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METHODS OF ECONOMIC ANALYSIS
APPLIED TO FUSION RESEARCH

Third Annual Report

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DOE Report #DOE/ET/52017-3

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METHODS OF ECONOMIC ANALYSIS
APPLIED TO FUSION RESEARCH
Third Annual Report

Prepared for
The Department of Energy
Division of Magnetic Fusion Energy

Under Contract No.
DE-AC02-79-ET 52017

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Prepared by
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December 18, 1979

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NOTE OF TRANSMITTAL

The application of principles of economics to the economic evaluation of fusion research reported in this document was prepared for the U.S. Department of Energy, Division of Magnetic Fusion Energy, under Contract No. DE-AC02-79-ET52017. ECON study manager for this effort has been Dr. George A. Hazelrigg, Jr. Other individuals contributing to this study include Mr. Keith R. Lietzke and Dr. Klaus P. Heiss. The DOE technical representative for this study was Dr. Charles Head.

Submitted by:

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President

ABSTRACT

In current and previous efforts, ECON has provided economic assessment of a fusion RD&D program. This evaluation has recognized the following facts: (i) pursuit of a fusion RD&D program is not a commitment to "buy" a technology; (ii) the use of a 10 percent real rate of discount is unwarranted for program evaluation and biases project selection in favor of short-term energy technologies; and (iii) expectations on future energy supply technologies can have immediate impacts on optimal prices of nonrenewable fuel sources.

The current study reported here has involved three separate tasks. The first re-evaluates previous benefit estimates derived, using more realistic rates of discount and other parameter changes. These results show fusion research to be considerably more beneficial than previously thought.

The second task investigates other possible commercial uses of technologies which must be developed in providing commercial fusion power. Several such applications have been identified and potential market sizes estimated. It is suggested that, since other sectors will benefit from the availability of these technologies, the fusion program should not bear the entire cost of this development.

The third task develops a methodology for evaluating the impact of additional projects in support technology RD&D on the value of the overall fusion program. This effort has shown that it is possible to economically prioritize RD&D on those functions which will be required in commercial fusion and to provide economic rationales for program changes. The results of this task indicate substantial benefit from increased pursuit of RD&D in several support technology areas.

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FOREWORD

The separate tasks were performed under this effort. The first reviews preliminary estimates of the benefits of fusion and fusion research reported in "The Economics of Fusion Research," ERDA Report No. C00/4181-1, ECON Report No. 77-158-2, October 1977. These estimates were updated using the results of analyses performed in ECON's second study, reported in "Methods of Economic Analysis Applied to Fusion Research: Discount Rate Determination and the Fossil Fuel Price Effect," DOE Report No. C00/4181-2, ECON Report No. 78-159-2, September 1978. The second task studies the supporting technologies which are required for the provision of commercial fusion power and potential applications of these technologies in other areas. The final task develops and demonstrates a methodology which economically evaluates research and development programs that are intended to lead to commercializable technologies. These efforts have been performed sequentially and this fact is reflected in the analyses reported.

1. A REVIEW OF THE BENEFITS OF FUSION

In previous phases of analysis of the fusion energy research program, ECON has identified both near-term and long-term benefits to be derived from fusion research. The near-term benefits derive from having improved information on the basis of which to make energy research and other economic decisions and also from expectations created about the potential availability of commercial fusion power. The effect and value of the former (improved information for energy research decision making) is described in greater detail in Section 3. The nature of benefits to be derived from the latter (changing expectations about the availability of fusion power) has been explored to some extent in previous ECON studies. One particular vehicle for such benefits is the reduction in optimal fossil fuel prices resulting from a changing expectation on the imminence of the commercial availability of fusion. The most recent results of this modeling effort were presented in "Methods of Economic Analysis Applied to Fusion Research: Discount Rate Determination and the Fossil Fuel Price Effect," September 25, 1978. Long-term benefits could be obtained from fusion research via consumer and producer surpluses to the extent that commercial fusion power proves to be economically attractive relative to alternative energy sources and is implemented.

An attempt was made in the previous study phases to estimate the magnitude of benefits from two sources: reduction in optimal fossil fuel prices and implementation benefits. As part of the second study phase an analysis was made to determine an appropriate rate of social discount to be used in evaluating long-term projects such as fusion research. This analysis developed evidence that a discount rate in the 3 to 5 percent range is more appropriate for the evaluation of

long-range energy RD&D than the 10 percent rate mandated by the Office of Management and Budget (OMB). The results of this analysis are also presented in the aforementioned report.

The review of fusion benefits described herein is a recalculation of the previously estimated benefits (which were arrived at using a 7.5 percent discount rate), this time parametrically examining the effect of discount rate on the size of perceived benefits from fusion research using discount rates in the range of 2 to 10 percent. The recalculated near-term benefits are presented below as they are expected to occur over time as a function of both importer and exporter discount rates. In addition, the effect of the elasticity of demand for fossil fuels on the magnitude of estimated benefits is examined. The benefits to be obtained from the commercial implementation of fusion power are approached parametrically in terms of projected generation cost savings over alternative technologies, social discount rate and the availability date of commercial fusion power.

1.1 Benefits from the Reduction of Optimal Prices for Fossil Fuels Through Energy RD&D

In its initial study of the economics of fusion research, ECON identified an area of near-term benefit that had not been made explicit in other studies. This benefit is due to the effect of future, new energy supplies upon the intertemporal consumption of conventional, nonrenewable energy resources such as fossil fuels and uranium. The depletable nature of these resources means that their present consumption precludes future consumption. Thus, the resource holders will "hoard" their inventory if the value of doing so--as measured by the discounted, expected future price--exceeds the price offered today. The expectation of a new energy source which will compete with the depletable resource in the future results in a decreased expected future demand for the resource, thus stimulating increased production today. Viewed from a societal welfare aspect, the availability of future

energy sources means that current energy resources need not be unduly saved for future generations. This phenomenon leads to benefits in the near-term, as changes in expectations on future energy supplies result in immediate changes in the optimal intertemporal allocation of the depletable resources.

In order to investigate this broad benefit area, ECON selected one particular market where this effect could be studied: the production decisions for OPEC oil. OPEC was selected due to the somewhat adversary nature between OPEC and its customers and because it represents a single (monopolistic) producer. The initial analysis was very preliminary, but the benefits identified were sufficiently large so as to provide additional economic incentive to the development of long-range energy technologies, and thus warranted further investigation.

The model of optimal petroleum pricing strategies employs the fundamental assumption that the holders of oil reserves wish to price their oil so as to maximize its value to themselves; specifically, the problem is one of maximizing the present value of net revenue accruing from the initial reserves. As such, it is a dynamic profit-maximization problem.

If the possibility of a substitute for petroleum as an energy resource exists through energy RD&D, the effect would be to lower the demand for petroleum, according to the substitute's supply characteristics, after the date at which it is first available. The change in demand affects the net revenue function and thus also the optimal consumption pattern. The date at which the substitute technology becomes available is uncertain; hence, it must be treated probabilistically. The form and parameters of the probability distribution describing the availability date of the substitute technology are knowable and are clearly influenced by RD&D investments in the technology. (The values that have been assumed in this analysis are set forth in Table 1.1.) Changes in the optimal resource consumption resulting

from changes in the expectation of the arrival of the substitute technology are properly attributable to RD&D expenditures on the substitute.

Another important aspect of modeling the technology is its effect upon the demand for OPEC oil. The ultimate market penetration is treated as an input parameter. The new technology, however, cannot be assumed to capture its entire share immediately but must be phased into production, allowing for new plant construction and adaptation of the energy consumption network to a new form. Figure 1.1 shows how the introduction of the new technology reduces the (growing) demand for OPEC oil from the pre-technology demand level to the level with full market penetration. The transition is modeled as a logistic-type decay from the higher to lower demand levels. The rate of penetration, as well as its ultimate level, is specified exogenously.

The type of benefit discussed here will be realized to the extent that OPEC's pricing policies are indeed intended to maximize the net present value of revenues accruing from their oil holdings. There is evidence from statements made by OPEC representatives that their approach is motivated by such a rationale. Furthermore, the extent to which the benefits estimated below are realized is dependent on an energy RD&D policy succeeding in changing the expectation of the arrival of a substitute technology in the manner assumed below (Table 1.1). The comparison being made for the purposes of benefit estimation is between the optimal oil consumption pattern if no substitute technology exists and the optimal consumption which would result if such an expectation on the availability of the substitute results from an energy RD&D program. The characteristics of a substitute technology outlined below might be achieved by a fusion research program.

TABLE 1.1 PARAMETERS USED IN THE ANALYSIS OF OPTIMAL FOSSIL FUEL CONSUMPTION PATTERNS	
•	OPEC DEMAND GROWTH RATE = 4 PERCENT PER YEAR
•	OPEC DISCOUNT RATE = 2 AND 4 PERCENT
•	OPEC DEMAND ELASTICITY = -1 AND -0.1
•	EARLIEST POSSIBLE COMMERCIAL AVAILABILITY = 2000
•	MOST LIKELY AVAILABILITY = 2010
•	ULTIMATE OPEC REDUCTION DUE TO NEW TECHNOLOGY = 75 PERCENT
•	TIME REQUIRED FOR 50 PERCENT MARKET PENETRATION BY NEW TECHNOLOGY = 30 YEARS
•	PROBABILITY OF ULTIMATE COMMERCIAL IMPLEMENTATION OF NEW TECHNOLOGY = 50 PERCENT
•	IMPORTERS DISCOUNT RATE = 2, 4, 6, 8 AND 10 PERCENT

FIGURE 1.1 DEMAND GROWTH PATHS AND TRANSITION AFTER AVAILABILITY OF SUBSTITUTE

A detailed discussion of the entire methodology for fossil fuel price effect benefits (which has been outlined only briefly above) can be found in the aforementioned report of September 25, 1978. The object here is to examine the effect of discount rate and demand elasticity on the benefits which would be perceived as a result of energy RD&D owing to this effect. The parameters which have been used for the analysis are summarized in Table 1.1.

The discount rate applied by importing countries in evaluating the type of benefits discussed here has a substantial effect on the magnitude of the perceived benefits. The significance of the discount rate chosen is shown in Figure 1.2, which presents time profiles of the total annual benefits perceived on an undiscounted (i.e., discount rate = 0 percent) and discounted (discount rates from 2 to 10 percent) basis. These benefits are the total for all consumers of OPEC oil not just the United States. In this particular case, the price elasticity of demand is assumed to be -1.0 and OPEC's discount rate to be 4 percent. (The effects of variations in these latter assumptions is examined below.) It has been determined that, for long-term RD&D projects such as the fusion energy research program, discount rates in the 3 to 5 percent range are appropriate, if risk has been explicitly accounted for. Perceived annual benefits 20 years or more in the future using discount rates in the 3 to 5 percent range may be seen to be two to three times higher than benefits at the 7.5 percent rate used in previous ECON studies and many times higher than benefits which would be perceived if the 10 percent discount rate mandated by OMB were employed. The discount rate used in benefit evaluations clearly has a significant effect on outcome, even in the evaluation of near-term benefits such as the fossil fuel price effects. The benefits estimated here using a 3 to 5 percent discount rate would support pursuit of a vigorous program of fusion research.

FIGURE 1.2 THE EFFECT OF IMPORTER DISCOUNT RATE ON ANNUAL BENEFITS FROM REDUCED OPTIMAL OPEC OIL PRICES

The discount rate which OPEC itself uses, of course, affects the present value of its revenue flows, hence its pricing policy and the resulting oil consumption patterns. The effect of variations in both importer and exporter discount rates is shown in Figure 1.3, where time profiles of benefits are presented for OPEC discount rates of 2 and 4 percent and importer discount rates of 0, 2 and 4 percent. As in Figure 1.2, the benefits disappear with the projected exhaustion of the oil reserves. If OPEC were to use a 4 percent discount rate in evaluating the revenues from oil sales, the reserves would be exhausted 10 years earlier than if a 2 percent rate were utilized. Whereas Figure 1.3 clearly demonstrates that the time distribution of benefits may be significantly altered by OPEC's selection of a discount rate--that is, importers accrue larger benefits earlier on and lower ones later on if OPEC uses a lower discount rate--the present values of the benefit streams for importers are not significantly affected by OPEC's discount rate. Table 1.2 lists the benefits to all importers and to the United States individually of reduced optimal fossil fuel prices for two different levels of OPEC discount rate (2 and 4 percent), two different levels of demand elasticity (-1.0 and -0.1), and five different levels of importer discount rate (2, 4, 6, 8 and 10 percent). The differences in benefits at different OPEC discount rates for a given demand elasticity are not significant. However, an order of magnitude difference in benefit levels exists as a result of the stated variation in the elasticity of demand. Time profiles of undiscounted benefits for two different levels of demand elasticity and two different OPEC discount rates are presented in Figure 1.4. Whereas the OPEC discount rate does alter the time distribution of benefits, as noted before, it is the elasticity of demand which has the predominant effect on the magnitude of the benefits. Given that very inelastic demand functions lead to much higher

FIGURE 1.3 THE EFFECT OF BOTH IMPORTER AND EXPORTER DISCOUNT RATES ON TOTAL ANNUAL BENEFITS FROM REDUCED OPTIMAL OPEC OIL PRICES

FIGURE 1.4 EFFECTS OF ELASTICITY OF DEMAND AND OPEC DISCOUNT RATE ON UNDISCOUNTED BENEFITS

TABLE 1.2 EXPECTED BENEFIT TO IMPORTERS REFERENCED TO JANUARY 1, 1980, \$ BILLIONS (1977)				
IMPORTER (U.S.) DISCOUNT RATE, %	ELASTICITY OF DEMAND = -1.0		ELASTICITY OF DEMAND = -0.1	
	OPEC DISCOUNT RATE = 2%	OPEC DISCOUNT RATE = 4%	OPEC DISCOUNT RATE = 2%	OPEC DISCOUNT RATE = 4%
2	U.S. = 2.42 TOTAL = 16.05	U.S. = 2.56 TOTAL = 16.94	U.S. = 18.68 TOTAL = 123.70	U.S. = 23.55 TOTAL = 155.98
4	U.S. = 1.59 TOTAL = 10.56	U.S. = 1.53 TOTAL = 10.14	U.S. = 12.75 TOTAL = 84.46	U.S. = 13.15 TOTAL = 87.11
6	U.S. = 1.10 TOTAL = 7.31	U.S. = 0.97 TOTAL = 6.44	U.S. = 8.96 TOTAL = 59.37	U.S. = 7.97 TOTAL = 52.80
8	U.S. = 0.80 TOTAL = 5.27	U.S. = 0.65 TOTAL = 4.33	U.S. = 6.50 TOTAL = 43.05	U.S. = 5.19 TOTAL = 34.38
10	U.S. = 0.60 TOTAL = 3.95	U.S. = 0.46 TOTAL = 3.05	U.S. = 4.86 TOTAL = 32.17	U.S. = 3.59 TOTAL = 23.76

benefit estimates, the use of the unitary demand elasticity in previous work may have underestimated the fossil fuel price efforts.

1.2 Benefits from the Commercial Implementation of Fusion Power

It is clear that the discount rate applied to long-term benefits, such as potential cost savings achieved from commercial implementation of fusion power, has a significant effect on the magnitude of perceived benefits. For example, if one assumes that fusion becomes available in the year 2010, then the present value in 1980 of any benefits which accrue that year when discounted at 10 percent reflect only about 7 percent of the undiscounted value of the benefits, whereas at a rate of 3 percent, the 1980 present value of benefits from that year would reflect over 40 percent of the undiscounted value of the benefits. The marked effect of discounting on long-term benefits can be seen in Figure 1.5 which shows the time profile of benefits from fusion implementation on an undiscounted basis, as well as at discount rates of 2, 4 and 6 percent. These benefit profiles are based on the assumption that fusion power generation costs prove to be two mills/kWh cheaper than alternative technologies including externalities such as environmental and

FIGURE 1.5 EFFECT OF DISCOUNT RATE ON FUSION IMPLEMENTATION BENEFITS
TIME PROFILE

safety costs and that fusion power plants are implemented according to a scenario developed at Brookhaven National Laboratory. This implementation scenario calls for the installation of 300 fusion plants: one plant operating as of 2010, two as of 2015, 16 as of 2025, 100 as of 2035, 300 as of 2055. It is assumed that these plants are installed at linear rates in order to meet each of these milestones and that these plants continue in operation (that is, are replaced as necessary to maintain a constant level of 300 plants, once this level is achieved) until the year 2100. This Brookhaven scenario is the same one used in ECON's earlier analysis of the market penetration of commercial fusion plants found in Section 4 of "The Economics of Fusion Research," October 15, 1977. The analysis presented in Section 3 gives a somewhat different approach to fusion's market penetration. In addition to this implementation scenario, it is assumed in all of the following implementation benefit analyses that fusion power plants have an output of 2.05 GW_e and a capacity factor of 83 percent. These values were the design values associated with the UWMAK III tokamak reactor plant which was modeled in earlier studies.

In addition to discounting, the effects of different levels of generation cost savings and escalation in the price of power of competing technologies is examined in Figure 1.6. Along the horizontal axis are displayed different levels of potential generation cost savings over alternative technologies. For each level of discount rate (2, 4, 6 and 8 percent) two different cases are presented: one in which there is no escalation in the cost of power from alternative sources and one in which there is a 1 percent per year increase. For discount rates higher than 6 percent--particularly if there is no escalation in the cost of alternative sources--the benefits are quite small, if not indeed negligible. However, for discount rates in the range of 2 to 5 percent the present values of benefits are fairly substantial, again providing a good case for the pursuit of a vigorous fusion research program,

FIGURE 1.6 EFFECT OF DISCOUNT RATE AND GENERATION COST SAVINGS ON FUSION IMPLEMENTATION BENEFITS

to the extent that the assumptions underlying these calculations are deemed to be reasonable.

One of the assumptions about which there definitely exists some uncertainty is that fusion power will be commercially available by the year 2010. The impacts of both discount rate and availability date on the present value of implementation benefits is displayed in Figure 1.7. The same pattern of implementation is used in calculating the benefits which occur as a function of when fusion becomes available. Hence, it is only the fact that the benefits accrue later and are therefore discounted over a greater period of time which serves to reduce the present value of total benefits. These benefit streams are based upon the assumption that fusion is constantly two mills/kWh cheaper than alternative technologies. Evaluated at discount rates in the 3 to 5 percent range, fairly substantial benefits remain even if the availability date slips considerably, say, to 2040 or 2050. However, at discount rates greater than 6 percent, perceived benefits from the commercial implementation of fusion rapidly become negligible as the availability date slides back in time.

All three factors (cost savings, discount rate and availability date) are combined parametrically in Figure 1.8 to show the interacting effects. For three different levels of cost savings (2, 6 and 15 mills/kWh) the present value of implementation benefits at two different discount rates (2 and 4 percent) are presented as a function of the availability date of commercial fusion power. If a cost savings of 2 mills/kWh were to be achieved then sufficient benefits would be perceived (at a 2 to 4 percent discount rate) from the implementation of fusion to justify a vigorous program of research. In addition, these benefits are relatively insensitive to the availability of commercial fusion power.

PRESENT VALUE (AS OF JANUARY 1, 1980) OF
BENEFITS OF IMPLEMENTING FUSION POWER,
DISCOUNTED AT INDICATED RATE, \$ BILLIONS

FIGURE 1.7 EFFECTS OF DISCOUNT RATE AND AVAILABILITY DATE ON FUSION IMPLEMENTATION BENEFITS

FIGURE 1.8 EFFECT OF AVAILABILITY DATE AND GENERATION COST SAVINGS ON FUSION IMPLEMENTATION BENEFITS

2. ALTERNATIVE USES OF TOKAMAK REACTOR TECHNOLOGIES

This chapter reviews and summarizes the technologies which will have application in the development of a tokamak reactor. It further attempts to identify required technological developments and suggest possible methods whereby they may be achieved. An attempt is then made to identify alternative uses for the required technologies.

In view of the anticipatory nature of the tokamak reactor program, i.e., reactor grade plasmas and economically viable solutions to problems such as the design of the first wall are yet to be demonstrated, the technological review contained herein must be regarded as transitory.

As a starting point the UWMAK [1]^{*} series of designs were reviewed. These were chosen as they probably represent the most comprehensive design studies yet performed on a tokamak fusion power system.

Recent experimental results with intense neutral beam injection [2], and theoretical predictions based on the so-called flux conserving equilibrium [3], have resulted in the belief that very much higher β values will be attainable in the tokamak than were believed a few years ago. These studies coupled with others which indicate that higher wall power loadings than those used in the UWMAK designs are feasible, have resulted in a decrease in both the physical size and output power of the tokamak reactor [4]. These developments date the UWMAK designs and also make fusion reactors more attractive to the utilities. In developing this summary the philosophy has been to update the UWMAK studies with the new thinking.

^{*}The UWMAK series of designs were used because of their availability at the time this work was conducted. It should be noted that these designs have been updated in the NUMAK design study.

2.1 Tokamak Reactor Technology

Figure 2.1 is a schematic of the general technological areas which are necessary for the development of a commercial tokamak fusion power system. Following is a brief description of each technology area and the currently perceived requirements for technology developments in order to achieve a commercially viable fusion technology.

2.1.1 Superconductivity

It is almost certain that both the toroidal and poloidal magnetic field systems will employ superconducting coils. In addition, as the tokamak is a pulsed device (duty cycle 90 percent), some form of energy storage will be required to restart it after each pulse. As all the necessary cryogenic facilities must be available to operate the coils, it will quite probably be economic to use a superconducting energy storage system. The same argument may hold true for superconducting high voltage power transmission lines within a fusion grid.

The individual coils themselves will quite probably be constructed from TiNb in a copper matrix stabilized with copper or aluminum. The mechanical support structure will be of stainless steel or high-strength aluminum alloy. Mylar is the likely insulation. Typical coil currents will be ~ 10 kA and the maximum fields at the conductor will be about 8 Tesla.

The coils will be kept in liquid helium cooled dewars and will have to be shielded from the neutrons. Neutron damage will tend to increase the resistivity of the stabilizer and decrease the critical current of the superconductor. Materials such as Mylar are particularly susceptible to neutron damage and may be the limiting feature in the design of the necessary neutron shielding. A typical reactor will use $\sim 100,000$ kg of superconductor--nothing this size has ever been constructed as a set of superconducting coils.

FIGURE 2.1 MAJOR TECHNOLOGY AREAS OF A TOKAMAK FUSION POWER SYSTEM

2.1.2 Radioactivity

Tritium is generally accepted as constituting the largest radioactive hazard associated with fusion reactors. This hazard results from its ability to diffuse through metals. Methods for its control cover such ideas as chemically active outer layers to all pipes, continual scrubbing of the air within the reactor building, etc. The problem is compounded by the fact that tritium will have to be bred in the blanket and then recovered from the liquid lithium coolant/lithium salt/FLIBE/lithium oxide blanket in some local recovery plant. It is believed that acceptable safety standards can be met.

Neutron activation of the first wall and blanket materials will result in the production of radioactive wastes. It will be necessary to compact these materials and dispose of them very much in the same way as is done by the existing nuclear industry. For an equivalent electrical power production the radioactive wastes produced by a fusion reactor will be less than that produced by a fission reactor; however, the amount is still considerable.

2.1.3 Environmental

Two prime considerations are the radioactivity discussed above, with tritium the major subject, and waste heat rejection. This problem is somewhat relieved by dropping from the 5,000 MW(th) UWMAK plants to the $\leq 1,000$ MW(th) plants which are now thought feasible. Dumping the waste heat from these plants into local water resources is unlikely to be tolerated; the use of dry cooling towers will become necessary.

2.1.4 Vacuum

It has become evident that ultra-high vacuum (UHV) grade vacuum systems will be mandatory for tokamak reactors. The most critical element in the vacuum system is the first wall which, in addition to providing UHV capability, will have

coolants at temperatures of 500° to 1,000° C on its blanket side, while it operates in a 14 MeV neutron flux, the magnitude of which at best can only be approximated in the laboratory when such devices as the Fusion Materials Irradiation Test Facility (FMIT) become available.

The vacuum pumps used will consist of a mixture of cryogenic sorption pumps which will handle the main gas load and turbomolecular pumps which will handle the basic pumping.

Fusion research already constitutes one of the major application areas of UHV technology and with the advent of commercial fusion reactors will completely dominate the UHV market.

2.1.5 Cryogenics

A tokamak reactor, if a divertor proves to be necessary, will consume $\sim 10^5$ liters/day of liquid helium and 10^6 liters/day of liquid nitrogen. The cooling is required principally to cool the sorption pumps used to pump the divertor chambers and secondly for the superconducting magnet systems.

The extra cost involved in increasing the size of the cryogenic plant so as to provide for superconducting energy storage systems and transmission lines may well prove to be modest.

2.1.6 Plasma Engineering

Many definitive experiments still remain to be done in the areas of: divertor operation versus cold gas blanket for impurity control, heating to ignition, increasing β to the MHD limit, understanding the effects of the ohmic heating (OH) current on the confinement, the development of the "final" scaling laws, the effective control of high β elongated plasmas, etc.

2.1.7 Plasma Heating

One of three techniques or combinations thereof will have to be used to ignite the plasma, viz., neutral beams, radio frequency (RF) heating and compression. The last, while very efficient, involves the use of oversized coils while neutral beams, used so very successfully to date, became unattractive owing to neutralizer inefficiencies at the high energies needed for reactor size plasma penetration. RF heating still awaits a definitive experiment.

The technological expertise developed to date in RF power sources is large and producing the necessary RF power supplies is not believed to be a major problem. RF technology and the understanding of the RF interaction with the plasma, however, is still a long way from producing reactor-type plasmas.

2.1.8 Teleoperators

The complex topological nature of the tokamak reactor (namely, the linking of the vacuum system, blanket, plasma and poloidal coils by the toroidal coils), coupled with the fact that the highly radioactive blanket and vacuum wall will require regular maintenance and replacement, indicates the need for highly sophisticated teleoperators.

In addition, hot cells, in which items such as neutral injectors (which will become radioactive in use) can be refurbished, will be needed. Similar operators will be needed in these.

2.1.9 Materials

The first wall and blanket components offer an extreme challenge to material scientists. The anticipated neutron damage is of an order which at best can only be approximated by such devices as FMIT. The final data will have to await the construction of a materials test reactor. Extrapolations indicate that the useful life of existing materials such as stainless steel will be about five years, provided

wall temperatures are kept below 450°C , higher temperatures will require the use of materials such as niobium-based alloys which may allow temperatures close to $1,000^{\circ}\text{C}$.

A further serious materials problem is that of sputtering, which will be particularly serious in the divertor regions.

2.1.10 Blankets

Blankets are needed to capture the energy release of the thermonuclear plasma, most of which is in the form of 14 MeV neutrons. A constraint on any design is the need to have a breeding ratio >1 for tritium, which appears to be readily achievable. The tritium is bred by the capture of neutrons by lithium which exists in the blanket. The design of the blanket will also be constrained by neutron damage problems and by the need to perform maintenance on it with teleoperators.

2.1.11 Thermodynamic Cycles

Early tokamak reactors will in all probability be coupled to very conventional steam cycles. The promise of higher temperatures in the blanket and first wall, held out by the niobium alloys, will allow the utilization of advanced Rankine and Brayton Cycles. Such a reactor system should achieve efficiencies approaching 50 percent.

2.1.12 Electrical Power Engineering

This area covers such technologies as energy storage systems, grid considerations if the reactor is to be restarted off the grid as well as the necessary power supplies for the superconducting magnets, neutral beams, etc.

2.1.13 Control Systems

Control systems include all apparatus related to the fundamental control of the reactor, its power supplies, the power plant, the neutral beam injections, the

safety interlocks, etc., that is, all functions needed for the safe and economic operation of the plant.

2.2 Required Technological Developments and Methods Whereby They May Be Achieved

The required technological developments and methods whereby they may be achieved will be separated into three sections:

1. Those technologies unique to a fusion program
2. Those technologies which fall within the umbrella of the existing nuclear industry
- 3.. Others.

Table 2.1 shows those technological areas which are unique to a fusion reactor and which further could only be successfully solved within the context of an experimental reactor test program. The one exception is the item on superconducting magnets and their power supplies, but there is little logic in pursuing these separately.

Table 2.2 lists those technologies which one could describe as in-hand within the existing nuclear industry. With the exception of tritium handling, existing techniques would most probably be adequate.

Table 2.3 gives other technologies which need to be developed. While cryogenics and grid considerations are basically size and optimization problems, energy storage and vacuum technology do require research and development programs in some areas such as superconducting energy storage and sorption pumps, respectively. Solutions to these problems do not require major technological advances.

2.3 Alternative Uses for These Technologies

In developing this summary of fusion reactor technologies it became apparent that one was dealing with high technology solutions, and it is therefore not too

TABLE 2.1 TECHNOLOGIES UNIQUE TO FUSION REACTORS*		
TECHNOLOGICAL DEVELOPMENT	REACTOR PROTOTYPE	
	NECESSARY	NOT NECESSARY
LARGE SUPERCONDUCTING TOROIDAL AND POLOIDAL MAGNETS AND POWER SUPPLIES		X
MATERIALS UNDER INTENSE NEUTRON FLUXES AND ION SPUTTERING	X	
PLASMA PHYSICS OF REACTORS	X	
PLASMA HEATING TO IGNITION	X	
IMPURITY CONTROL UNDER REACTOR CONDITIONS	X	
TRITIUM HANDLING IN CTR ENVIRONMENT	X	
TRITIUM BREEDING--BLANKET STUDIES	X	

TABLE 2.2 TECHNOLOGIES WHICH THE EXISTING NUCLEAR INDUSTRY COULD BE EXPECTED TO DEVELOP	
TECHNOLOGICAL DEVELOPMENT	
•	RADIOACTIVE WASTE DISPOSAL
•	NUCLEAR ENVIRONMENTAL ASPECTS
•	BUILDING DESIGN
•	HOT CELL DESIGN
•	BIOLOGICAL SHIELDING
•	TRITIUM HANDLING
•	BLANKET DESIGN

TABLE 2.3 OTHER TECHNOLOGICAL SOLUTION AREAS	
TECHNOLOGICAL DEVELOPMENT	SOLUTION AREA
VACUUM--LARGE THROUGHPUT PUMPS	INDUSTRY AND CRYOGENIC SORPTION PUMP RESEARCH PROGRAM
ENERGY STORAGE	INDUSTRY AND SUPERCONDUCTING STORAGE RESEARCH PROGRAM
GRID CONSIDERATIONS	UTILITIES
CRYOGENICS	INDUSTRY

surprising to find that alternative uses of these solutions also lie in areas of advanced technologies.

2.3.1 Superconductors

The following are the major alternative uses which were found for superconducting magnets:

1. Power generation MHD
2. Superconducting motors and generators
3. Transportation systems
4. Fundamental nuclear research
5. Electrical power transmission lines
6. Superconducting energy storage systems.

Of these six areas, MHD power generation and superconducting energy storage systems are the areas most in sympathy with fusion, in that both require strong fields over large volumes. In all three, the electrical energy required to create fields of the necessary strength is enormous. A superconducting magnet system allows a two-orders-of-magnitude reduction in the electrical power required to achieve a given field strength versus the power required by conventional magnets. Consequently, neither a tokamak reactor, nor an MHD generator, nor a magnetic

energy storage device could be commercially feasible without superconducting magnets.

MHD electrical generation is potentially attractive because energy conversion efficiencies of 40 to 50 percent are possible with current technologies, and efficiencies in the neighborhood of 70 percent are thought possible with advanced materials. Superconducting magnets are one of the key factors necessary for commercial success; whereas there is little question concerning their technical feasibility, their cost is a concern. Superconducting magnets represent approximately 30 percent of the capital cost of an MHD generator. Mutually beneficial research in production and fabrication techniques might be conducted by those interested in superconducting magnets for both the fusion and MHD research programs. No cost reductions for MHD magnets (beyond minimal extrapolations of current techniques) are projected to be necessary for MHD to be cost-competitive, if capacity factors of 65 percent or more can be achieved. Any reduction in the cost of superconducting magnets beyond these minimal projections would, of course, incrementally improve the economics of MHD generation. The Edison Electric Institute has estimated* that capital expenditures for investor-owned utilities will be on the order of \$35 billion in 1980. Investor-owned utilities generate about 77 percent of the electrical demand in the United States and own about that percentage of the total capacity. Assuming that the remaining utilities make capital expenditures at a proportional rate, and taking into account that typically a third of utility investments are for generating facilities, then the size of the total market for electric generating plants is about \$15 billion in 1980. To place an upper bound on the size of the potential market for superconducting

*"Economic Growth in the Future--The Growth Debate in National and Global Perspective," undated.

magnets for MHD applications, one could assume that all new generating facilities were MHD in design, in which case approximately \$5 billion of superconducting magnets would be needed at the 1980 rate of construction.

Magnetic energy storage is attractive because energy storage density is theoretically 10^4 times greater in a magnetic field than an electrical field (e.g., a capacitor), although this differential is not likely to be achieved in practice. In addition, a superconducting magnetic energy storage system could offer quick response time relative to other technologies. An assessment of such superconducting energy storage systems three years ago by the Electric Power Research Institute (EPRI) called them "a long shot," primarily because very large size is necessary before such systems could become economically competitive. It is clear that the necessity for having cryogenic facilities anyway at a fusion power plant will favorably affect the economics for superconducting energy storage at fusion plants. Whether or not they become economic elsewhere depends upon the extent to which costs can be reduced both for superconducting materials (i.e., whether a higher temperature superconductor can be developed) and for refrigeration. It is very difficult to estimate what the size of the potential market might be, as the existence of an economical means of large-scale energy storage would be likely to alter radically the pattern of utility operations, that is, it would represent a new capability rather than economically replacing an existing capability.

Fundamental nuclear research programs, which already use large superconducting magnets and plan to use larger ones in the future, are already the nucleus of superconducting magnet research. The uses for these magnets include steady-state operation of bubble chambers, beam lines and steering magnets for particle research. This is the primary area for current use of and research on

superconducting magnets. Approximately 25 percent of the cost of building fundamental nuclear research facilities involves superconducting magnets.

Disagreement exists over the power level at which underground superconducting power transmission lines become cost-competitive with overhead lines. Conservative estimates indicate that no system under 3000 MVA can be competitive, while more optimistic assessments find 2000 MVA systems to be competitive. Current research is directed at finding higher temperature superconductors (hopefully with critical temperatures around 14°K), improving refrigeration technology, and improving the dielectric characteristics of the working fluids. If all underground transmission lines were constructed as superconducting lines, then this would represent about a \$1.5 billion a year market at the projected 1980 rate of utility construction, assuming that superconductors were reasonably cost-competitive. If adequate progress in materials can be achieved, then underground superconducting lines might become competitive with overhead lines, in which case the potential size of the market would be about \$15 billion a year at projected 1980 utility construction rate.

Transportation systems and superconducting motors and generators will most probably come about when the "price is right," which is likely to come about when one has a large-scale superconducting and cryogenics industry to support them--i.e., a reactor spinoff. Currently, research prototypes of magnetically levitated vehicles exist in Germany, France and Japan. However, economical applications of these vehicles do not yet exist, and it is difficult to predict when and in what areas they might occur. Superconducting motors and generators would probably have to be quite large (perhaps 10,000 HP and up) in order for it to be worthwhile to use superconducting magnets. The effect of superconducting magnets would be to increase the generation/conversion efficiency by about 20 percent. However, little

research could be identified in this area. Another application which might merit further inquiry is superconductor-driven ships or locomotives.

In summary, the superconductor technology area has substantial alternative applications which could justify development of the technology independent of fusion research. MHD generation, magnetic energy storage and power transmission programs would be most in concert with work to be done in fusion research. Other areas of alternative application are in a position to benefit substantially from the development of a large-scale cryogenics and superconducting material support industry.

2.3.2 Teleoperators

A teleoperator industry capable of producing the unit required for the maintenance of the first wall would also be able to produce units for application in:

1. Sea bed mining/oil well drilling
2. Extreme depth mining--i.e. 20+ miles down
3. Mining in hazardous environments--i.e., shallow coal mines
4. Exploration of other planets
5. Orbital assembly of spacecraft
6. Precision operations in hazardous areas--i.e., fire fighting in oil refineries, submarine rescue.

Overlap between fusion plant teleoperators and teleoperators for the applications listed above exists probably only in the area of man/machine interface design and control software, owing to the fact that machines of this type are usually very specialized. With adequate development, precision teleoperators might replace manned operations in each of the first three areas listed above, creating an annual market which could reach multi-billion dollar proportions by the time commercial fusion power is achieved.

2.3.3 Plasma Heating Technologies

The ion sources of neutral injectors could be developed as ion thrusters for space vehicles. All of the physical processes involved in both neutral beam injectors and ion thrusters are similar, and designers of both types of devices are seeking high current densities and long life.

Another application for high-powered ion beam devices which might merit study is the controlled "doping" of materials such as steel to achieve desired surface properties. The potential magnitude of this application is unknown at this time.

Technologies used for RF heating of plasmas might find alternative application in: industrial application of microwave radiation (primarily for uniform heating); phase control technology (communications); consumer goods (such as microwave ovens); terrestrial power transmission and high-altitude powered platforms. These areas represent comparatively small markets, however, and are not likely to be candidate areas for cooperative research.

Table 2.4 serves to summarize the major alternative uses of tokamak reactor related technologies.

TABLE 2.4 POTENTIAL ALTERNATIVE USES OF FUSION TECHNOLOGIES	
•	MHD POWER GENERATORS
•	SUPERCONDUCTING ENERGY STORAGE SYSTEMS
•	PRECISION TELEOPERATORS
•	ION THRUSTERS

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3. EVALUATING THE ROLE OF SUPPORT TECHNOLOGY PROJECTS IN A TOKAMAK REACTOR PROGRAM

This section of the report documents a study of the economic value of the tokamak fusion RD&D program including supporting technologies, and the incremental value of changes in that program that might come about by accelerating planned RD&D or performing more. Three types of possible effects of program changes are discussed. The first considers only a shift in the time at which specific tests are performed, affecting only the timing of the information, but not expectations as to what the entire program will ultimately produce. The second considers the purchase of more information about underlying physical laws so that one or more of the parameters modeled is known with greater certainty at some future date. The third considers the purchase of more information which changes not only the level of uncertainty but also results in a greater expected capability at performing some function modeled.

Example changes to the baseline tokamak fusion RD&D program are made, and their effects evaluated. The results of this study show that: (i) there exists substantial economic argument for accelerated and/or additional RD&D in the supporting technology areas; strong economic evidence can be presented that such changes can increase the economic value of fusion RD&D by as much as several billion dollars; and (ii) this type of approach could be very useful in providing information for prioritizing activities within a fusion RD&D program.

3.1 Introduction

The effort which seeks to provide commercial fusion energy to the U.S. and world economy at a competitive cost is an exceedingly complex one. Not only does there exist uncertainty as to whether sustained ignition yielding net energy output

is possible, but there are also questions as to the best means by which this energy might be made available as commercial power and as to its economic and environmental attractiveness. Much of the uncertainty regarding the ultimate viability of fusion energy rests not with the reactor physics, but instead with the variety of support technologies necessary for the successful commercialization of any fusion energy system. One of the more difficult tasks in fusion RD&D planning is to assure the timely provision of these support technologies. They include such areas as:

- Superconducting magnets
- Tritium breeding, recovery and handling
- First wall
- Blanket and shield
- Plasma heating
- Impurity control
- Fueling
- Remote maintenance.

Due to the great expense of the necessary RD&D in these areas, it is important that (i) the technologies developed are not premature, i.e., they do not satisfy a need in a way which is no longer appropriate at the time of commercial application; (ii) the technologies are nonetheless available when needed such that the time of commercialization does not have to be delayed; and (iii) dead-end paths to solutions be quickly identified and terminated as other options are explored.

The question addressed in this effort is this: Can funding decisions on support technology RD&D be evaluated against economic criteria? In particular, this effort seeks to estimate the economic benefit of a research activity, say, on first wall lifetime, added to the overall RD&D program. The approach

taken is consistent with the notion that programs to develop long-term, high-technology energy sources are not programs to "buy" a technology; rather they are programs which buy information to be used in developing theoretical and applied understanding, in determining the attractiveness of the technology and in guiding future decisions as regards further RD&D. Research in the support technology areas identifies potential problem areas, and possible solutions to those problems. For example, if it is determined that impurity control is very difficult and expensive, one might look to reactors designed to burn for short periods only; as a result, one would have increased interest in how quickly start-up and clean-out can be accomplished and in thermal stress properties of first wall materials. Alternatively, if an outstanding structural material for first wall and blanket is found, having a lifetime of 100 MW-yrs/m², procedures permitting timely and inexpensive methods of first wall replacement can be de-emphasized.

The methodology employed herein is based in part on the recent HFCTR reactor conceptual design^{*} and develops a model of fusion power in a way which ties the cost of fusion power, and therefore the economic value of fusion power, to parameters which are measures of the effectiveness of the supporting technologies developed to meet the needs of commercial fusion. The model employs a benefit function, $B(\bar{x})$, which relates the value of fusion power to a set of technical and market parameters, $\bar{x}$. As uncertainty on $\bar{x}$ gets resolved (and perhaps as expected values for $\bar{x}$ improve), it is possible to identify those parameters in $\bar{x}$ for which information or improvement is most needed, as judged by economic measures.

As examples of the parameters modeled, the cost per kilowatt-hour of fusion-generated electricity is related to the first wall lifetime, the level of

^{*}"High Field Compact Tokamak Reactor (HFCTR) Conceptual Design," D. R. Cohn et al, MIT Plasma Fusion Research Center Report RR-79-2, January 1979.

plasma impurities, magnetic toroidal field strength and other important parameters. The model which accomplishes this is only a first-order model and warrants further development and refinement, but nonetheless provides meaningful outputs. This model is discussed in Section 3.2.2 and in Appendix A. A second, evaluation model is also employed. This model evaluates multi-phased RD&D programs which are intended to lead to commercializable technologies. It takes as inputs (i) expectations on the results of tests to be performed in each of the RD&D subprojects as well as market expectations and (ii) a benefit function, $B(\bar{x})$, which describes the economic benefit associated with any possible project result, $\bar{x}$. The model calculates the economic value of an RD&D program having the priors and benefit function specified. This model is discussed in Section 3.2.1 and is mathematically and statistically developed in Appendix B.

These models are then used to "prioritize" the information to be obtained in a fusion RD&D program, providing answers to the question: What information does one want to buy first? The results show the current fusion program to be economically well-conceived. Next, the value of accelerating RD&D in specific areas is considered. Such exercises are essential in judging the economic merits of, say, a more aggressive first wall program. The results of these analyses are presented in Section 3.3.

3.2 Methodology

This section discusses the technical methodology used in (i) the evaluation of RD&D programs, (ii) the valuation of fusion energy and (iii) the evaluation of supporting technology programs.

3.2.1 RD&D Evaluation Methodology: An Overview

In the first year of study under this effort, ECON argued that the use of decision analytic techniques is essential to the evaluation of long-range energy

RD&D. Since that time, ECON has more fully developed the mathematics and tools for applying decision analysis to the economic evaluation of energy RD&D. The methodological approach taken is to view an energy RD&D project as a sequence of subprojects separated by decision points at which the project may be continued as planned or terminated.* This sequence of subprojects, which takes a technology from its present state of development through to commercial readiness, can be illustrated in the form of a decision tree such as that shown in Figure 3.1. The example project shown here consists of three subprojects, referred to as Subprojects ϕ_1 , ϕ_2 and ϕ_3 . These three subprojects are followed by a commercialization phase in which the technology is placed in use and derives economic benefit. For any of the confinement technologies, the RD&D project probably consists of several of the following subprojects, each yielding specific information about the likely characteristics of a commercial reactor: proof of principle, fusion test reactor, engineering test facility, engineering prototype reactor and demonstration reactor(s).

The decisions which separate the RD&D subprojects are denoted by the black squares in Figure 3.1 and the branches emanating from the squares denote the options available at each point: here, to continue the project as originally planned or to terminate it.

Each RD&D subproject consists of a set of analyses, experiments, engineering tests and/or technology demonstrations. The outcome of each subproject can be described in terms of the results obtained. For example, a subproject could be as small as the addition of a neutral beam heating device to a tokamak test reactor or

*The methodology can consider additional alternatives, such as continuing the project in a modified form, but this added degree of freedom merely serves to complicate the discussion. Thus, only "go/no-go" decisions are discussed here.

FIGURE 3.1 A TYPICAL R&D PROJECT DECISION TREE

it could be the design and construction of a new EPR. The outcome of a neutral beam subproject might include the cost of manufacturing the beam device, its efficiency in providing thermal energy to the plasma center, its lifetime and so on. Knowledge of these parameters may be of importance in the decision to use neutral beams in further experimental and commercial reactors and in the design of the reactors which make use of the beam technology. The outcomes of each subproject are, thus, vectors or ordered sets of parameters which describe the results of the subproject. These outcomes are labeled $\bar{\phi}_1$, $\bar{\phi}_2$, and $\bar{\phi}_3$.

At the end of the RD&D project, if the project has been successful, a commercial technology is available. The attributes of this technology—efficiencies, outputs, sizes, costs, lifetimes, etc.—and the market parameters which determine its value are denoted by the vector $\bar{x}$.

The solid dots in the decision tree denote the time at which $\bar{\phi}_1$, $\bar{\phi}_2$, $\bar{\phi}_3$ and $\bar{x}$ are known. Thus, Subproject ϕ_1 results in knowledge of $\bar{\phi}_1$, based upon which the decision is made to conduct Subproject ϕ_2 , or terminate the project. Similarly, Subproject ϕ_2 , if conducted, results in knowledge of $\bar{\phi}_2$, based upon which the

decision is made to conduct Subproject ϕ_3 or terminate the project. And so on through commercialization. At the time of commercialization, potential implementors of the technology may perceive that a benefit can result from its use. The total benefit to society, net of user costs (but not of RD&D costs as they are considered sunk by the time of commercialization), from use of the technology is the aggregation of the net benefit derived from each individual use and is, in general, expressible as a function of $\bar{x}$, namely, $B(\bar{x})$. It is assumed that the technology will be implemented, given its commercial availability, by those potential users who believe that they will obtain net benefit from its use.

Finally, each RD&D subproject has an associated cost. This cost, C_1, C_2, C_3 , is the cost of doing the subproject.

The objective now is to evaluate the information provided by Subproject ϕ_1 (the next subproject in the project). To do this requires first expressing the state-of-knowledge and expectations at each decision point by specifying probability distributions on the future outcomes of each subproject, $\bar{\phi}_1, \bar{\phi}_2$ and $\bar{\phi}_3$, and on $\bar{x}$. Specifically, needed as input are the probability density functions $f_1(\bar{\phi}_1)$ and $f_i(\bar{\phi}_i | \bar{\phi}_{i-1})$,* i.e., expectations on the first phase outcomes and of subsequent outcomes given results from the previous subproject. The pdfs $f_i(\bar{\phi}_i)$ for i greater than one are not input because they are influenced by decisions made prior to the i th phase. $f_1(\bar{\phi}_1)$ and $f_i(\bar{\phi}_i | \bar{\phi}_{i-1})$, however, are decision independent. By an appropriate convolution of these probability density functions (pdfs), the phase-specific expectations imply an expectation on overall project results, $f_x(\bar{x})$, again a

*The use of the notations $f_1(\bar{\phi}_1)$, $f_i(\bar{\phi}_i | \bar{\phi}_{i-1})$ and $f_x(\bar{x})$ represent a notational simplification over those found in Appendix B, $f_{\bar{\phi}_1}(\bar{\phi}_1)$, $f_{\bar{\phi}_i}(\bar{\phi}_i | \bar{\phi}_{i-1})$ and $f_{\bar{x}}(\bar{x})$, respectively.

decision-free, prior distribution. For a project having three RD&D phases before commercialization, this convolution is written

$$f_x(\bar{x}) = \int_{\bar{\phi}_1} \cdot \cdot \int_{\bar{\phi}_2} \cdot \int_{\bar{\phi}_3} f_1(\bar{\phi}_1) f_2(\bar{\phi}_2 | \bar{\phi}_1) f_3(\bar{\phi}_3 | \bar{\phi}_2) d\bar{\phi}_1 d\bar{\phi}_2 d\bar{\phi}_3$$

and implies a consistency condition between $f_1(\bar{\phi}_1)$, $f_i(\bar{\phi}_i | \bar{\phi}_{i-1})$ and $f_x(\bar{x})$. The distributions, $f_1(\bar{\phi}_1)$ and $f_i(\bar{\phi}_i | \bar{\phi}_{i-1})$, and the benefit function, $B(\bar{x})$, are the inputs used in this methodology.

The value of the information provided by Subproject ϕ_1 is then obtained by evaluating each decision in the project, starting with the last and working back to the first, by a process referred to as backward induction. At each decision point, the decision is made to choose the alternative with the highest expected value.* In the case of the simple go/no-go decision tree shown in Figure 3.1, the decision is "go" if the next subproject has a positive expected value (net of cost), and "no-go" otherwise. The set of those possible outcomes, $\bar{\phi}_i$, of phase ϕ_i for which a "go" decision is warranted for the subsequent phase is referred to as the go-set and is denoted D_i . $D_i = \{ \bar{\phi}_i : E[\phi_{i+1} | \bar{\phi}_i] > 0 \}$. D_x is the go-set for the commercialization phase. The net expected value of each subproject is the expected value of the outcome of the subproject given success, weighted by the probability of success, less the cost of the subproject. This expected value looks much like an expected benefit using the convolution given above:

* By "expected value" is meant the mathematical expectation, that is, the weighted average: each possible value weighted by its probability of occurrence.

$$E [\Phi_1] = \int_{\bar{\Phi}_1 \in D_1} f(\bar{\Phi}_1) \left[\int_{\bar{\Phi}_2 \in D_2} f(\bar{\Phi}_2 | \bar{\Phi}_1) \left[\int_{\bar{\Phi}_3 \in D_3} f(\bar{\Phi}_3 | \bar{\Phi}_1) \int_{\bar{x} \in D_x} B(\bar{x}) f(\bar{x} | \bar{\Phi}_3) \right. \right. \\ \left. \left. d\bar{x} \, d\bar{\Phi}_3 - C_3 \right] d\bar{\Phi}_2 - C_2 \right] d\bar{\Phi}_1 - C_1$$

Notice that this is a type of expected value of $B(\bar{x})$ and that the integration is only over the go-sets and not the entire range of $\bar{\Phi}_1$, $\bar{\Phi}_2$, $\bar{\Phi}_3$ and $\bar{x}$.

The above RD&D evaluation methodology provides the following useful information:

- The net economic value of the next subproject for each alternative project plan, in the context of each overall project plan
- An economically meaningful criterion for determining those results which imply success or failure
- The probability that subsequent phases of the project will be undertaken
- The expected commercial value of the technology given successful development.

A computer model for implementing this methodology applied to the tokamak fusion research program has been developed and used for example evaluations. The methodology is described in more detail in Appendix B.

3.2.2 The Value of Fusion Energy

This section describes a model consisting of three submodels which yields a benefit function, $B(\bar{x})$, describing the economic value of a fusion technology characterized by a vector of parameters, $\bar{x}$. $B(\bar{x})$ is a deterministic function in that it yields a unique value, B , for each vector $\bar{x}$; uncertainties in $\bar{x}$ and thus in the benefit, $B(\bar{x})$, are treated via the evaluation methodology described in the previous

section. The three submodels of this value model--(i) a plasma power model, (ii) a cost model, and (iii) a benefit model—are now described.

Plasma Power Model

This model was developed using the High Field Compact Tokamak Reactor (HFCTR) conceptual design as the reference reactor. This reactor is small (major radius = 6.0 meters, minor radius = 1.2 meters) and has a high magnetic field (toroidal field strength = 7.4 Tesla). These features yield a low cost, low output device which is felt compatible with the electrical energy system; nominal projected values of plant capital cost and thermal power output are \$1.263 billion and approximately 2000 MW_{th} during burn, respectively, although both parameters are treated probabilistically in this analysis. Another feature of this device is that it is designed to achieve a high plant availability level—85 percent in the conceptual design study, but as high as 92 percent seems achievable. The reader is referred to the source document for further information on the reactor.

The plasma power model describes temperature and density profiles, collisionality, beta, impurities, power and power losses to determine if ignition conditions are met. Two margins of safety, empirical and neoclassical, are calculated, both of which must exceed unity for ignition to take place. The model has as inputs: peak density and temperature (n_0 and T_0 , respectively), plasma density and temperature profile parameters (γ and θ , respectively), impurity level (Z_{eff}), minor radius (a), aspect ratio (A), safety factor (q), and β , the first five of which are treated probabilistically. The model calculates requisite toroidal field and poloidal current strengths (B_T and I_P , respectively), alpha power (P_α), Bremsstrahlung and line radiation power losses from the plasma (P_B and P_L , respectively), margins of safety (MS_{emp} and MS_{nc}), and finally thermal power output and first wall 14-mev neutron flux (P_{th} and P_w , respectively) if ignition takes place.

The model is described in detail in Appendix A. The model is only a first-order approach to the problem. Several processes important to commercial fusion technology, and thus program planning, are not incorporated. These include plasma fueling and heating, tritium breeding, recovery and handling, and others.

Fusion Cost Model

This model calculates the levelized cost per unit of fusion energy. This levelized cost is the amount which would have to be charged in order to cover all costs and interest over the plant's lifetime. The inputs are total capital cost of the plant (C_k), plasma burn time (t_b), first wall lifetime (τ_w), efficiency of conversion from thermal to electrical energy (η), thermal and wall power outputs, clean-out and start-up time (t_s), octant replacement time (t_r), fixed annual costs of operation (C_a), maintenance costs (C_m), plant lifetime (L), plant construction time (t_c), and the discount rate (ρ). The first four of these parameters (C_k , t_b , τ_w and η) are treated probabilistically. The remaining parameters are deterministic and are exogenously specified. P_{th} and P_w are also inputs, and are given by the plasma power model.

Two cycles are of interest over the lifetime of the plant. The first is the "duty cycle" which consists of the burn time and the clean-out and start-up time. Thus the length of the duty cycle is given as:

$$t_d = t_b + t_s \quad (\text{seconds})$$

The second cycle is the maintenance cycle. The HFCTR is designed so that one octant of the reactor can be replaced quickly during shutdown, with the replaced octant receiving maintenance attention (first wall and blanket replacement) during the ensuing maintenance cycle. Thus, the length of the maintenance cycle is:

$$t_m = \frac{n_1}{3600} (t_b + t_s) + t_r \quad (\text{hours})$$

where t_m is the length of the maintenance cycle and where n_1 is the integer number of duty cycles per maintenance cycle. How large n_1 is depends upon the wall lifetime (τ_w) and the first wall neutron flux (P_w). As all eight reactor octants must be replaced during one wall lifetime, the following constraint holds:

$$\frac{n_1}{3600} t_b P_w \leq \frac{1}{8} \tau_w$$

yielding

$$n_1 = \text{int} \left(\frac{3600 \tau_w}{8 t_b P_w} \right)$$

Additionally the number of maintenance cycles per year (n_2) is given as

$$n_2 = \frac{8760}{t_m}$$

The reactor requires electrical power for start-up and operation. Average power consumption during the burn time is taken to be linear in burn time. Thus, net electrical power generated is given by

$$P_e = \eta P_{th} - (k_e + \tau_e t_b) \quad (\text{MW}_e)$$

This yields the measure of annual net electrical energy output of

$$E_e = n_1 n_2 \frac{t_b}{3600} P_e \quad (\text{MWh}_e/\text{yr})$$

Revenues generated over the plant lifetime must be sufficient to cover all costs, plus interest. This statement leads to the following equation:

$$e^{\rho t_c} C_k = \int_0^L e^{-\rho t} \left[c_l E_e - n_2 C_m - C_a \right] dt$$

The right-hand side of the above equation represents the present value sum of net revenues over the lifetime of the plant, referenced to the start of operation. The left-hand side is the present value of capital expenditures on the plant, also referenced to the start of operations, t_c years after the beginning of construction.* Integrating and solving for c_ℓ , the following expression is obtained

$$c_\ell = \frac{\left(\frac{e^{\rho t_c}}{1 - e^{-\rho L}} \right) C_k + n_2 C_m + C_a}{E_e} \quad (\$/kWh)$$

This is the amount per kilowatt-hour which must be charged (in real dollars, over the lifetime of the plant) to cover all costs. Where c_ℓ is below the cost of competitive sources at the time of commercial fusion availability, there will be incentive to supply electricity using fusion power.

Benefit Model

The benefit model takes cost per kilowatt-hour of fusion-generated electricity, the date of commercial availability and market parameters and yields a present value benefit estimate of fusion technology. The model inputs are the levelized cost per kilowatt-hour of fusion generated electricity (c_ℓ), the number of years until commercial availability (t_a), upper and lower values of the range of costs of baseload electricity at the time of availability ($c_{\max}$ and $c_{\min}$, respectively), market penetration parameters--fraction of competitive share attainable (F_f), initial market captured (M_o), and number of years until one-half of the available market is captured ($t_{1/2}$)--current annual baseload electricity generation (E_o) and growth rate of annual baseload electricity generation (g). All of these

* Since construction costs are also spread over time, t_c is not, strictly speaking, the actual construction time, but rather a proxy.

parameters, except c_ℓ which is the output of the cost model, are treated deterministically.

First, annual benefit in a steady state situation (i.e., no growth and full, immediate market penetration) is modeled. If a utility now produces electricity at a cost c_b , the annual benefit for it is

$$B_i = \begin{cases} (c_b - c_\ell) E_i & \text{for } c_b > c_\ell \\ 0 & \text{otherwise,} \end{cases}$$

where E_i is the annual baseload electricity generation for that utility. Not all utilities, however, will bear the same cost for electricity generation, as energy will derive from a variety of sources under varying economic conditions. If utilities are uniformly distributed over the range of generation costs ($c_{\min} \leq c_b \leq c_{\max}$), the demand for fusion-generated electricity will be linear in c_ℓ , as shown in Figure 3.2. The share of the market which fusion could capture ($0 \leq S(c_\ell) \leq 1$) will depend upon its cost:

$$S(c_\ell) = \begin{cases} 0 & \text{for } c_\ell \geq c_{\max} \\ \frac{c_{\max} - c_\ell}{c_{\max} - c_{\min}} & \text{for } c_{\min} < c_\ell < c_{\max} \\ 1 & \text{for } c_\ell \leq c_{\min} \end{cases}$$

There may, however, be other institutional or size-of-local-market constraints which limit fusion's market share, so the additional constraint is imposed that fusion captures only some fraction, F_f , of the otherwise-available market. Thus, given an average cost savings over the market captured of $\frac{1}{2} (c_{\max} - c_\ell)$, for $c_{\min} < c_\ell < c_{\max}$, the annual benefit is

$$B(c_\ell) = \frac{1}{2} (c_{\max} - c_\ell) S(c_\ell) F_f E \quad (\$/\text{yr})$$

FIGURE 3.2 POTENTIAL ANNUAL DEMAND FOR FUSION-GENERATED ELECTRICITY AT COMMERCIALIZATION

where E is the total annual baseload generation, measured in kilowatt-hours.

Taking a present value sum of the annual $B(c_p)$ would suffice as a benefit estimate except for the following facts: (i) market penetration is not immediate; (ii) at constant real prices, the demand for electricity grows over time; and (iii) fusion becomes commercially available t_a years from present. The first of these points is captured by using a model of logistic growth in modeling the market penetration of the fusion technology. Denote as $M(t)$ the fraction of the ultimate market (demand growth is not yet incorporated) captured by the year t . The logistic growth model is then

$$M(t) = \frac{1}{1 + \left(\frac{1 - M_0}{M_0} \right) e^{-ht}}$$

where M_0 is the fraction captured initially at introduction ($M_0 > 0$) and h is a parameter which specifies how quickly the penetration is achieved. h can be specified in relation to the time at which one-half of market penetration is

accomplished by the following equation

$$h = \frac{1}{t_{1/2}} \ln \left(\frac{1}{M_0} - 1 \right)$$

where $t_{1/2}$ is the number of years (after introduction) until one-half the ultimate market is captured. Figure 3.3 shows how these equations model market penetration, with the values $g=0.01$, $M_0=0.01$, $t_{1/2}=35$ years.

To model exponential demand growth, let E_0 be the current annual demand for baseload electricity and let g be the annual growth rate in demand. Given t_a as the number of years until commercial availability, demand t years after availability is simply

$$E(t) = E_0 e^{g(t_a + t)} = E_0 e^{gt_a} e^{gt}$$

Thus, annual benefit after introduction can be given as

$$A(t, c_\ell) = \frac{1}{2} (c_{\max} - c_\ell) S(c_\ell) M(t) F_f E(t).$$

Finally net present value of a technology supplying electricity at cost c_ℓ beginning t_a years from present is:

$$\begin{aligned} V(t_a, c_\ell) &= \int_{t_a}^{\infty} e^{-\rho t} A(t, c_\ell) dt \\ &= \frac{1}{2} (c_{\max} - c_\ell) S(c_\ell) F_f e^{gt_a} E_0 \int_{t_c}^{\infty} \frac{e^{(g-\rho)t}}{1 + \left(\frac{1 - M_0}{M_0} \right) e^{-ht}} dt \end{aligned}$$

3.2.3 Value of Additional Support Technology RD&D

A number of support technologies are required for a commercial fusion technology. Thus, their development contributes directly to the economic value of the fusion program. In considering individual RD&D activities which seek to

FIGURE 3.3 MARKET PENETRATION PATHS

provide new information on some aspect of the support technologies, a useful evaluation tool is one which estimates how the activities contribute to the value of the fusion RD&D program.

Changes in the RD&D program plan, affecting the state-of-knowledge as a function of time on the support technologies or on the basic reactor technology, affect expectations on the results of the RD&D phase. Changes in the RD&D program plan are reflected in the probability distributions, $f_1(\bar{\phi}_1)$, $f_i(\bar{\phi}_i | \bar{\phi}_{i-1})$ and $f_x(x)$. There are two basic types of changes that can be made in an RD&D program. The first is to simply rearrange the order of the RD&D activities in the program. For example, testing of first wall materials might be moved from the EPR phase forward into the ETF phase. Such a rearrangement of the RD&D activities affects the phase specific expectations, $f_{\bar{\phi}_1}(\bar{\phi}_1)$ and $f_{\bar{\phi}_i}(\bar{\phi}_i | \bar{\phi}_{i-1})$, by changing the timing at which information is gained. Initially, one might expect that changes of this sort do not affect the overall outcome of the RD&D program. Indeed they would not, if it were not for the decisions which separate the RD&D

phases. Since these decisions are made based upon the information available at the time at which they are made, however, changing the state-of-knowledge at each decision point can affect the outcome of the decisions and the decisions, in turn, affect the outcome of the program. The advantages of moving RD&D activities to an earlier date in time lie mainly in the fact that the decisions which follow are all made under an improved state-of-knowledge. The principal disadvantage of moving RD&D activities to an earlier date lies in the fact that this increases the present value of costs associated with these activities. Furthermore, it is not always desirable to commit to large expenditures of money early in a program prior to the resolution of some of the uncertainty which exists at the outset of the program.

The second way in which RD&D programs can be changed is to purchase more or less information, that is, to perform more or fewer RD&D activities than in the baseline plan. A change of this sort can affect program expectations in two ways: it can impact the state-of-knowledge as a function of time through the program; and it can alter the expected level of performance in various technology areas. The first effect should be relatively obvious. Conducting additional RD&D activities should improve the state-of-knowledge, at least early in the program. For example, conducting a fusion energy generation system study at this point in time can provide information on the ultimate commercial desirability of a potential reactor configuration. This information will be clearly superceded by future research activities. However, in the interim it can provide information useful to the decision making process.

The effect of added RD&D activities on performance in various technological areas needs further explanation. At the most fundamental level, RD&D is aimed at the measurement of physical parameters such as reaction cross sections. Sometimes

these measurements are later incorporated into predictive physical laws which enable engineers to create new designs without the need for testing each particular design in order to predict its performance. The measurement of physical parameters, however, does not affect their value. For example, a reaction cross section is what it is, and measuring it doesn't change its value, it merely establishes its value. Likewise, measuring the lifetime of a candidate first wall material does not change the lifetime of that material, it merely establishes what that lifetime is. Prior to testing a first wall material all that might be known about the material could be expressed in the form of a probability distribution on its lifetime. Changing the level of RD&D activity relating to first wall materials will not change the lifetime of a specific first wall material. What it will do, however, is to permit the testing of more or fewer different first wall materials, and will result, therefore, in different states-of-knowledge from which a first wall material might be selected.

Assume that the objective of a first wall materials RD&D effort is to find the acceptable first wall material with the longest lifetime. For sure, today every conceivable material is a candidate. The problem that the engineer faces is that of selecting the best material from among this myriad of candidates. Many potential first wall materials can be eliminated quite easily based upon existing knowledge of the performance of these materials. To point to some extreme examples, concrete could be eliminated immediately due to its porosity. Lead could be eliminated due to its inability to withstand high temperature. But some subset of materials will appear to have reasonably attractive characteristics and, without further testing, may be quite difficult to discriminate between. Three such examples are shown in Figure 3.4. Material M_1 has an expected value lifetime of 20 MW-yrs/m^2 , somewhat better than the 18 MW-yrs/M^2 for M_2 . M_3 , if manufacturable, will

FIGURE 3.4 PROBABILITY DISTRIBUTIONS OF LIFETIMES FOR THREE HYOPHTHETICAL FIRST WALL MATERIALS

almost surely provide a lifetime of 30 MW-yrs/m², but there is only a 60 percent chance that it will prove to be manufacturable. If a decision had to be made between materials M_1 , M_2 and M_3 without any further testing, it is likely that M_1 would be chosen. But one should not overlook the possibility that M_2 or M_3 is, in fact, a better material, that is, it has a longer lifetime than M_1 . One RD&D scenario might be to choose material M_1 and to measure its lifetime. Say, for sake of argument, that upon measurement its lifetime turns out to be 18 MW-yrs/m². An alternative scenario, however, might be to test the three materials and then make the decision as to which material to use. According to the distribution shown, it is entirely possible that material M_3 will prove manufacturable or that M_2 will have a lifetime well in excess of 30 MW-yrs/m², considerably greater than the assumed lifetime for M_1 .

If the RD&D program followed the route of the first scenario developed above, then the cumulative distribution function on material lifetime would be that shown in Figure 3.5(a) for material M_1 , the material chosen according to that scenario. If on the other hand, the RD&D activity were increased to include tests on all three materials, the prior distribution, that is, the distribution of expectations before conducting the test, would be modified to take into account the possibility that material M_2 or M_3 is better than material M_1 . To determine this prior, one calculates the probability that all materials demonstrate lifetimes less than or equal to a specified lifetime

$$P\left[L^* \leq \ell\right] = \prod_{i=1}^3 P\left[L_i \leq \ell\right]$$

where L_i is the lifetime of the i th material and L^* is the lifetime of (what will prove to be) the best of the materials tested; both are random variables, while ℓ is a specific lifetime value. The combined distribution function representing the best material is shown in Figure 3.5(b) and is compared there with the distribution function without the added RD&D activity, that of material M_1 . It is clear from Figure 3.5(b) that the added RD&D activity produces an improved expectation on the lifetime of the first wall material. It should be equally clear, however, that this improvement occurs because of an implicit decision process, namely, the decision to choose the best first wall material as evidenced by the results of the RD&D activity. The expectations on performance improvement can be quantified first by quantifying expectations on each alternative, and then by applying the equation given above to combine these expectations into a post-decision expectation assuming that the best alternative is chosen upon completion of the RD&D activity.

(a) PRIORS ON EACH OF THREE MATERIALS

(b) PRIORS ON BEST OF THREE

FIGURE 3.5 CUMULATIVE DISTRIBUTION FUNCTIONS OF LIFETIMES FOR HYPOTHETICAL FIRST WALL MATERIALS

3.3 Implementation of Methodology

Using the methodology developed in Section 3.2, several types of analyses useful for fusion program planning and guidance of technology development are performed. First, the expectations as to what commercial fusion will look like, based upon the most recent (HFCTR) reactor conceptual design, are discussed. Second, in an update of the value of RD&D information analysis reported in the first year of study,^{*} the value of the fusion research program is estimated. Finally, examples of hypothetical RD&D program changes are examined and the value of these changes calculated. Before discussing these analyses, however, the basic data used are developed and reported.

3.3.1 Data

The commercialized fusion reactor used for evaluation herein is based upon the High Field Compact Tokamak Reactor, conceptual design by the M.I.T. Plasma Fusion Center and others. To the extent that the fusion device actually commercialized does not look like the HFCTR, the analyses presented herein will have underestimated the value of fusion RD&D.

The Deterministic Case

The HFCTR is a small device with major radius of 6 meters and minor radius of 1.2 meters. The reactor is presumed to operate with a beta (β) of 4 percent and a safety factor (q) of 3. It uses a D-T reaction, breeding its own tritium in a molten salt blanket of FLIBE ($2\text{LiF} \cdot \text{BeF}_2$). A gas blanket and limiter is used for impurity control. The structural material proposed for first wall and blanket is a molybdenum alloy, TZM (99.39% Mo, 0.5% Ti, 0.08% Zr, 0.03% C), which would give off sputtered material dominantly having an atomic number of 42. Other

^{*}"The Economics of Fusion Research," ERDA Report No. C00/4181-1, ECON Report No. 77-158-2, October 1977.

inputs to the plasma power model are modeled stochastically. Their most likely values are taken to be a peak density (n_0) of $5 \times 10^{20}/\text{m}^3$, a peak temperature (T_0) of 12.4 keV, γ and θ of 1.0, and an impurity level (Z_{eff}) of 1.5. Such a reactor does not lead to conditions sufficient for ignition. A lowering of Z_{eff} to 1.2 does result in ignition, yielding thermal power output of 2185 MW as shown in Table 3.1; however, it is felt that $Z_{\text{eff}} = 1.2$ is too optimistic given the state of information prevailing today. In the analysis reported, a $Z_{\text{eff}} = 1.5$ is used as a most likely value, with which ignition conditions are not met ($MS_{\text{emp}} = 0.88$ and $MS_{\text{nc}} = 0.12$).

Using a thermal-to-electric energy conversion efficiency of 0.365, a reactor achieving Z_{eff} of 1.2 produces net electric power of 558 MW during a 300 second burn (Table 3.1). Electric power consumption during burn is taken to be $213(\text{MW}) + 90\left(\frac{\text{kW}}{\text{sec}}\right) \times t_b(\text{sec})$, where t_b is the length of the burn time. Maintenance cost is taken to be \$5 million, one-eighth of the blanket and shield cost estimated in the MIT report, labor to be supplied by full-time staff. Annual fixed costs are taken to be \$4.68 million (117 full time employees @ \$20,000 per year with 100 percent overhead). For a reactor costing \$1.263 billion to construct, achieving Z_{eff} of 1.2, taking six years to build and having a lifetime of twenty years, the levelized cost of output is \$0.025/kWh, a very competitive cost.

The values cited above are almost all taken out of the HFCTR conceptual design already cited. This study did not fix a burn time, but said it was in the range of 100-500 seconds; a most likely value of 300 seconds is used here. Given the high operating temperatures which can be withstood by TZM, a conversion efficiency of 36.5 percent is used, slightly greater than the 35 percent used in the conceptual design study. The plasma power model outputs are similar to those of the HFCTR study except that the empirical margin of safety and thermal power output found here are lower than those in the design study, both by about one-third.

TABLE 3.1 PLASMA POWER MODEL OUTPUTS AND COST MODEL MOST LIKELY INPUTS AND RESULTING OUTPUTS, USING $Z_{eff} = 1.2$

PARAMETER	UNITS	VALUE ASSUMED
<u>PLASMA POWER MODEL OUTPUTS ($Z_{eff}=1.2$)</u>		
TOROIDAL FIELD AT PLASMA, B_T	TESLA	6.9
PLASMA CURRENT, F_p	MA	6.2
$(n\tau_E)_{ign}$		6.5×10^{21}
EMPIRICAL MARGIN OF SAFETY, MS_{emp}		1.35
NEOCLASSICAL MARGIN OF SAFETY, MS_{nc}		2.28
THERMAL POWER OUTPUT, P_{th}	MW	2185
NEUTRON WALL LOADING, P_w	MW/M ²	5.1
<u>COST MODEL INPUTS</u>		
BURN TIME, t_b	SEC	300*
FIRST WALL LIFETIME, τ_w	MW-YRS/M ²	20*
CONVERSION EFFICIENCY, η		0.365*
MAINTENANCE COST, C_m	\$/MAINTENANCE CYCLE	5.0×10^6
ANNUAL FIXED COST, C_a	\$/YR	4.68×10^6
PLANT CAPITAL COST, C_k	\$	1.263×10^9 *
PLANT LIFETIME, L	YEARS	20
ELECTRICITY CONSUMPTION PARAMETERS $\begin{cases} k_e \\ \tau_e \end{cases}$	MW	213
	MW/SEC	0.090
DISCOUNT RATE, ρ	YR ⁻¹	0.03
<u>COST MODEL OUTPUTS</u>		
MAINTENANCE CYCLES PER YEAR, n_2	YR ⁻¹	1.9
PLANT AVAILABILITY		0.92
NET ELECTRIC POWER OUTPUT, P_e	MW	558
ANNUAL ELECTRIC GENERATION, E_e	MWH/YR	4,549,000
LEVELIZED COST OF OUTPUT, c_l	MILLS/KWH	25
LEVELIZED COST OF OUTPUT @ $C_k = \$2.526 \times 10^9$	MILLS/KWH	47
*THESE NUMBERS REPRESENT MOST LIKELY VALUES		

A first wall lifetime of 20 MW-yrs/m² is used as a most likely value; the stated fusion program goal is 40.*

As capital costs are notorious for being underestimated, levelized cost of output is also calculated using two times the HFCTR-estimated capital cost; this leads to a result of \$0.047/kWh, which probably will be barely competitive.

The value to society of having fusion available at \$0.025 or \$0.047 per kilowatt-hour depends upon the market in which fusion must compete as an electricity source. Needless to say, it is not possible today to say what the competitive rate for baseload electricity will be in the year 2020. In this report, market rates for baseload electricity at the time of fusion commercial availability are taken to lie within the range $\$0.020 \leq c_b \leq \0.050 per kilowatt-hour in constant 1980 dollars. These costs are assumed to be distributed uniformly over that range and thus fusion electricity generated at \$0.025/kWh could be expected to be more competitive than 83 percent of the market, while 90 percent of the market would be more competitive than fusion costing \$0.047/kWh. Due to other constraints, however, such as size of demand for baseload electricity in a locale, fusion is presumed to capture only 75 percent of its otherwise available market. Thus, fusion-generated electricity costing \$0.025/kWh is assumed to eventually capture $(.83) \times (.75)$ of the market with an average cost savings of \$0.0125/kWh. Given today's market for baseload electricity generation of 1.644×10^{12} kWh, this would generate an annual cost savings of \$20 billion dollars. At a real discount rate of 3 percent, the present value of this annual benefit beginning forty years from today would be

$$\begin{aligned} \text{PVB} &= \frac{1}{\rho} \times (\text{annual benefit}) \times e^{-\rho t_a} \\ &= \$201 \text{ billion} \end{aligned}$$

*"The United States Magnetic Fusion Energy Program," DOE-ET-0072, August 1978.

where t_a is the number of years until commercial availability. But this number has not taken into account the fact that (i) market penetration is not immediate and (ii) the demand for baseload electricity is growing. In this study, the rate of future demand growth for baseload electric generation (g) is assumed to average 1 percent per year, considerably less than historical levels. At the time of fusion's commercial introduction, not all plants would be replaced immediately, simply because they have not reached the end of their useful lifetimes; about half of these plants would need replacement by the end of ten or fifteen years. Owing to the fact that fusion would represent a new technology and given risk aversion demonstrated in the private sector, a total time until one-half market penetration ($t_{1/2}$) of thirty years is used. Using these values for baseload growth and market penetration, the steady state annual benefit figure (shown above to be \$20 billion for $c_l = \$0.025/\text{kWh}$) is multiplied by 12.2 (as opposed to 10.1 in the steady-state case; given these values, the effect of demand growth outweighs the effect of nonimmediate market penetration), yielding an estimated present value of 245 billion dollars for a technology producing electricity at \$0.025/kWh, available in forty years and penetrating one-half its market in 30 years. Similarly, a technology producing electricity at \$0.047/kWh is worth 2.3 billion dollars today. Figure 3.6 translates cost per kilowatt-hour of a technology available in 2020 into present value benefit in 1980.

Fusion Program Phases and Costs

Consistent with current DOE policy, four phases are seen as leading to the commercialization of a tokamak-based fusion technology, TFTR (currently underway), ETF, EPR and DEMO. A decision tree showing these phases with the possibility of program termination at the end of each phase is shown in Figure 3.7. A model of a tokamak reactor is employed to estimate the benefits of fusion

FIGURE 3.6 PRESENT VALUE BENEFIT OF NEW TECHNOLOGY AS A FUNCTION OF LEVELIZED COST OF OUTPUT

FIGURE 3.7 TOKAMAK FUSION PROGRAM PLAN AND COSTS

research. This is a restriction on the fusion program which DOE policy does not embrace, as the decision on what type of fusion technology will be selected for demonstration and commercialization awaits the outcomes of ongoing and future research. Since this is a degree of freedom not modeled herein (i.e., the possibility that some other confinement scheme will be shown superior to tokamak), the value of fusion research calculated in the following section is likely to be an underestimate. Program costs of 1.0, 3.5, 7.0 and 7.0 billion dollars (undiscounted) are used for TFTR, ETF, EPR and DEMO, respectively; these appear to be consistent with the Deutch policy statement of a year ago.* As all dollar values employed herein are discounted back to 1980 at a 3 percent annual discount rate, so are program costs for ETF (1984), EPR (1997) and DEMO (2005). Commercialization, if reached, takes place in 2020.

The Stochastic Parameters

The uncertainty parameters-- n_o , T_o , γ , θ , Z_{eff} , η , t_b , τ_w , C_k --are all modeled using triangular distributions on the phase-specific outcomes. These triangular distribution are characterized by three parameters: the most likely or mode of the distribution (M), the lower limit and the upper limit, these latter two expressed as fractional changes from the mode, μ_L and μ_H , respectively where

$$\begin{aligned}\mu_L &= 1 - \frac{\text{minimum}}{\text{mode}} \\ \mu_H &= \frac{\text{maximum}}{\text{mode}} - 1\end{aligned}$$

The values used for these distributions are given in Table 3.2. The most likely value for Phase 1 outcomes is the mode specified in Table 3.2. For subsequent

*"The Department of Energy Policy for Fusion Energy," DOE/ER-0018, September 1978.

TABLE 3.2 STATE-OF-KNOWLEDGE ON STOCHASTIC PARAMETERS FOR BASE CASE TOKAMAK FUSION RD&D

PHASE	PARAMETER								
	PEAK DENSITY, n_0 (10^{20} m^{-3})	PEAK TEMPERATURE, T_0 (keV)	DENSITY PROFILE, γ	TEMPERATURE PROFILE, θ	IMPURITY LEVEL, Z_{eff}	BURN TIME, t_b (sec)	FIRST WALL LIFETIME, τ_w (MMyrs/m ²)	CONVERSION EFFICIENCY, η	PLANT CAPITAL COST, C_k (\$ BILLIONS)
MODE OF PRIOR DISTRIBUTION	5.0	12.4	1.0	1.0	1.5	300.0	20.0	0.365	1.263
μ_L	TFTR	0.10	0.10	0.50	0.50	0.20	0.67	0.0	0.05
	ETF	0.05	0.05	0.0	0.0	0.10	0.05	0.50	0.10
	EPR	0.0	0.0	0.0	0.0	0.0	0.02	0.20	0.40
	DEMO	0.0	0.0	0.0	0.0	0.0	0.01	0.10	0.20
μ_H	TFTR	2.0	0.33	1.0	1.0	0.20	0.67	0.0	0.05
	ETF	0.10	0.10	0.0	0.0	0.10	0.05	1.0	0.20
	EPR	0.0	0.0	0.0	0.0	0.0	0.02	0.50	0.80
	DEMO	0.0	0.0	0.0	0.0	0.0	0.01	0.20	0.20

phases, the most likely value is taken to be the outcome of the previous phase. To illustrate how these pdfs work, an example is shown in Figure 3.8, using efficiency(η). As essentially no information will be obtained on efficiency in TFTR, the original mode is simply passed through to the second phase, the outcome of which can deviate from the mode by as much as five percent upwards and four percent downwards. Whatever outcome results from the second phase, which could be anything in the range 0.350 to 0.038, it becomes the mode of the distribution characterizing Phase 3 results. A Phase 2 outcome of 0.375 is shown in Figure 3.8. Somewhat less information is shown resulting from Phase 3 tests, so that the Phase 3 results will not deviate much from the Phase 2 outcome, ± 1 percent. The rest of the uncertainty is resolved in the demonstration phase, wherein a final result of 0.383 is found. Note that the final result could have been as small as 0.336 ($0.365 \times 0.96 \times 0.99 \times 0.97$) or as large as 0.403 ($0.365 \times 1.05 \times 1.01 \times 1.04$).

Table 3.2 shows that all uncertainty in the plasma profile parameters, γ and θ , is resolved by the end of TFTR. The other plasma parameters-- n_o , T_o and Z_{eff} --are fixed by the end of ETF. No information is shown to come on wall lifetime and efficiency, and relatively little on total plant capital costs, during TFTR, whereas the bulk of information needed to predict ultimate burn time should be available by the end of that phase. Uncertainty on burn time, wall lifetime, efficiency and total plant capital costs persists to the end of the DEMO phase.

It is important that the reader realize that these values presented in Table 3.2 are only those estimated by ECON and do not necessarily reflect the position of DOE or a consensus of the fusion research community. It is hoped that the presentation of these variables and specific numerical assignment stimulates a dialogue which will eventually lead to better choices for them and, thus, better information for estimating the economic value of support technology developments.

FIGURE 3.8 SAMPLE OUTCOMES AND PDFs FOR TESTS ON EFFICIENCY

3.3.2 Results

The data described in the previous section, together with the models of Section 3.2, imply certain expectations on the technical and economic feasibility of tokamak fusion. A test of the "reasonableness" of the data used can be made by investigation of these resulting expectations. Given the stochastic (and deterministic) inputs to the plasma power model, conditions necessary for ignition are achieved 45 percent of the time, i.e., there is a 45 percent chance of technological success, given the configuration modeled. Thus, there is a 55 percent chance that no direct economic benefit will be realized from tokamak fusion RD&D. Should the reactor succeed technologically, however, it is almost certain that the power produced will be competitive, i.e., that it will be available at a cost less than \$0.050 per kilowatt-hour. In fact, the most likely cost (given success) is somewhat below \$0.010 per kilowatt-hour; the mean of cost per kilowatt-hour is \$0.007 and the standard deviation \$0.005. Figure 3.9 shows the pdf representing today's expectations on cost, and corresponding benefit, for the base case data developed in Section 3.3.1.*

Figure 3.10 shows the same pdfs, only for the case that the most likely value for plant capital costs is 2.526 billion dollars.

The expected value of the fusion research plan analyzed, given the data of the previous section, is found to be 194 billion dollars, which is somewhat more than the mean benefit of around 400 billion dollars (Figure 3.9) times the chance of technological success, 0.45. Figure 3.11 shows the results of the base case fusion research evaluation in decision-tree format. The net expected value of pursuing

*Lack of smoothness in the pdfs is due to numerical "noise," approximation error and aggregation effects.

FIGURE 3.9 PROBABILITY DISTRIBUTIONS OF COST PER KILOWATT-HOUR AND BENEFIT OF FUSION POWER FOR BASE CASE, CONDITIONED ON TECHNOLOGICAL SUCCESS

FIGURE 3.10 PROBABILITY DISTRIBUTION OF COST PER KILOWATT-HOUR AND BENEFIT OF FUSION POWER FOR TWO TIMES CAPITAL COST CASE, CONDITIONAL ON TECHNOLOGICAL SUCCESS

FIGURE 3.11 VALUE OF FUSION RESEARCH, BASE CASE

the TFTR phase of research (compared with program abandonment) is 194 billion dollars (all dollar numbers are present value in 1980, measured in 1980 dollars). There is a 0.733 chance that the results of TFTR will be sufficiently "good" to warrant continuation to ETF. Given "success" of TFTR, the expected value of pursuing the ETF phase is 266 billion dollars. Given pursuit of ETF, the probability that its results will warrant program continuation is 0.618. Having gotten this far in the program, most of the plasma parameters are now known with near certainty (see Table 3.2), and so it is known whether a burning plasma of the type expected is technologically possible. If the answer is yes, program continuation is definitely warranted due to the very "cheap" electricity expected to be produced (Figure 3.9). Correspondingly, the value of continuation to EPR, DEMO and commercialization is very high--362, 366 and 369 billion dollars, respectively--the difference among them due to whether or not the RD&D costs for each phase have already been sunk.

Even if plant capital costs have been underestimated by a factor of two, the value of fusion research is still high, 158 billion dollars, as shown in Figure 3.12.

FIGURE 3.12 VALUE OF FUSION RESEARCH, AT TWICE MOST LIKELY PLANT CAPITAL COST

As the first illustration of a program change, consider somehow restructuring fusion RD&D so that all uncertainty regarding Z_{eff} is resolved by the end of TFTR (clearly a hypothetical case). A change in TFTR which accomplishes this would be worth 17.7 billion dollars. The very high value is due to the fact that the reactor probably will not achieve sustained ignition with a Z_{eff} of 1.5; perfect information on other parameters not relating to technological success are worth substantially less than those which affect the plasma margins of safety. Thus, it can be said, based on Table 3.2, that the present fusion RD&D program, designed to demonstrate proof of principle and research the plasma parameters, is well-structured.

A second program change evaluated is the inclusion of an extensive first-wall research program during ETF of the type discussed in Section 3.2.3. Instead of a distribution having a mean of 20 MW-yrs/m², one with 27 MW-yrs/m² is used. Also, all information on τ_w is presumed known by the end of ETF. An added program which would accomplish these changes in expectations is worth an additional 1.5 billion dollars.

Finally, consider what the effect would be if the information obtained on cost shown in Table 3.3 was delayed for one phase (i.e., no information in TFTR, ± 5 percent in ETF, ± 20 percent left after DEMO). The decrement to the total value of fusion RD&D of this delay is 23.3 billion dollars.

3.3.3 Discussion

A methodology for evaluating changes in the tokamak fusion research program, including support technology RD&D, has been developed and demonstrated. In so doing, a benefit function for fusion technology has been quantified and the value of the tokamak fusion research program estimated. This value is placed at approximately 200 billion dollars, present value in 1980 compared against

a program cost of \$1.0 billion.* This yields a "value"-to-cost ratio of 200. Examples of possible RD&D program changes were examined and their effect on total program value estimated. The methodology which was developed to accomplish these things is quite sophisticated: it explicitly considers (i) the stochastic nature of the technology to provide fusion power, (ii) the market in which fusion-generated electricity will have to compete and (iii) RD&D program decisions to be made on the way to providing commercial fusion. The models used certainly warrant further development for refining the analyses; however, they represent good, first-order approximations.** Two facts must be kept in mind in using the results of this study:

1. The actual fusion research program is enormously more complex than modeled herein. The value estimated is based solely upon one conceptual design of a tokamak reactor. The possibility of other tokamak designs or of other fusion technologies for the commercial reactor is not incorporated into the analysis.
2. The results depend upon the data employed, as cited in Section 3.3.1, and are only as good as these data. These data have been developed by ECON for the purpose of demonstrating the methodology. A validation of these data within the fusion research community would provide more accurate and reliable information.

Besides showing that the fusion research program has substantial economic merit, the analysis performed also highlights the importance of two parameters in considering future program decisions: (i) the probability of technology success, i.e., the probability that sustained ignition yielding net electric power output is achievable, and (ii) the ultimate capital cost of a commercial fusion plant. These

* \$1.0 billion is used here because that is the amount that is committed to in order to obtain the \$200 billion expected value.

** Further development of the plasma power model is particularly important, especially if one wishes to examine programs affecting parameters not explicitly modeled, such as plasma heating or tritium breeding, handling and recovery.

two parameters swing estimates of the value of commercial fusion and are more important than, say, first wall lifetime or the efficiency of thermal-to-electric conversion. Future research efforts should emphasize the generation of information concerning the probability of technology success and commercial plant capital cost.

APPENDIX A

PLASMA POWER MODEL

This appendix serves to lay out the steps taken in sizing a tokamak reactor. The format of the equations follows closely those developed in Reference 1 upon which this appendix is based. The reader is referred to Reference 1 and the references referred to therein for a fuller development of the equations. The units used throughout are MKS with the exception of the kinetic temperature T which is in keV.

The reaction resulting in fusion power is that occurring in a 50:50 mixture of deuterium and tritium, viz.,

which results in the formation of an α -particle (He^4) and a neutron. In the ignited plasma it is assumed that all the heating is provided by the α -particles which are considered to deposit their energy in the plasma. Classically, the validity of this assumption is limited by orbit effects, as a fraction of the α -particle will be born with banana trajectories intersecting the wall. It has been shown that this fraction depends essentially only on the product $I_p A$ where I_p = plasma current

$$A = \text{aspect ratio} = \frac{\text{Major Radius}}{\text{Plasma Halfwidth}} = \frac{R}{a} \quad (A.2)$$

As a rule of thumb Reference 2 suggests the relationship

$$I_p A \geq 7.5 \text{ MA} \quad (A.3)$$

giving a condition under which ≤ 10 percent of the α -particles are lost.

The geometry and coordinate system used are defined in the following sketch.

The plasma cross-section is slightly deformed from circular, the measure of this deformation being the shape factor S ,

FIGURE A.1 MACHINE GEOMETRY

$$S = \frac{\text{Plasma Circumference}}{\pi a} \quad (\text{A.4})$$

The mean plasma halfwidth being given by

$$\bar{a} = a(2S^2 - 1)^{1/4} \quad (\text{A.5})$$

and represents the radius of the equivalent circular plasma.

The density and temperature profile assumed are

$$n(r) = n_0 \left(1 - \frac{r^3}{a^3} \right)^\gamma \quad (\text{A.6})$$

$$T(r) = T_0 \left(1 - \frac{r^2}{a^2} \right)^\theta \quad (\text{A.7})$$

where n_0 and T_0 are the peak center value of density and temperature, respectively, while γ and θ are free parameters whereby it is possible to vary the steepness of the profile. The HFCTR assumes $\gamma = \theta = 1$.

The number of nuclear reactions taking place for unit volume per unit time is

$$\frac{dN}{dt} = \frac{1}{4} n^2 \langle \sigma v \rangle \quad (\text{A.8})$$

where $n = n_i \approx n_e$ and $\langle \sigma v \rangle$ is the rate coefficient averaged over the Maxwellian distribution. For $T \leq 25\text{keV}$ this may be represented by:

$$\langle \sigma v \rangle = 3.68 \times 10^{-18} T^{-2/3} \exp(-19.94 T^{-1/3}) \text{ m}^3/\text{sec} \quad (\text{A.9})$$

Incorporating (A.7)

$$\begin{aligned} \langle \sigma v \rangle (r) = & 3.68 \times 10^{-18} \left\{ T_0 \left(1 - \frac{\gamma^2}{a^2} \right)^\theta \right\}^{-2/3} \\ & \exp \left(-19.94 \left\{ T_0 \left(1 - \frac{\gamma^2}{a^2} \right)^\theta \right\}^{-1/3} \right) \end{aligned} \quad (\text{A.10})$$

Radial dependences are eliminated by integrating over γ and redefining quantities in terms of area averages, viz.,

$$\bar{f} = \frac{\int_0^{\bar{a}} f(r) 2\pi r dr}{\int_0^{\bar{a}} 2\pi r dr} \quad (\text{A.11})$$

The only exception to this redefinition is the temperature which is density averaged so that T reflects the average energy per particle, viz.,

$$\bar{T} = \frac{\int_0^{\bar{a}} T(r) n(r) 2\pi r dr}{\int_0^{\bar{a}} n(r) 2\pi r dr} \quad (\text{A.12})$$

Hence we get

$$\begin{aligned} \bar{n} &= \frac{1}{\pi \bar{a}^2} \int_0^{\bar{a}} n_0 \left(1 - \frac{r^3}{\bar{a}^3} \right)^\gamma 2\pi r dr \\ &= \frac{2n_0}{\bar{a}^2} \int_0^{\bar{a}} \left(1 - \frac{r^3}{\bar{a}^3} \right)^\gamma r dr \end{aligned} \quad (\text{A.13})$$

and

$$\begin{aligned}
 \bar{T} &= \frac{\int_0^{\bar{a}} T_0 \left(1 - \frac{r^2}{a^2}\right)^\theta n_0 \left(1 - \frac{r^3}{a^3}\right)^\gamma 2\pi r \, dr}{\int_0^{\bar{a}} n_0 \left(1 - \frac{r^3}{a^3}\right)^\gamma 2\pi r \, dr} \\
 &= \frac{T_0 \int_0^{\bar{a}} \left(1 - \frac{r^2}{a^2}\right)^\theta \left(1 - \frac{r^3}{a^3}\right)^\gamma r \, dr}{\int_0^{\bar{a}} \left(1 - \frac{r^3}{a^3}\right)^\gamma r \, dr} \quad (A.14)
 \end{aligned}$$

The pressure may be written

$$\bar{nT} = \frac{2 n_0 T_0}{a^2} \int_0^{\bar{a}} \left(1 - \frac{r^3}{a^3}\right)^\gamma \left(1 - \frac{r^2}{a^2}\right)^\theta r \, dr \quad (A.15)$$

The Bremsstrahlung radiation is given by

$$P_B = 5.35 \times 10^{-37} Z_{\text{eff}}^2 n^2 T^{1/2} \quad (\text{Watts/m}^3) \quad (A.16)$$

and

$$\begin{aligned}
 \bar{P}_B &= \frac{5.35 \times 10^{-37} Z_{\text{eff}}^2}{\pi a^2} \int_0^{\bar{a}} n_0^2 \left(1 - \frac{r^3}{a^3}\right)^{2\gamma} T_0^{1/2} \left(1 - \frac{r^2}{a^2}\right)^{\theta/2} 2\pi r \, dr \\
 &= 1.07 \times 10^{-36} \frac{Z_{\text{eff}}^2 n_0^2 T_0^{1/2}}{a^2} \int_0^{\bar{a}} \left(1 - \frac{r^3}{a^3}\right)^{2\gamma} \left(1 - \frac{r^2}{a^2}\right)^{\theta/2} r \, dr \quad (A.17)
 \end{aligned}$$

Where Z_{eff} is the effective atomic number of the plasma ions. In pure D-T plasma $Z_{\text{eff}} = 1$, however, the presence of α -particles seems to cause $(Z_{\text{eff}})_{\text{min}} = 1.1$ in an ignited plasma.

The presence of impurities in the plasma gives rise to line radiation. The model chosen to represent this is that developed by Post (Reference 3) which assumes that the molybdenum (the dominant impurity assumed in the HFCTR) is stripped to a lithium-like state in which case the 2p - 2s transition dominates. This may be written

$$P_L = 1.2 \times 10^{-32} f(Z_I) n^2 \frac{S_x}{T^{1/2}} \text{ (Watts/m}^3\text{)} \quad (\text{A.18})$$

where

$$f(Z_I) = \frac{(Z_{\text{eff}} - 1)}{Z_I(Z_I - Z_{\text{eff}})} \left[1 + \frac{(Z_I - 2)(Z_{\text{eff}} - 1)}{Z_I(Z_I - Z_{\text{eff}})} \right] \quad (\text{A.19})$$

$$S_x = -.5772 - \ln x + x - \frac{x^2}{4} + \frac{x^3}{18} \quad (\text{A.20})$$

$$x = 2 \times 10^{-3} \frac{(Z_I - 2)}{T} \quad (\text{A.21})$$

— where Z_I is the atomic number of the impurity ion for molybdenum, $Z_I = 42$. Hence

$$\bar{P}_L = 2.4 \times 10^{-32} \frac{f(Z_I) n_0^2}{T_0^{1/2} a^2} \int_0^{\bar{a}} \left(1 - \frac{r^3}{a^3}\right)^{2\gamma} \left(1 - \frac{r^2}{a^2}\right)^{-\theta/2} S_x r dr \quad (\text{A.22})$$

where $x(r)$ may be expressed

$$x(r) = 2 \times 10^{-3} \frac{(Z_I - 2)}{T_0 \left(1 - \frac{r^2}{a^2}\right)^\theta} \quad (\text{A.23})$$

The power delivered to the plasma by the α -particle may be computed from Equation A.8

$$P_\alpha = \frac{1}{4} n^2 \langle \sigma v \rangle E_\alpha \text{ (Watts/m}^3\text{)} \quad (\text{A.24})$$

where E_α = the energy yielded per α -particle = 3.5 MeV. From Equations A.24 and A.10

$$\begin{aligned} \bar{P}_\alpha = 1.036 \times 10^{-30} \frac{n_0^2}{a^2 T_0^{2/3}} \\ \int_0^{\bar{a}} \left(1 - \frac{r^3}{a^3}\right)^{2\gamma} \left(1 - \frac{r^2}{a^2}\right)^{2/3 \theta} \\ \exp \left(-19.94 \left\{ T_0 \left(1 - \frac{r^2}{a^2}\right)^\theta \right\}^{-1/3} \right) r \, dr \end{aligned} \quad (\text{A.25})$$

For the plasma to ignite we must have the condition

$$\bar{P}_\alpha \geq \bar{P}_L + \bar{P}_B + \frac{3 \bar{n} \bar{T} \times 1.6 \times 10^{-16}}{\tau_E} \quad (\text{A.26})$$

where τ_E is the energy confinement time, the numerator of the same term being the energy density.

$$\tau_E = 3.2 \times 10^{-21} \langle n_L \rangle q^{1/2} a^2 \quad (\text{A.27})$$

where $\langle n_L \rangle$ is the line-averaged density and where

$$q = \frac{B_T}{B_\phi} \frac{a S}{R} \quad (\text{A.28})$$

is the so-called safety factor--normally taken as 3 or 4--and

B_T = the toroidal magnetic field

$$B_\phi = \text{the poloidal magnetic field} \approx \frac{\mu I_p}{2\pi a S} \quad (\text{A.29})$$

From Equations A.28, A.29 and A.2 we get

$$q \approx \frac{5 \times 10^6 B_T a S^2}{I_p A} \quad (\text{A.30})$$

where I_p is the plasma current.

Equation A.27 is the so-called "empirical scaling" which is based on results from a variety of low temperature plasmas. (Recent measurements at $T_e(0) \geq 3$ keV and $T_i(0) \geq 5$ keV in PLT indicate that confinement is at least as good at higher temperatures.) This scaling law is the energy confinement law upon which HFCTR is based. Later we will introduce a restriction in the application of the rule.

From Equation A.24 the minimum ignition criteria may be written as

$$(\overline{n\tau})_{\text{IGN}} = \frac{4.8 \times 10^{-16} \overline{n} \overline{nT}}{\overline{P}_\alpha - \overline{P}_B - \overline{P}_L} \quad (\text{A.31})$$

Equation A.31 gives $(\bar{n}\tau)_{\text{IGN}}$, which is the minimum required to ignite the plasma and is a function of n_o , T_o , γ , θ and Z_{eff} .

Although higher densities have led to better confinement in present tokamaks, the relation is expected to break down when the neoclassical limit is reached. For collisionality ≈ 0.1 the appropriate neoclassical scaling gives

$$\tau_{\text{nc}} = 8.8 \times 10^6 \frac{\bar{T}^{1/2} A^{1/2} I_p^2}{Z_{\text{eff}} \bar{n} S^{1/2}} \quad (\text{A.32})$$

Comparing this to Equation A.27 one sees that, in contrast, τ_{nc} varies inversely with plasma density.

It is believed that, as density is increased, confinement will follow Equation A.27 until the appropriate neoclassical limit is reached. This point will represent a turnover in Equation A.27 and any further increase in density will lead to a decrease in τ_E , the confinement time. This critical density may be expressed as

$$\bar{n}_{\text{max}} \tau_E = \left[\frac{5.5 \times 10^{40} \bar{T}^{1/2} B_T^2 S^{7/2}}{A^{3/2} q^{5/2} Z_{\text{eff}}} \right]^{1/2} \quad (\text{A.33})$$

As the design philosophy of HFCTR requires it to operate as near to the turnover point as possible it will be necessary to define the margin of safety

$$\text{MS} = \frac{(\bar{n}\tau)}{(\bar{n}\tau)_{\text{IGN}}} = \frac{\bar{n}\tau \text{ achieved}}{\bar{n}\tau \text{ from eqn A.31}} \quad (\text{A.34})$$

in terms of both empirical and neoclassical scaling. MS should be viewed as a factor of safety: $\text{MS} > 1$ means the reactor ignites, $\text{MS} < 1$ it does not. The relations are

$$MS_{(EMP)} = \frac{2.475 \times 10^{21} q^{1/2} \bar{B}_T^2 B_T^4 a^2 \bar{a} \int_0^{\bar{a}} \left(1 - \frac{r^3}{a^3}\right)^\gamma dr}{\bar{T}^2 (\bar{n}\tau)_{IGN} \int_0^{\bar{a}} \left(1 - \frac{r^3}{a^3}\right)^\gamma r dr} \quad (A.35)$$

$$MS_{(NC)} = \frac{2.2 \times 10^{20} a^2 B_T^2 \bar{T}^{1/2} S^{7/2}}{q^2 Z_{eff} A^{3/2} (\bar{n}\tau)_{IGN}} \quad (A.36)$$

In applying this model, at all times the lesser of the values of MS calculated from Equations A.35 and A.36 is the one which must be chosen, viz.

$$MS = \text{Min of } (MS_{(EMP)}, MS_{(NC)}) \quad (A.37)$$

In Equation A.35 we introduce $\bar{B}_T$ the average value of the toroidal β defined as

$$\bar{B}_T = \frac{2N_0}{B_T^2} \sum_j n_j k T_j \quad (A.38)$$

For MHD stability $\bar{B}_T$ must be kept below some critical value (for HFCTR, $\bar{B}_{T_{init}} \approx 5\%$)

$$\bar{B}_C = \frac{f(\text{shape})}{A q^2} \quad (A.39)$$

Above this value it is predicted that the so-called ballooning modes will arise and degrade the confinement. This is unfortunate as one would like $\bar{B}_T \approx 10$ percent in a reactor. It is not yet known if this sort of $\bar{B}_T$ is realistic or not. We may write $\bar{B}_T$ as

$$\bar{B}_T = 1.616 \times 10^{-21} \frac{n_0 T_0}{B_T^2 \bar{a}^2} \int_0^{\bar{a}} \left(1 - \frac{r^3}{\bar{a}^3}\right)^\gamma \left(1 - \frac{r^2}{\bar{a}^2}\right)^\theta r dr \quad (\text{A.40})$$

The above set of equations enable us to size the reactor once we have chosen S , a , A and q . All other parameters follow.

We now develop the equations which give the output powers expected from the reactor.

The total thermal power is developed from Equations A.1 and A.25

$$P_{th} = \pi \bar{a}^2 \times 2\pi R \times \frac{17.6}{3.5} \bar{P}_\alpha \quad (\text{A.41})$$

$$= 99.26 \bar{a}^3 A \bar{P}_\alpha \quad (\text{A.42})$$

The power loading of the first wall must be divided into two classes:

Class 1 Neutron flux

$$\begin{aligned} P_{wn} &= \frac{\pi \bar{a}^2 \times 2\pi R}{\text{wall circumference} \times 2\pi R} \times \frac{14.1}{3.5} \bar{P}_\alpha \\ &= \frac{\pi \bar{a}^2 \times 4.028 \bar{P}_\alpha}{\text{wall circumference}} \\ &= \frac{2.685 \bar{a}^2 \bar{P}_\alpha}{a + L_{SC}} \end{aligned} \quad (\text{A.43})$$

where the average neutron power density is seen to be

$$\bar{P}_n = 4.028 \bar{P}_\alpha \quad (\text{A.44})$$

and where L_{SC} is the width of the scrape-off layer. Only a fraction of this power is deposited in the first wall. The majority being deposited in the blanket. It does however represent an equivalent neutron flux, and hence damage, parameter.

Class 2 α -Particles and Radiation

On the assumption of the efficient operation of the proposed HFCTR cold gas blanket and limiter arrangement, the wall will, to zero-order, receive only the radiation losses, viz.

$$P_{w_{rad}} = \frac{\pi \bar{a}^2 (\bar{P}_B + \bar{P}_L)}{\text{wall circumference}} \quad (\text{A.45})$$

Hence the total wall power is

$$P_w = \frac{\pi \bar{a}^2 (4.028 \bar{P}_\alpha + \bar{P}_B + \bar{P}_L)}{\text{wall circumference}} \quad (\text{A.46})$$

The balance of power

$$P_{um} = 2\pi^2 \bar{a}^3 A (\bar{P}_\alpha - \bar{P}_B - \bar{P}_L) \quad (\text{A.47})$$

being that deposited on the limiters.

REFERENCES TO APPENDIX A

1. D. R. Cohn et al., "High Field Compact Tokamak Reactor (HFCTR) Conceptual Design," MIT Plasma Fusion Research Center Report R.R.-79-2, January 1979.
2. "Compact Ignition Experiment," an internal status report prepared jointly by the Max-Planck-Institute for Plasma Physics, Yarching and CERN, Frascati.
3. Post, R. F., Plasma Physics, 3, 1961.

APPENDIX B

RD&D PROJECT/PROGRAM EVALUATION METHODOLOGY

An overview of this methodology has been given in Section 3.2.1. This appendix discusses in more detail the components of the methodology: (i) modeling the benefit function which ascribes a value to a technology as a function of its characteristics, (ii) characterizing the states-of-knowledge on the technology, and finally (iii) the project evaluation.

A key objective of the methodology presented here is to divide the analysis into model building and data collection tasks such that each task can be accomplished by an expert working only within his area of expertise. The division of model building and data collection tasks described below is such as to accomplish this objective.

B.1 Modeling $B(\bar{x})$

The analytical effort called for by this methodology begins by developing a model of the economic benefit of technology commercialization in terms of a set of parameters, $\bar{x}$, which describe the technology and the marketplace at the time of commercialization. Accordingly, the $\bar{x}$ -vector is separated into two parts, those elements, $\bar{x}_T$, which describe the technology and those elements, $\bar{x}_M$, which describe the marketplace. The parameters $\bar{x}_T$ include such things as sizes, weights, efficiencies, costs and so on. They are the technical parameters which result from the RD&D project and which a system engineer would use to design or model a commercial system using the technology. In the engineering design process there are usually a number of design parameters, $\bar{u}$, that the engineer can choose as he sees fit to make the system best accommodate its use. For example, in the case of a battery storage system, the storage capacity and maximum discharge rate can be

chosen by the engineer (within limits) to best suit the application. It may be appropriate for different technology customers to demand different designs, within reason; for example, not all utilities would want the same amount of battery storage capacity. A full specification of $\bar{x}_T$ and $\bar{u}$ should lead to a full determination of the engineering system.

The net economic benefit of technology commercialization depends upon the marketplace for the technology and upon the cost of using the technology. Parameters describing the cost of using the technology, $\bar{C}_T$, are dependent upon the state-of-the-technology in use and the engineering system design. Consider a case where use of a technology results in cost savings. The economic benefit is the present value of future cost savings. This present value depends on the rate and ultimate extent of market penetration of the technology and on the cost savings per unit of technology use (per kilowatt-hour of installed battery storage capacity, for example).

The process of modeling $B(\bar{x})$ is illustrated in Figure B.1. First, the economic model is developed. This can be done by an economist with relatively little knowledge of the engineering system. The inputs to the economic model are generally system cost data, $\bar{C}_T$, system design parameters, $\bar{u}$, and market parameters, $\bar{x}_M$. A key result of the economic modeling process is an identification of the elements of the $\bar{C}_T$, $\bar{u}$ and $\bar{x}_M$ vectors. The economic model outputs a scalar value measure, B , dependent only on the above input parameters. The engineering system model can be constructed by an engineer with very little knowledge of the economic model. A key result of the engineering system modeling process is the identification of the elements of the $\bar{x}_T$ vector. The outputs of the engineering system model is the $\bar{C}_T$ vector. The only area where it is necessary for the engineer and the economist to interface is in the selection of the elements of $\bar{C}_T$ and $\bar{u}$.

FIGURE B.1 LOGIC FOR MODELING $B(\bar{x})$

In general, any time the value of a technology is estimated, it must be under the condition that the technology is optimally used. For example, given a technology for battery energy storage for large-scale electric energy systems, the value of the technology must be estimated under the condition that each utility that makes use of the technology buys the optimal amount of storage and discharge capacities. Thus, the elements of the $\bar{u}$ vector contain system design parameters which allow optimal use of the technology. Determination of the elements of the $\bar{u}$ vector can be accomplished by some form of optimization algorithm, separate from both the engineering system and economic models. The process may be an iterative one beginning with an initial guess, $\bar{u}_0$, and proceeding through a sequence of updated $\bar{u}$ vectors until $B(\bar{x})$ has been maximized.

B.2 Determining States-of-Knowledge

After the elements of the $\bar{x}$ vector have been identified, the next step in the analysis is to identify the elements of the $\bar{\phi}$ vectors, $\bar{\phi}_1, \bar{\phi}_2, \bar{\phi}_3$. A simple assumption that often suffices is to take the elements of the $\bar{\phi}$ vectors to be the

same as the elements of the $\bar{x}$ vector.* This assumption is made here. Then, having identified the $\bar{\phi}$ vectors and the $\bar{x}$ vector, it is next necessary to quantify the present state-of-knowledge, that is, the information which is known, on them. The state-of-knowledge on a $\bar{\phi}$ or $\bar{x}$ vector may be written mathematically as a probability density function (pdf).** It is reasonable to assume that, in planning the next RD&D subproject, Subproject ϕ_1 , the technical people involved will have an expectation on the outcome of that subproject that can be expressed in the form of a pdf on ϕ_1 ***. This pdf, written $f_{\bar{\phi}_1}(\bar{\phi}_1)$, is a function of the elements of the $\bar{\phi}_1$ vector and is referred to as a multivariate distribution. This distribution merely reflects the subjective opinions of the people who specify it on how likely they believe one particular outcome is compared to another. More will be said on the determination of this pdf shortly.

Next consider the outcome of Subproject $\phi_2, \bar{\phi}_2$. As one attempts to place a pdf on $\bar{\phi}_2$, and subsequently $\bar{\phi}_3$, one is faced with the problem that these outcomes will occur further into the future and that they will depend on the outcomes of previous work. Thus, for example, the outcome $\bar{\phi}_2$ may clearly depend on the outcome $\bar{\phi}_1$. Hence, the pdf that will be placed on $\bar{\phi}_2$ will be dependent, that is, it will be conditional, on the outcome $\bar{\phi}_1$. The conditional pdf on $\bar{\phi}_2$ is written $f_{\bar{\phi}_2}(\bar{\phi}_2 | \bar{\phi}_1)$. It determines the likelihood of a particular outcome $\bar{\phi}_2$, given that an

* The methodology does not require this assumption to be made but, if it is not, additional work is necessary to define the relationships between the elements of $\bar{\phi}_1$ and $\bar{\phi}_2$, $\bar{\phi}_2$ and $\bar{\phi}_3$, and $\bar{\phi}_3$ and $\bar{x}$ --for example, "scaling laws" between pilot and demonstration plants and demonstration and commercial plants.

** A probability density function is a function on a random variable, y , written $f_y(y)$, that gives the probability density (or just the probability in a discrete pdf) that the variable takes on a specific value y .

*** Were it impossible to express some expectation of the results of a subproject, it would not be possible to provide a justification for doing it.

outcome $\bar{\phi}_1$ has occurred. To obtain $f_{\bar{\phi}_2}(\bar{\phi}_2 | \bar{\phi}_1)$, the experts in each area of technology are asked to consider that a particular outcome, $\bar{\phi}_1$, has occurred and, based on that outcome, to assess the range and relative likelihood of outcomes, $\bar{\phi}_2$, of Subproject ϕ_2 . This process is repeated for different potential outcomes $\bar{\phi}_1$ until the conditional distribution is adequately determined. (It may be that the likelihood of some ϕ_2 outcomes do not depend on ϕ_1 results. If so, this simplifies the process.) Seeking to quantify only the conditional distributions has the advantage that a person is being asked to consider only one subproject ahead each time, not to aggregate, in his mind, the possible ranges of outcomes over successive subprojects.

The process outlined above is repeated to obtain pdfs on $\bar{\phi}_3$ and $\bar{x}$. In general, the distribution on $\bar{\phi}_3$ may be conditional on both outcomes $\bar{\phi}_1$ and $\bar{\phi}_2$ and the distribution on $\bar{x}$ would be conditional on the outcomes $\bar{\phi}_1$, $\bar{\phi}_2$ and $\bar{\phi}_3$. However, given that the elements of the vectors $\bar{x}$, $\bar{\phi}_1$, $\bar{\phi}_2$ and $\bar{\phi}_3$ have been taken to be the same parameters, it is reasonable to assume also that the outcome $\bar{\phi}_3$ is conditional only on $\bar{\phi}_2$ and $\bar{x}$ is conditional only on $\bar{\phi}_3$.*

One further simplification is made here that greatly reduces the effort necessary to develop the necessary pdfs. This is to assume that the elements of $\bar{x}$ (and thus also the $\bar{\phi}$ s) can be chosen so that they are independently distributed, that is, so that the likelihood of a particular outcome on one element of $\bar{x}$ is independent of the outcomes of the other elements of $\bar{x}$. With this simplification, the evaluation of the necessary pdfs becomes a job of assessing a set of individual

*Again, this simplification is taken, but it is not a necessary assumption for the use of the methodology.

pdfs on each element of the vector in question. The necessary multivariate pdf is then simply the product of the individual pdfs.*

It is now interesting to consider the specific form which the individual pdfs might take. In general, engineering and market parameters, such as costs, weights and so on, are limited in their possible range of outcomes: usually they must be positive numbers. One useful distributional form for such parameters is the triangular pdf as shown in Figure B.2. The triangular distribution is fully specified by three parameters, the minimum parameter value, the maximum parameter value and the most likely parameter value (the mode) or their surrogates, for example, as shown in Figure B.2, the mode, m , and the parameters μ_L and μ_H . μ_L and μ_H define the possible variation from the mode that the parameter may assume, for example, $\mu_L = .5$ and $\mu_H = 1$ indicates that the mode is an estimate of the parameter value that could differ from the actual (resulting) parameter value by as much as a factor of two. Using the triangular distribution to obtain the pdf on $\bar{\Phi}_1$, it is necessary to specify values of m , μ_L and μ_H for each element of $\bar{\Phi}_1$. Then $p_{\bar{\Phi}_1}(\bar{\Phi}_1)$ is the product of the individual pdfs on each element of $\bar{\Phi}_1$.

The pdf on $\bar{\Phi}_2$ may be similarly generated. If the elements of the $\bar{\Phi}_1$ and $\bar{\Phi}_2$ vectors are the same parameters, it is reasonable to assume that the best estimate

*The usefulness or inapplicability of this assumption of independence can only be judged in applications of the methodology to real-world problems. It is asserted that, in most cases where modeling shows two parameters to be interdependent, a different model configuration (equally representative) can be found which removes this interdependence. Such modeling, then, needs to be performed intelligently. For example, in an illustrative example of a solar photovoltaic technology developed elsewhere, it would have been possible to model the technology in terms of efficiency and cost per kW capacity. Clearly, these two parameters are not independent. By modeling the technology in terms of efficiency and cost per unit area, however, independence is achieved. Similarly, in the mini-example on battery storage technologies, it was not difficult to construct a system model which preserved independence of the parameters. In repetition, this assumption is not, however, fundamental to the methodology described herein.

FIGURE B.2 THE TRIANGULAR PROBABILITY DENSITY FUNCTION

of $\bar{\phi}_2$ is the outcome $\bar{\phi}_1$.^{*} Thus, it is reasonable to take, as the modes of the pdfs on the elements of $\bar{\phi}_2$, the elements of the outcome $\bar{\phi}_1$.^{**} Further simplifying the problem by assuming that, on each element of $\bar{\phi}_2$, the distributional parameters μ_L and μ_H are independent of the outcome $\bar{\phi}_1$, the pdf $f_{\bar{\phi}_2}(\bar{\phi}_2 | \bar{\phi}_1)$ can be fully specified by specifying only values of μ_L and μ_H for each element of the $\bar{\phi}_2$ vector. This is also the case for $f_{\bar{\phi}_3}(\bar{\phi}_3 | \bar{\phi}_2)$ and $f_{\bar{x}}(\bar{x} | \bar{\phi}_3)$.

^{*} This is not always true. For example, in certain cases, data obtained from a test can be used in the Bayesian sense to update a "prior" distribution. Then it is appropriate to use Bayes Law to update the prior. More often, however, energy RD&D does not produce data which have this property. Instead, the measurement of a particular parameter in an RD&D subproject often results directly in the best estimate of the parameter value obtained to date.

^{**} An example may help here. Suppose the efficiency of a process is of interest. The efficiency is unknown today, but will be resolved through a sequence of experiments at different scales; for example, tenth-scale, quarter-scale and full-scale. Each successive experiment provides an improved estimate of efficiency. There are two ways to deal with this problem. The first is to say that the tenth-scale experiment provides an estimate of the efficiency that will be obtained in the quarter-scale experiment and this, in turn, provides an estimate of the full-scale efficiency. The second way, that taken here, is to translate the result of the tenth-scale test into a best estimate of the full-scale efficiency. This best estimate is then taken to be the mode of the probability distribution on efficiency upon completion of the tenth-scale experiment. The uncertainty expressed by the distribution on efficiency resulting from the quarter-scale experiment is then a measure of the amount by which the quarter-scale experiment might modify the tenth-scale estimate. Likewise, the full-scale experiment may modify the quarter-scale estimate.

The simplicity and eloquence of the resulting probability distributions and their data requirements, while retaining the fundamental essence of the problem, will become apparent in the discussion on an example problem which follows. A major attribute of the distributional forms obtained is that they lead to a data collection dialogue which asks questions of technology and economic experts only in their individual fields of expertise. The dialogue may be further confined to a reasonable set of questions for which there is a reasonable basis for expecting valid answers. Also, importantly, since experts are questioned on specific elements only in their particular areas of expertise, they remain accountable for the answers which they provide. That is, the RD&D results obtained should lie within the estimate ranges provided. If they do not, the experts responsible for these estimates have done an invalid job in estimating the RD&D outcomes. In this methodology, these individuals are identifiable.

B.3 Project Evaluation

Having described an RD&D project in the form of Figure 3.1 (in the main text), given a model for $B(\bar{x})$, and given pdfs on the $\bar{\phi}$ s and $\bar{x}$, it is now possible to evaluate the project. This is done using a process referred to as backward induction which begins by examining the last decision in the project, the decision to commercialize the technology. It is assumed that the technology will be commercialized if, given the results of the RD&D project, the technology users expect that there will be a positive net benefit to be gained, that is, if the "expected value" of technology commercialization is positive. Mathematically, the expected value of commercialization, given an RD&D outcome ($\bar{\phi}_3$ for Figure 3.1), can be written

*The "expected value" is a mathematical term to indicate a type of average. It is the integral or sum of all possible values of a variable weighted by their respective probabilities of occurrence.

$$E[B(\bar{x}) | \bar{\phi}_3] = \int \dots \int_{\bar{x}} B(\bar{x}) f_{\bar{x}}(\bar{x} | \bar{\phi}_3) d\bar{x}.$$

This equation is read: The expected value of $B(\bar{x})$ given an RD&D outcome $\bar{\phi}_3$ is equal to the sum over all $\bar{x}$, of $B(\bar{x})$ multiplied (or weighted) by the probability of $\bar{x}$ occurring given the outcome $\bar{\phi}_3$. Commercialization will occur if this quantity is positive. Thus, the decision will be to commercialize the technology if $\bar{\phi}_3$ is such that $E[B(\bar{x}) | \bar{\phi}_3]$ is positive.

The set of $\bar{\phi}_3$ for which $E[B(\bar{x}) | \bar{\phi}_3]$ is positive, that is, the set of $\bar{\phi}_3$ for which the decision is to proceed with commercialization, is referred to as the "go set," D_3 , of $\bar{\phi}_3$. Mathematically, the set D_3 is written

$$D_3 = \{ \bar{\phi}_3 : E[B(\bar{x}) | \bar{\phi}_3] > 0 \}.$$

This expression is read: D_3 is the set of RD&D outcomes, $\bar{\phi}_3$, for which the expected value of commercialization is positive. D_3 defines the success of the RD&D project. If the project results in an outcome, $\bar{\phi}_3$, which is contained in the go set, D_3 , it can be said that the project has been successful.

It is now possible to evaluate Subproject ϕ_3 , given an outcome from Subproject ϕ_2 . The net expected value of Subproject ϕ_3 , given the outcome $\bar{\phi}_2$, is equal to the expected value of technology commercialization, given that the technology is successfully developed, weighted by the probability of successful technology development, minus the cost, C_3 , of Subproject ϕ_3 . This value can be written mathematically as

$$E[\phi_3 | \bar{\phi}_2] = \int \dots \int_{\bar{\phi}_3 \in D_3} E[B(\bar{x}) | \bar{\phi}_3] f_{\bar{\phi}_3}(\bar{\phi}_3 | \bar{\phi}_2) d\bar{\phi}_3 - C_3.$$

It is read: The expected value of Subproject ϕ_3 , given the outcome $\bar{\phi}_2$ of Subproject ϕ_2 , is the sum over all $\bar{\phi}_3$ contained in the go set D_3 of the expected

values of $B(\bar{x})$, given an outcome $\bar{\phi}_3$, weighted by the probability of the occurrence of $\bar{\phi}_3$ given the outcome $\bar{\phi}_2$, minus the subproject cost, C_3 .

Again, the logical economic decision is to perform Subproject ϕ_3 if its expected value is positive. Thus, the decision is "go" if $\bar{\phi}_2$, the outcome of Subproject ϕ_2 , is such that $E[\phi_3 | \bar{\phi}_2]$ is greater than zero. This condition defines D_2 , the go set of $\bar{\phi}_2$:

$$D_2 = \{ \bar{\phi}_2 : E[\phi_3 | \bar{\phi}_2] > 0 \}.$$

D_2 defines the success outcomes of Subproject ϕ_2 .

The process of backward induction is continued to yield first an expected value of Subproject ϕ_2 and then of Subproject ϕ_1 .

$$E[\phi_2 | \bar{\phi}_1] = \int_{\bar{\phi}_2 \in D_2} \dots \int E[\phi_3 | \bar{\phi}_2] f_{\bar{\phi}_2}(\bar{\phi}_2 | \bar{\phi}_1) d\bar{\phi}_2 - C_2$$

which defines the go set of $\bar{\phi}_1$,

$$D_1 = \{ \bar{\phi}_1 : E[\phi_2 | \bar{\phi}_1] > 0 \}$$

and

$$E[\phi_1] = \int_{\bar{\phi}_1 \in D_1} \dots \int E[\phi_2 | \bar{\phi}_1] f_{\bar{\phi}_1}(\bar{\phi}_1) d\bar{\phi}_1 - C_1.$$

$E[\phi_1]$, the expected value of the next subproject, is not conditioned on any future RD&D outcomes because it is based on the state-of-knowledge extant. It is the most relevant parameter obtained in the entire analysis because it relates to the only decision to be made: whether to perform Subproject ϕ_1 . The decisions to pursue future subprojects need not be made until future dates and, as such, should be evaluated at the time when they are to be made, given the results obtained in earlier RD&D efforts. The economic objective of the program planning process

should be to structure the program in such a way so as to maximize the expected value of the next subproject.

While it is the economic purpose of the program planning process to structure the project so as to maximize the expected value of the next subproject in the project, and while the above methodology provides a means of evaluating the next subproject, the methodology can also provide a number of other output parameters that can guide the program manager in efficient project planning. These output parameters include a clear definition of success and failure in the project (the go sets: D_1 , D_2 and D_3), the probability of achieving success in each subproject (the probability that $\bar{\phi}_1 \in D_1$, $\bar{\phi}_2 \in D_2$, etc.), a forecast of the developed technology that can be expected if the project is a success (the distribution on $\bar{x}$ conditional upon success) and a measure of the economic value of commercialization given that the technology reaches that stage.