource data for coal from 1087 to 2020, at which time all coal reserves are exhausted. The growth rate of production and the rate of cumulative discoveries are held constant. Figure 7 illustrates the movement of the cumulative discoveries curve should the rate of discoveries increase to 1%. In these two figures, we observe the importance of initial production, p_o, in the determination of cumulative discoveries, as well as cumulative reserves. By decreasing the value of p_o, which appears in Equation [1.1], the cumulative production is also decreased. This provides a model of developing resource technologies and it is possible to vary the rate at which those technologically accessed reserves are developed. Since Equation [1.2] states that cumulative reserves equals cumulative production subtracted from cumulative discoveries, if cumulative production decreases, cumulative reserves increases. If Equation [1.2] is rearranged, we find that:

$$D_t = R_t + P_t$$

Therefore, increasing cumulative reserves results in increasing cumulative discoveries. Furthermore, by increasing cumulative discoveries and decreasing cumulative production, the number of years before the two are equal increases, prolonging the life of the resource. Note that in Figure 7, the number of years remaining in the life of the resource has increased from 33 to 62 years. Figure 8 illustrates the movement of the cumulative discoveries curve should the rate of discoveries increase to 3%. At this rate, we have increased the life of coal to 82 years. Referring to Figure 9, the rate of discoveries has increased to 5%. Again, the remaining life of the resource has increased, resulting in approximately 105 years of coal remaining.

Although these calculations take into account an estimate of depletable resources and the remaining life of these resources, they do not allow for energy conservation . On the other hand, as the quantity of available resources decreases, the price will increase until it is no longer economically feasible to produce electricity with these resources. Therefore, the economically useful life of a resource will diminish before the calculated life time is reached.

Nuclear fusion represents the ultimate technological access to undeveloped reserves. The deuterium used in a fusion reactor is found in ordinary seawater. Enough deuterium is available to provide a source of fusion fuel for many millions of years.(11) Furthermore, fusion fuel releases a million times more energy than does burning a comparable weight of coal. In fact, 100 lbs of deuterium could fuel a 1000 megawatt power station for one year.(12)

Capital costs and fuel costs are an appreciable part of producing electricity. Compared to conventional fossil fuel plants, fusion is expected to have negligible fuel costs but high capital costs. Although the actual cost of constructing a fusion reactor is unknown, demonstration plant designs such as the STARFIRE plant designed by Argonne National Laboratory provide a realistic estimate of the cost involved with a reactor of this type. The STARFIRE is a 1200 megawatt power facility. The annual cost of electricity in 1980 dollars was estimated to be 35.1 mill/Kwh.(6) This figure is slightly more than the average estimates for fission plants, 22.8 mills/Kwh, or coal plants, 31.26 mills/Kwh. However, over a period of time, rising fuel costs for nuclear fission and coal plants will eventually allow fusion power to become increasingly competitive. Furthermore, the capital costs of a fusion plant may not be so important if the costs are predictable. One of the major difficulties involved with nuclear fission plants is rapidly increasing construction costs. "The House Committee on Government Operations found that nuclear power plants are experiencing serious cost overruns; as much as 26.7% for one plant and more than 100% for others."(9) The primary cause of these cost overruns is delayed construction. Delays increase labor costs, postpone the day when the plant can produce revenues from the sale of electricity, and can result in the escalating price of component parts if they are purchased at a later date. When delays for 28 plants were examined, it was found that 9 months of delay were attributed to legal challenges by citizens groups and, 229 months were due to poor labor productivity, shortages, and manufacturing breakdowns.(8)

A major component in the economic efficiency is the technical efficiency of resource conversion. All energy, whether from the combustion of fuel or a nuclear reaction, is available as heat for increasing the temperature of the surroundings. The amount of heat which is delivered to the surroundings is dependent upon the design of the heat engine. A source delivering heat which is entirely converted to electrical work would result in a decrease in entropy of the universe; an impossibility. Since the entropy of the universe increases rather than decreases, it follows that some heat must be lost to the surroundings. The requirement that the entropy of the universe does not decrease allows only a certain degree of efficiency in the conversion of heat to electrical work. This may be illustrated by two systems: one at temperature T_h, the other at T_c. The two systems are susceptible to a heat flow, q, from T_c to T_h. If the systems are so large that the heat flow does not create a measurable temperature change in either,(17) the change in entropy is:

$$\Delta S = q/T_h + q/T_c \qquad [2.1]$$

However, a smaller amount of heat, q', can be delivered to the system at T_c without resulting in a negative ΔS. The minimum allowable value of q' is the value which satisfies the equation:

$$0 = q/T_h + q'/T_c \qquad [2.2]$$

This value leaves open the possibility of getting some work:

$$w = q - q'$$

For a specified output of work, there is a required uptake of a resource, q, so that the efficiency, E, is at most:

$$E = w/q = (q - q')/q$$

But the smallest possible value for q' is that which satisfies the requirement that entropy not decrease, and from equation [2.2], we find that:

$$q'/q = T_c/T_h$$

When this result is substituted into the expression for the efficiency, we arrive at:

$$\epsilon = 1 - T_c/T_h = (T_h - T_c)/T_h$$

Using this equation, we may calculate the efficiencies for coal and nuclear fission generated plants. Since the exit temperature for most steam generated plants is on the average of 373 K, and the entry temperature for the fission process is approximately 588 K, the theoretical efficiency for a nuclear fission plant equals:

$$\epsilon = (588 - 373)/588 = 37\%$$

For a coal plant the efficiency equals:

$$E = (831 - 373)/831 = 55\%$$

If the entry temperature were to be increased or the exit temperature decreased, the thermal efficiency would be improved. Since the entry temperature of the fusion process is so great, it may be possible to operate a fusion plant with a thermal efficiency considerably greater than that of conventional energy production. However, since fusion offers an abundance of fuel at low costs, the thermal efficiency is less of a concern for the fusion industry.

As our present methods of electricity production become increasingly expensive as a result of inflation as well as environmental damage, alternative resources are becoming more attractive. Fusion energy may offer many economic advantages. A large portion of our environmental costs may be eliminated with the use of fusion power. Unlike coal fired plants, fusion reactors produce virtually no air pollutants. A reduction of coal related air pollution could result in lower medical costs and increased productivity of labor. Furthermore, by reducing the acid content of the atmosphere, we provide wildlife with a habitat which enables them to thrive. Fusion energy may also be the answer to our problems with hazardous waste storage. While fission plants require long term monitoring of radioactive waste, the waste generated from fusion plants will require tens rather than hundreds of years to decay to a harmless radiation level.

The most important attribute of fusion power may be the abundance of fuel. As coal and uranium become increasingly scarce, the price of producing electricity will increase. The deuterium used in the fuel cycle is found in sufficient quantities to assure inexpensive fuel provisions. Moreover, the production and refining costs which are a major portion of the expense of coal and uranium are not present in the fuel preparation of fusion reactors. The reactive fuel for fusion reactors is produced inside the reactor.

The comparison of fusion power with conventional resources suggests that fusion may offer many advantages over our present methods of electricity production. Environmental costs for fusion power appear to be significantly less than those of conventional methods. While construction costs for fusion reactors may be more than for fission or coal plants, this cost may not be so important in light of fusion's negligible fuel costs. Furthermore, the calculation of the lifetime of coal and uranium, shows that fusion fuels have a much longer lifetime. However, although the fusion energy program is showing progress, research is expensive and varying opinions exist as to where the Department of Energy should disperse its funds. While most agree that the development of new technologies is important, others feel that funding would be most beneficial if it were directed toward improving existing technologies. Over the past decade, a decrease in funding has slowed the development of fusion research. Toward the end of the 1970's, the Department of Energy had plans of funding a fusion engineering project with estimated costs of 2.5 billion dollars.(4) However, by the early eighties, the concept had dwindled to a project with estimated costs of 1.3 billion dollars. In the mid-eighties, a further change in the fusion research budget decreased these plans to a project which must be kept below 0.5 billion dollars. However, even with these setbacks, fusion power is gradually nearing the point of feasible operation. Taking into account all factors involved in the production of electricity, nuclear fusion power may be a safe, clean, and economical alternative energy source for the future.

Table of Figures

Figure 1 is a plot of price verses quantity. The intersection of the supply and demand curves represent the equilibrium quantities and prices. As the supply curve moves from S_2 to S_1, the equilibrium price decrease while equilibrium quantity increases.

Figure 2 is a plot of quantity verses time for coal in which the rate of cumulative discoveries is held constant and the growth rate of production is increasing at 3%. The remaining reserves curve indicates that there are 153 years of coal remaining.

Figure 3 represents the movement of cumulative discoveries, cumulative production and remaining reserves for coal if the rate of cumulative discoveries remains constant while the growth rate of production is increasing at 5%. By increasing the growth rate of production, the remaining reserves have decreased from that of the 3% rate illustrated in Figure 2.

Figure 4 illustrates the movement of cumulative discoveries, cumulative production, and remaining reserves for uranium. The growth rate of production is 2.5% while cumulative discoveries are constant. At this rate, the remaining reserves curve indicates that there are 272 years remaining for coal.

Figure 5 demonstates the effect of increasing the growth rate of production to 4%. Again, the rate of cumulative discoveries are held constant. As the growth rate of production is increased, a decline in remaining reserves is observed.

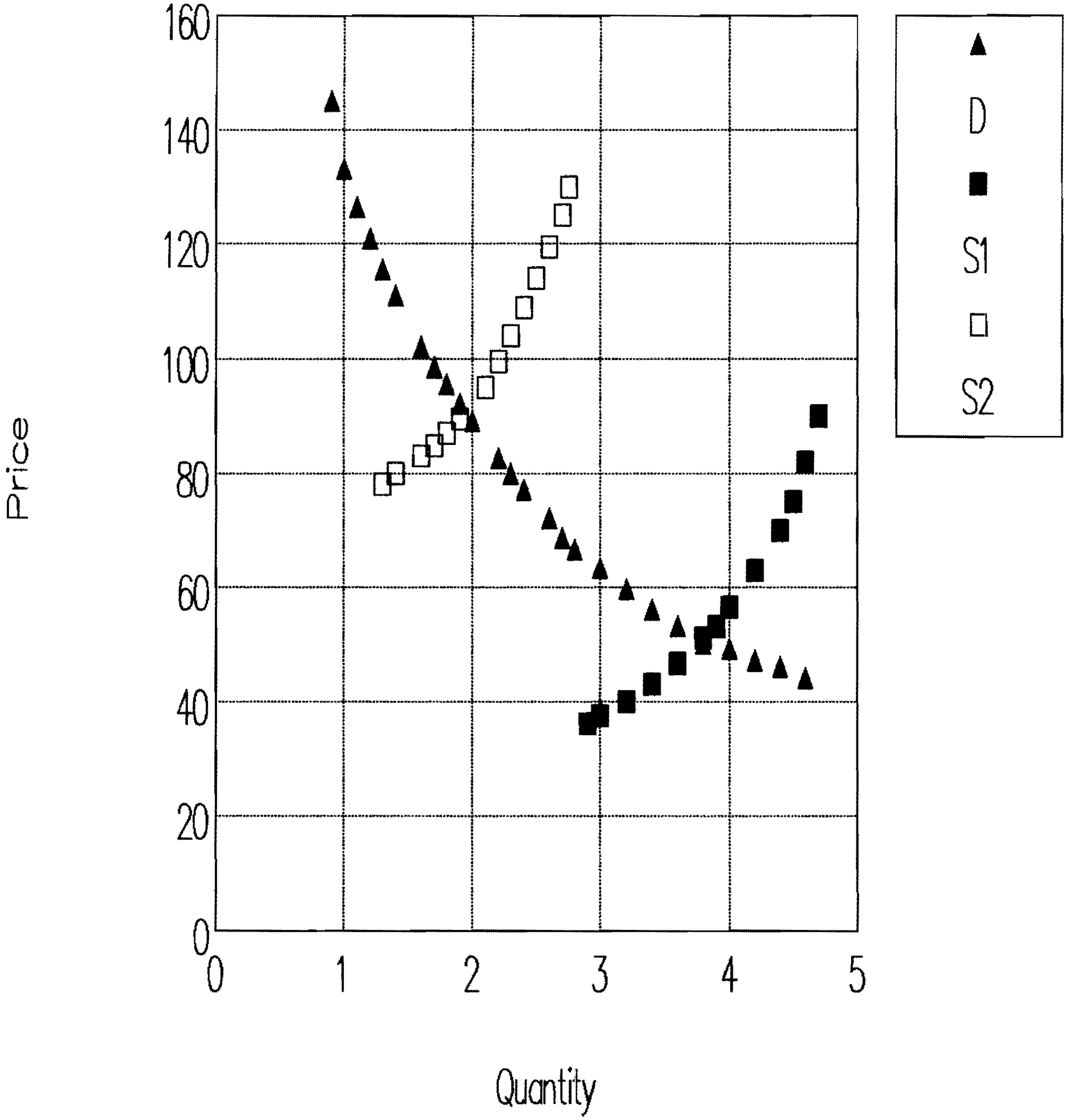
Figure 6 illustrates the movement of cumulative production, cumulative discoveries, and remaining reserves if the rate of cumulative discoveries and the growth rate of production are held constant. At this point, the remaining reserves curve has declined to 33 years.

Figure 7 represents the movement of cumulative discoveries, cumulative production, and remaining reserves over time. The growth rate of cumulative production is again held constant while while cumulative discoveries increase at a rate of 1%. The remaining reserves curve has been increased by the increase in cumulative discoveries.

Figure 8 is a plot of quantity verses time for coal, illustrating a situation in which the growth rate of cumulative production is constant and the rate of cumulative discoveries is 3%. By increasing the rate of cumulative discoveries, the number of years of remaining reserves have also increased from that of the 1% rate illustrated in Figure 7.

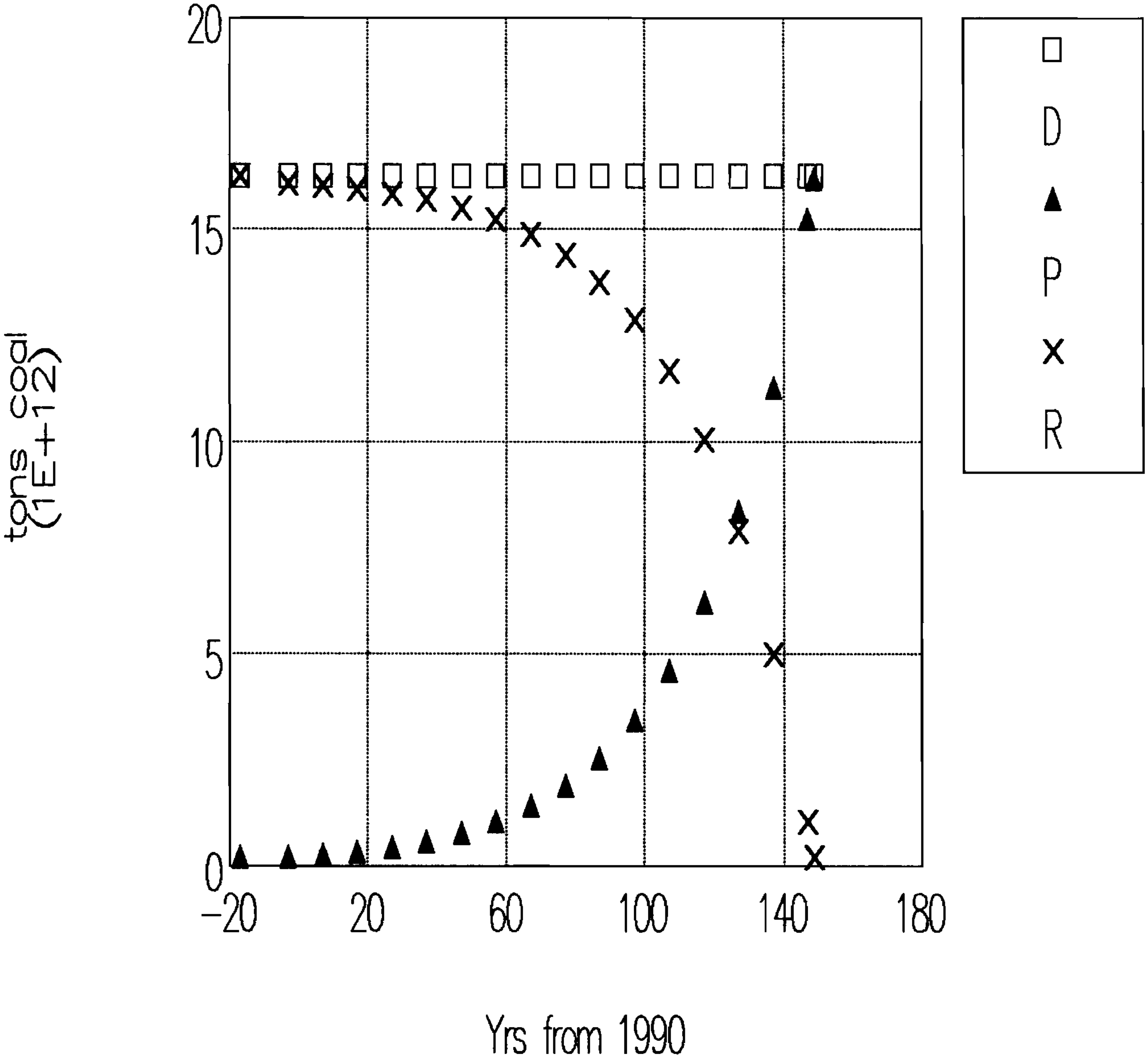
Figure 9 is a plot of quantity verses time for coal. Three curves are illustrated: cumulative production, cumulative discoveries and remaining reserves. The growth rate of cumulative production is held constant while cumulative discoveries are increasing at a rate of 5%. The remaining reserves are determined by the extent at which cumulative discoveries exceed the cumulative production. At the point where cumulative discoveries equals cumulative production, remaining reserves are exhausted.

Price Decrease for Increased Supply



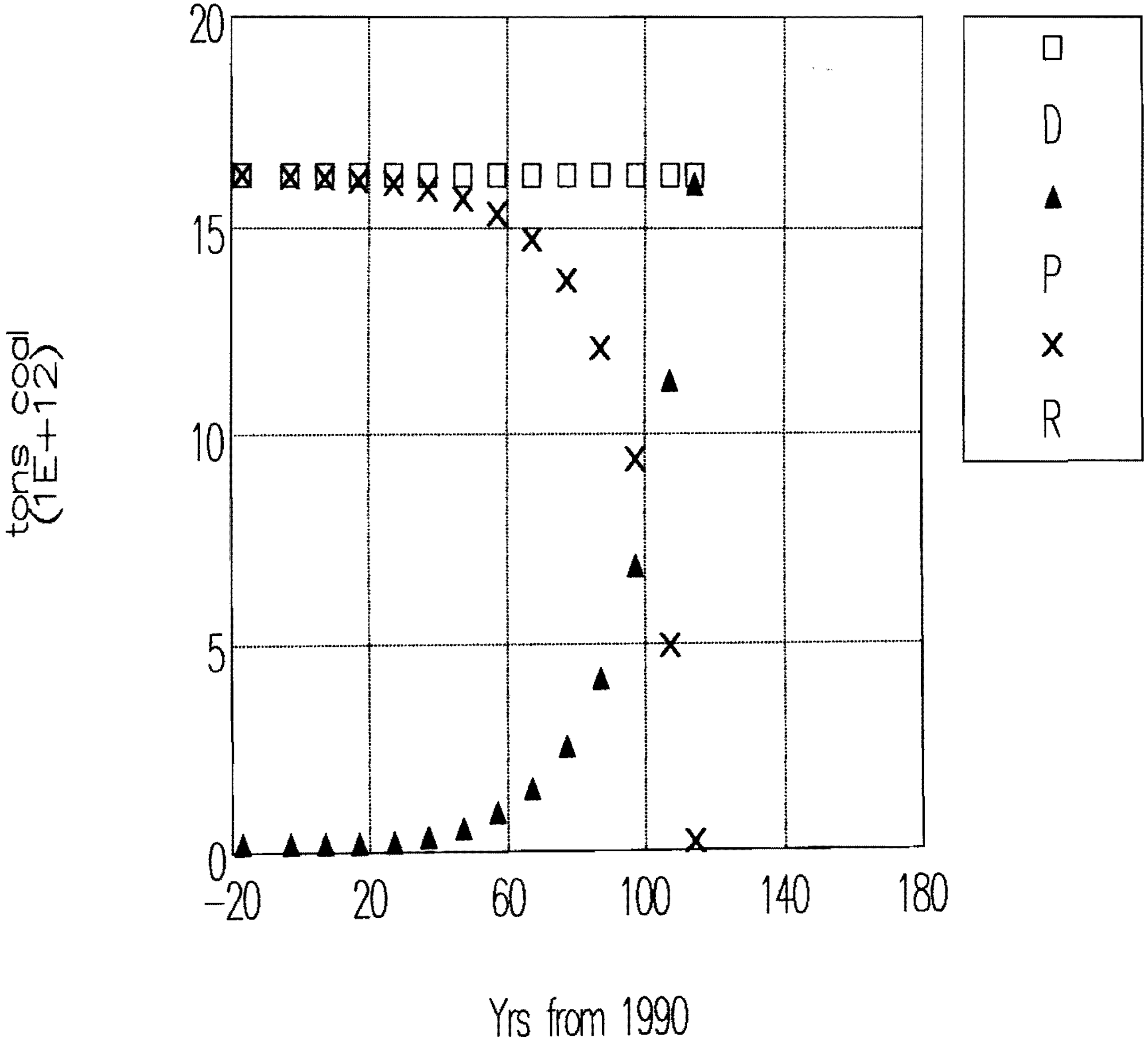
Coal Reserves

static discoveries, r=3%



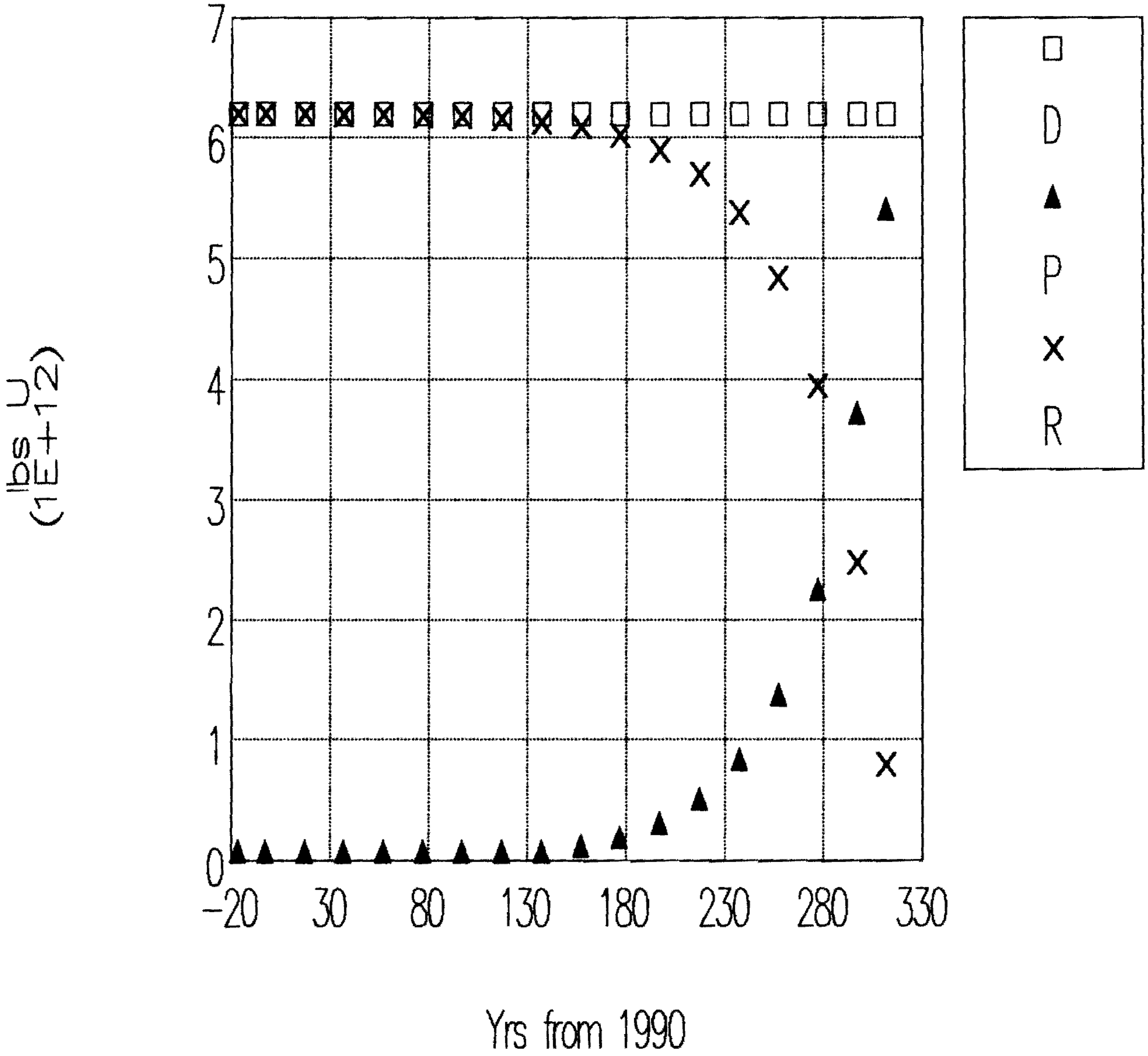
Coal Reserves

static discoveries, r=5%



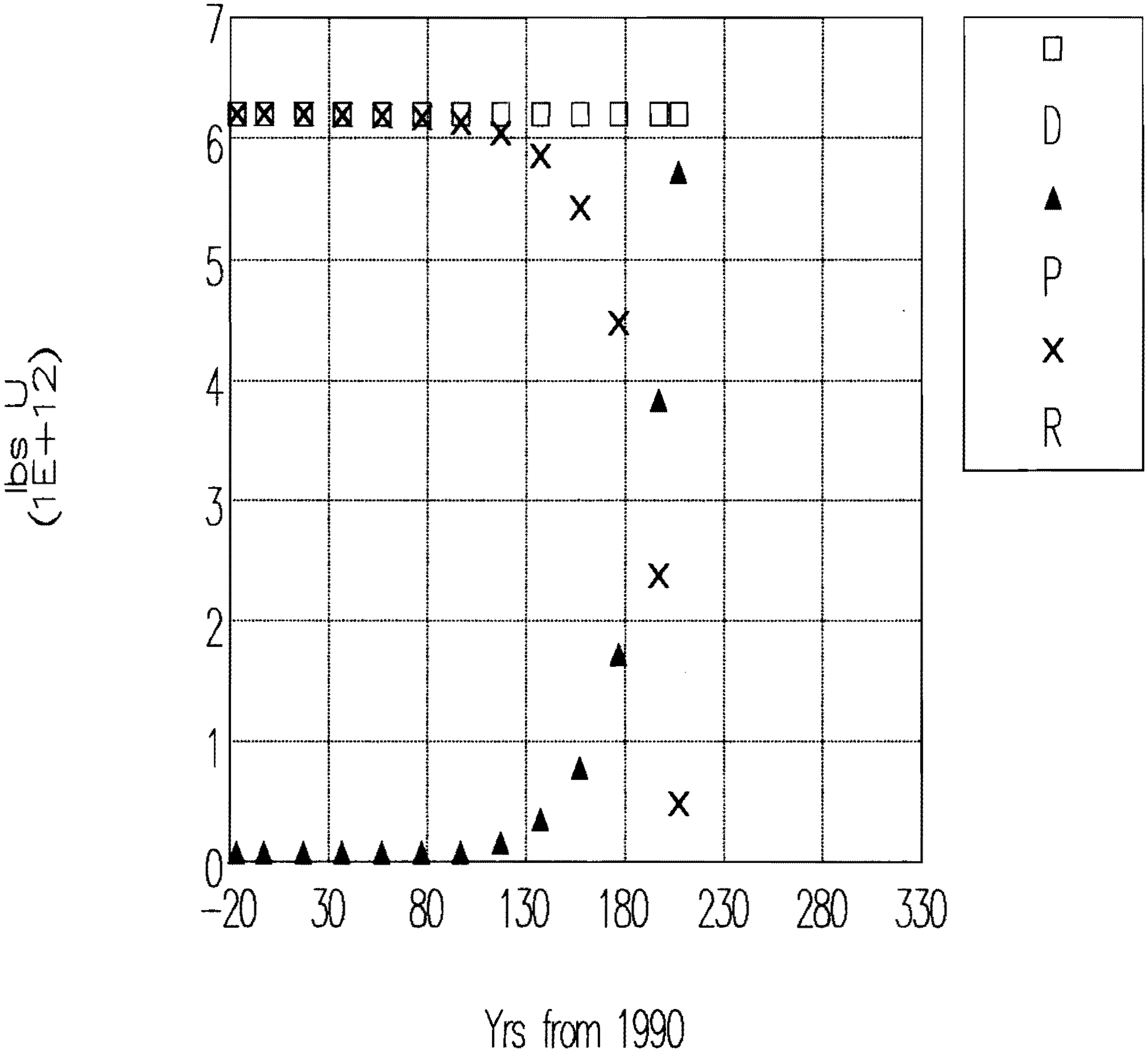
Uranium Reserves

static discoveries, r=2.5%



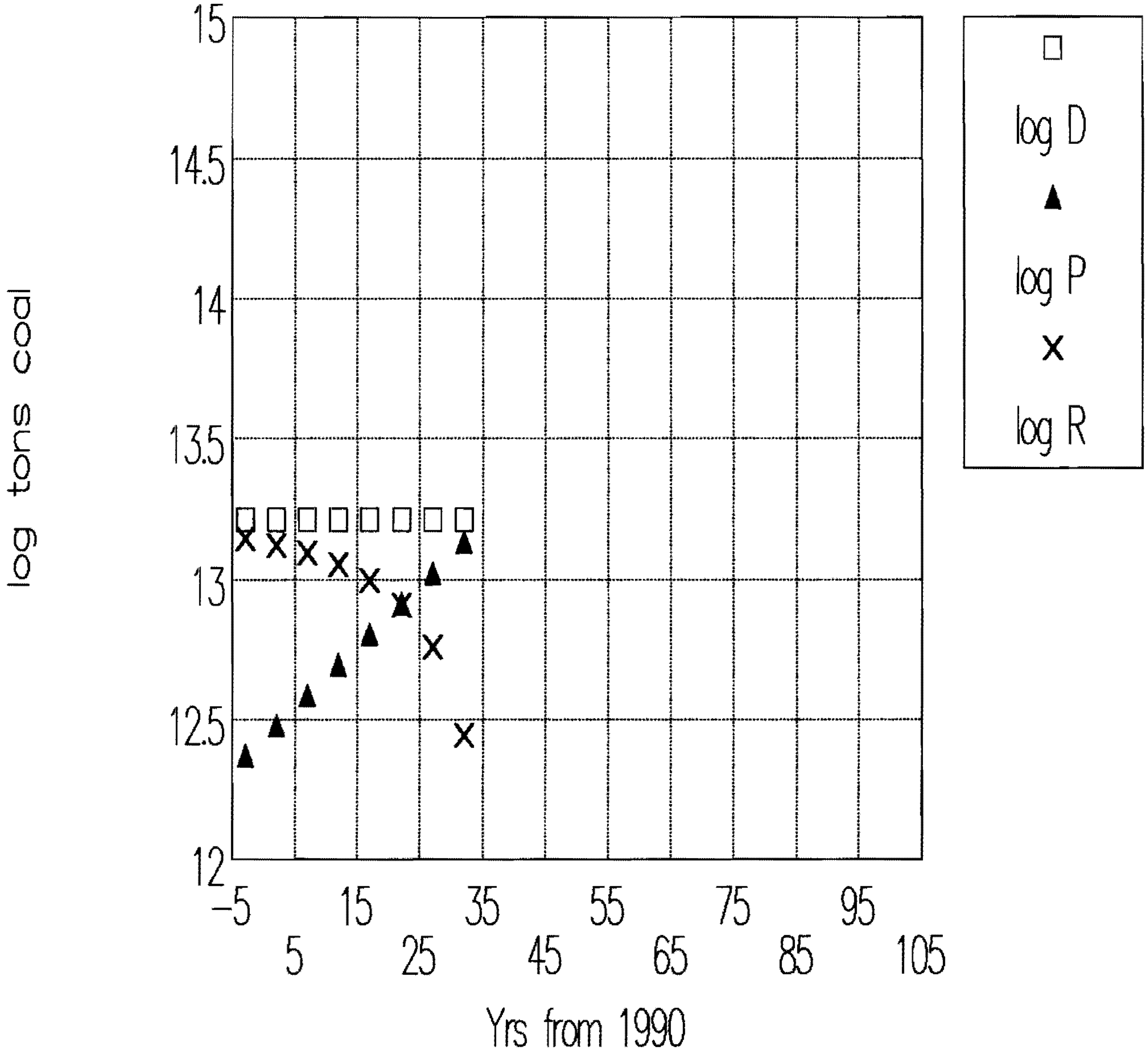
Uranium Reserves

static discoveries, r=4%



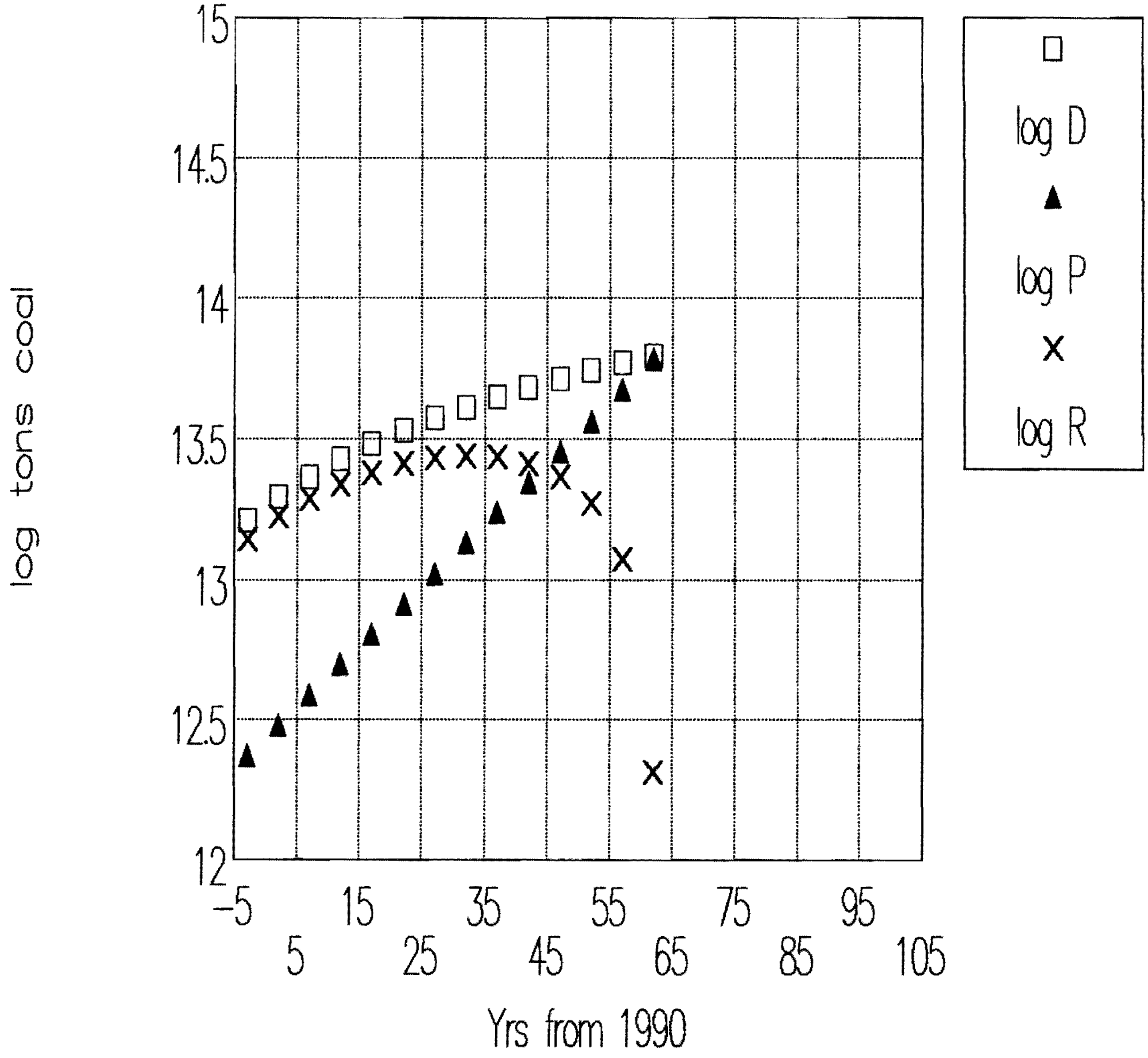
Coal Reserves

by cumulative discovery, production



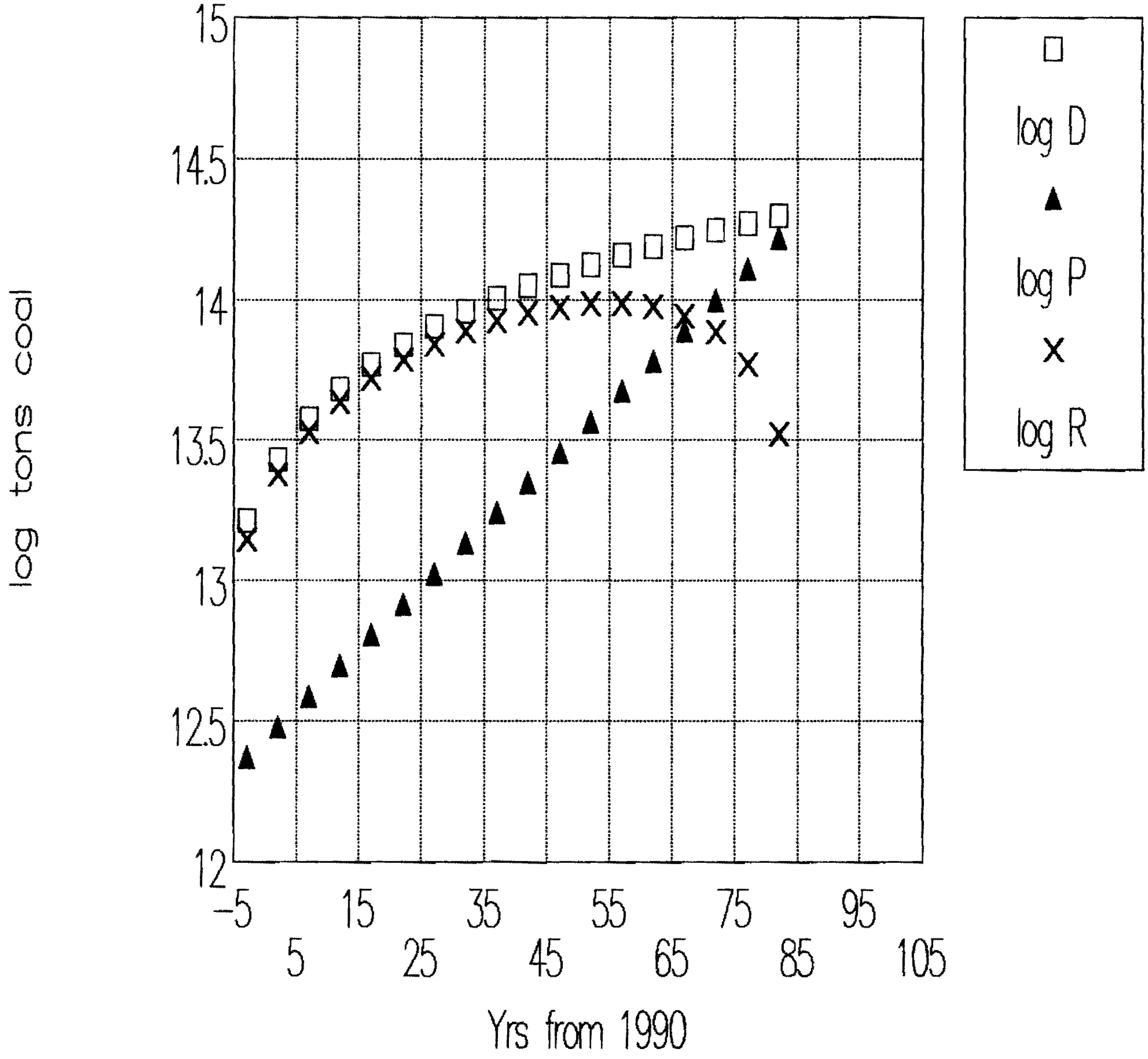
Coal Reserves

by cumulative discovery, production



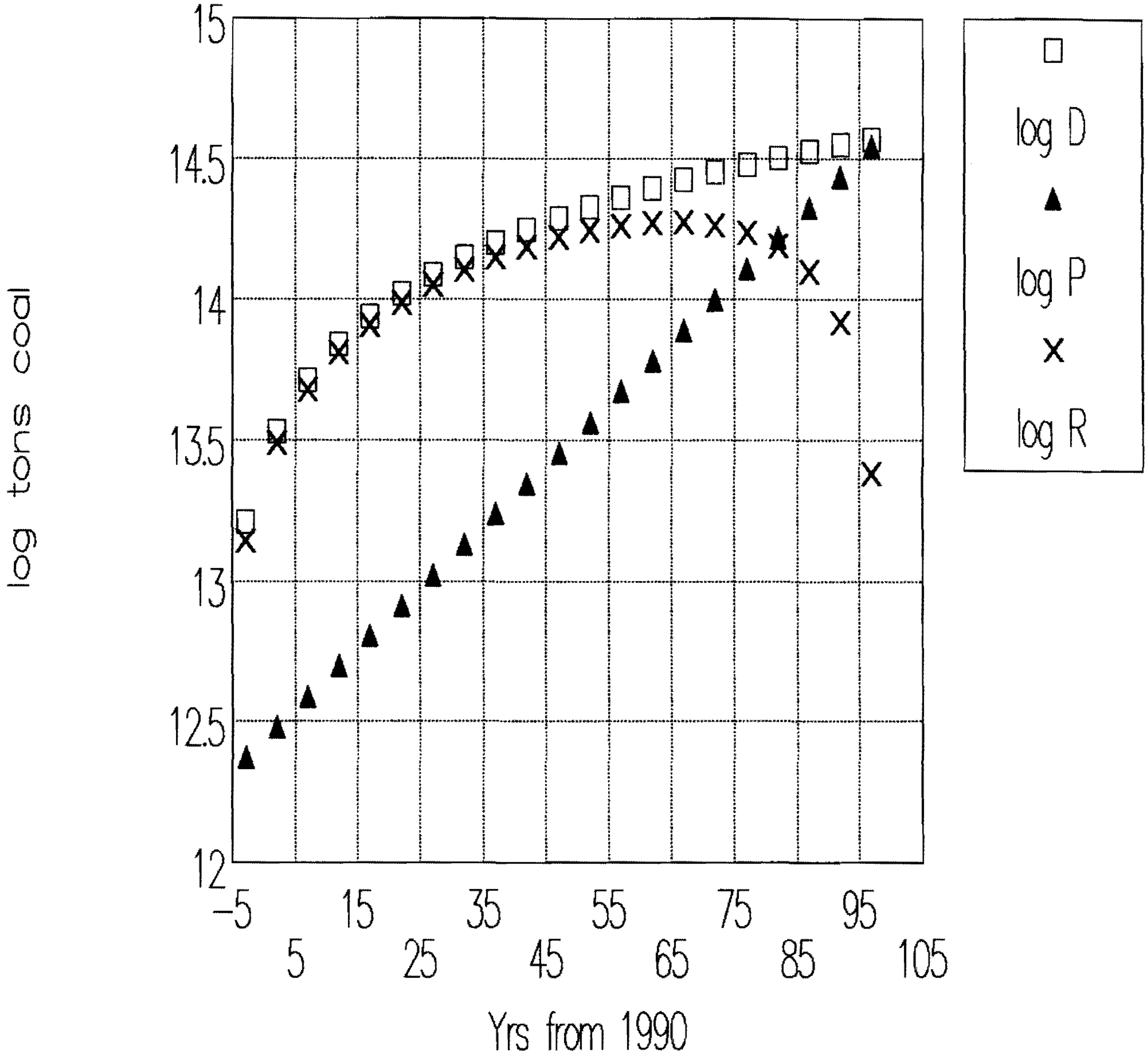
Coal Reserves

by cumulative discovery, production



Coal Reserves

by cumulative discovery, production



Bibliography

(1) Annual Energy Review 1988. Energy Information Administration

(2) Dalton, Aurthur W. "Electronic Measurement of Tritium Breeding in a Fusion Blanket Assembly." Fusion Technology 15 (January, 1989), 49-54

(3) Faulkner, Peter, ed. The Silent Bomb. N.Y.: Random House, 1977.

(4) Furth, Harold P. "Reaching Ignition in the Tokamak." Physics Today 38 (March, 1985), 54-61

(5) Gibson, A. Energy Industries Atlases. Massachusetts: World Eagle Inc. 1983.

(6) Gross, Robert A. Fusion Energy. New York: J. Wiley and Sons Inc; 1984.

(7) Hagler, M.O. and M. Christiansen. An Introduction to Controlled Thermonuclear Fusion. Massachusetts: D.C. Heath and Company, 1977.

(8) Hansen, Kent and Eric Beckjard; Elias P. Hyflapoutos; Michael Geloy; Richard Lester. "Making Nuclear Power Work." Technology Review (February/March, 1989) 30-40

(9) Kaku, Michio and Jennifer Trainer, ed. Nuclear Power: Both Sides. New York: W.W. Norton and Company, 1983.

(10) LeBel, Phillip G. Energy, Economics and Technology. London: The John Hopkins University Press, 1982.

(11) Meyers, Robert A., ed. Handbook of Energy Technology and Economics. N.Y.: John Wiley and Sons, 1983.

(12) Miley, George. Fusion Energy Conversion. American Nuclear Society, 1976.

(13) Mohnen, Volker A. "The Challenge of Acid Rain." Scientific American 25 (August, 1988), 30-47

(14) Paul, Bill. "Power Supply Forecasts Grow Pessimistic." Wall Street Journal (October 12, 1989), A2

(15) Pentrath, R.J. Nuclear Power, Man and the Environment. London: Taylor and Francis Ltd., 1980.

(16) Raloff, J. "Acid Rain: Lowdown on Health of Lakes." Science News 135 (May 20, 1989), 311

(17) Reissner, John. "Nail in the Pail: When is S = q/T ? " (April 17, 1990)

(18) Rogers, Phila Withrell. "Fusion Update: Stoking the Furnace." LBL Research Review 5 (Winter 1980-81), 4-7

(19) Scheiba, Shirley Hobbs. "Going Fission." Barron's (February 20, 1989), 14-15; 24-25

(20) Two Energy Futures: A National Choice for the Eighties. Washington D.C.: American Petroleum Institute, 1980.