technological strategies that differ from normal light water reactor designs:

1. Use of thorium-^{233}U cycle, rather than ^{238}U-plutonium.

2. Use of a seed-plus-blanket layout with variable geometry. Each fuel module consists of a more-highly-enriched axial core (the seed), surrounded by a less-enriched subcritical blanket. The relative geometry of these elements are varied over time, so that the neutron captures needed for coarse control are productive ones in thorium, and so that the amount of such captures is adjustable over the fuel lifetime.

3. Minimizing water content of the cores via close fuel rod spacing in order to minimize captures of slow neutrons in light water, and to keep the neutron energy spectrum high (thus enhancing direct fission of thorium by fast neutrons).

Since the LWBR represents a smaller extension from current technology than other breeder concepts, its characteristics are easier to predict, it could be available sooner and it would have fewer problems of acceptability. Furthermore it has the potential of improving the performance of light water plants already built. On the other hand, breeding in the LWBR will be marginal at best. The demonstration core presently being assembled is predicted to breed only 1.5% more fuel than it burns after three years operation. Even this performance comes about at substantial cost, in terms of more expensive core design and fuel cycle costs. In addition, the close fuel rod spacing makes more difficult the solution of some safety problems, such as effects of fuel rod distortion, or loss of coolant.

The present activity, supported by the AEC's naval reactors program, aims toward installation of a new core in the Shippingport prototype reactor in 1974, toward collection of operating data 1974-77, and analysis of the spent fuel after that.

The current annual funding level for this program is almost $24 million. This will probably decrease somewhat in the next two years since the principal fabrication costs for the breeder core are already funded.

Because of its very limited breeding potential, the LWBR is more properly considered an advanced converter than a breeder. Nontheless, even with a conversion ratio of 0.97, the reactor can extend the energy derivable from an initial U-233 charge by a factor of 30, using thorium as a source material.

If the concept proves to be technically and economically viable, the LWBR will find real application in specific instances: for example, conversion of installed pressurized water reactors (PWR's) (of which there will be many by the 1980's and 1990's), or siting in more populous areas where the more experimental LMFBR's or other alternates might not find ready acceptance.

PROGRAM RECOMMENDATIONS

In addition to continued high priority development of the LMFBR along the lines currently being pursued by the AEC, the following elements would assure a balanced, strategically insured breeder program.

Molten Salt Breeder Reactor

The critical problems of the MSBR on which work should now be concentrated are (1) demonstrating that proposed materials for containing fused salt plus fission products are in fact satisfactory for a 30-year lifetime, (2) preventing escape of tritium, and (3) demonstration of an operable complete reprocessing system.

Continuation of the present budget allocation of $5 million per year would permit continued investigation of the fused-salt container material and tritium problems. Additional funds will be required to complete development of fuel reprocessing techniques. An appropriate level for the overall program would be $8 million in FY 1975 and $12 million in FY 1975. This would permit an initial attack on fuel processing on an adequate scale and would permit the Oak Ridge group and some of their industrial associates to give more attention to the engineering problems of larger MSBR's. At the end of this two year period, the molten salt concept should be reassessed, taking into account the degree of progress made in solving its principal problems and the status of LMFBR projects in this country and abroad at that time.

During the coming years greater industrial involvement should be sought, both to reduce the financial burden on the government and to provide input from the groups who would be required to design, build and operate molten salt reactors.

Gas Cooled Fast Reactor

Government encouragement of and support for development of the GCFR should be continued but with the principal initiative for this development remaining with GGA and its associates. The GCFR development program should have as a key objective demonstration of solutions to the critical problems noted earlier--vented fuel performance, pressure vessel integrity, and adequacy of emergency cooling--and should culminate in construction of one GCFR demonstration plant. The plans for this program should be developed by the industrial participants.

While these plans are being developed, government support for the GCFR should be increased to the level of $4 million annually to maintain momentum for this project and to permit conduct of meaningful work requiring government facilities, such as fuel testing. Cooperative liaison with European programs should be strengthened.

Light Water Breeder Reactor

The light water breeder program seems viable as it is now constructed. It should continue as planned at least until the performance of the modified Shippingport plant can be analyzed.

Program Summary

Table III-15 presents a summary of the funding proposed for alternate breeders.

Table III-15

SUMMARY OF ALTERNATIVE BREEDER PROGRAM

Program Element	Current R&D Objectives	First Year Cost $ Millions	Long-term Cost $ Million/year	Notes
Molten Salt Breeder	Materials development and reprocessing technology	8	20/2	Reassess after 2 years.
Gas Cooled Breeder	Technology of emergency cooling, pressure vessel integrity and fuel performance	4	50/5	In addition to substantial industrial program utilizes LMFBR fuel and HTGR technology
	Total	12	70	

Note: The light water breeder reactor is considered an important development program appropriately funded, but not a true alternative to the LMFBR.

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H. FUSION

INTRODUCTION*

The central problem confronting the energy system in this country in the long run is the limited extent of economical indigenous energy resources. Even if it is assumed that the environmental problems associated with current energy technologies can be resolved, those technologies are all based on the consumption of finite energy resources. As was demonstrated in Chapter II, these resources are being consumed at rates that are significant relative to the total amounts with which this country was originally endowed.

Controlled thermonuclear fusion is one of the few technologies that promise a possible resolution to the long term problem of the supply of clean energy. The fuel resources on which fusion power is based, either deuterium or lithium, are sufficiently abundant that they present no realistic constraint on the use of fusion power.

Fusion appears to have several attractive environmental and safety characteristics. For example, there is no possibility of a loss-of-coolant accident and no production of volatile radioactive waste. Still, it is not, as some would have it, "the ultimate, clean safe" energy source. In fact it faces many of the safety problems of fission reactors--albeit in much less severe form.

The magnitude of the potential rewards of the successful development of fusion power are matched by the severity of the scientific and engineering problems to be solved in the course of that development. The question of scientific feasibility--does nature allow the net production of energy from controlled fusion?--has yet to be answered. The engineering development program required to produce a viable fusion reactor system is a very difficult problem. At this stage of development any estimates of the economics of fusion power reactors are speculative. Such estimates as have been made, however, are not discouraging.

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* This section is based in large part on a report prepared by a committee sponsored by the AEC Division of Controlled Thermonuclear Research (see reference 26). References 27-37 provide a further bibliography of the subject.

Viewed in the broad context of all potential energy R&D a high priority must be given to the accelerated development of controlled thermonuclear fusion. By accelerating the current program the demonstration of scientific feasibility in the next 8-10 years can be a realistic target.

CURRENT STATUS OF FUSION R&D

The basic nuclear processes from which the sun and the stars derive their energy were first reproduced in terrestrial laboratories almost forty years ago. Over the past twenty years research in controlled fusion has developed at an increasing pace around the world. In the early 1950's fusion was a classified field of research, and little was known about its root science--the physics of high temperature plasmas. In 1958 the U.S. fusion program was declassified, and by the early 1960's a number of the relevant scientific problems were identified and a systematic study of them begun.

The isolation of a reacting fusion plasma from its surroundings was soon recognized as the central problem of fusion research. The principal approach to this problem, then as now, was to confine a fusion plasma through the use of specially shaped magnetic fields, which were to control the motions of its individual ions and electrons.

In the early 1960's it was recognized that the production of fusion by lasers had potential military applications. Although the development of laser fusion has been carried out within the military context, increasing interest has focused on it as an approach to civilian power production.

To give an idea of the current status of fusion research, a brief summary will be given of the main programs and their current goals. But first a brief review will be presented of the scientific bases for all approaches to controlled fusion.

Scientific Bases of Controlled Fusion*

Fusion reactions occur when two light nuclei such as deuterium (D), tritium (T), or helium (^3He) collide and rearrange themselves so as to

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* This section is based on reference 27.

form two other nuclei of smaller mass with a consequent release of energy. The following reactions are of primary interest in CTR research:

Energy Required	Fusion Reaction		Energy Released
~10 KeV	D+T	$^{4}He+n$	17.6 MeV
~50 KeV	D+D	$^{3}He+n$ T+p	3.3 MeV 4.0 MeV
~100 KeV	$D+^{3}He$	$^{4}He+p$	18.3 MeV

There are several important features of these reactions. Because of the strong Coulomb repulsion between approaching nuclei they can take place only at very high energy. To achieve particle energies of 10 KeV the mixture must be at a temperature of about 100 million degrees Kelvin. At this extreme temperature the gas atoms are fully ionized--they have all shed their electrons. Such a fully ionized gas is called a plasma, and the fact that the particles are charged particles makes possible their containment with magnetic fields.

The reaction products of a fusion reaction carry away the energy of the reaction as kinetic energy. In the DT reaction most of the energy is carried away by a 14 MeV neutron whereas in the $D^{3}He$ reaction all of the energy is released to the charged particles. The form in which the energy is released determines the method of energy conversion. In the case of the DT reaction, the energy of the escaping neutrons must be degraded to heat and converted through a thermal cycle to electricity. When the energy appears in the charged particles, a unique direct conversion of their energy to electricity is possible. This has the potential for very high efficiency and low waste heat.

In the DT reaction, which is generally regarded as the easiest to achieve because of its relatively low reaction energy, tritium must be supplied as a fuel. Breeding of tritium from lithium and thermalization of the DT neutrons would be accomplished in the blanket which surrounds the plasma of a DT fusion reactor.

A measure of success in obtaining net power from thermonuclear reactions is the ratio of thermonuclear power generated to the power required to create and sustain the hot reacting mixture. Lawson first stated the requirement for power balance in a fusion reactor by assuming that the entire energy, both the energy from thermonuclear reactions and the energy invested in initially creating the hot plasma could be reinvested, with an efficiency of one-third in creating new plasma. For the DT reaction, this leads to the requirement on the density-containment time product:

$$n\tau > 10^{14} \text{ sec cm}^{-3} \text{ for } T \sim 10 \text{ KeV}$$

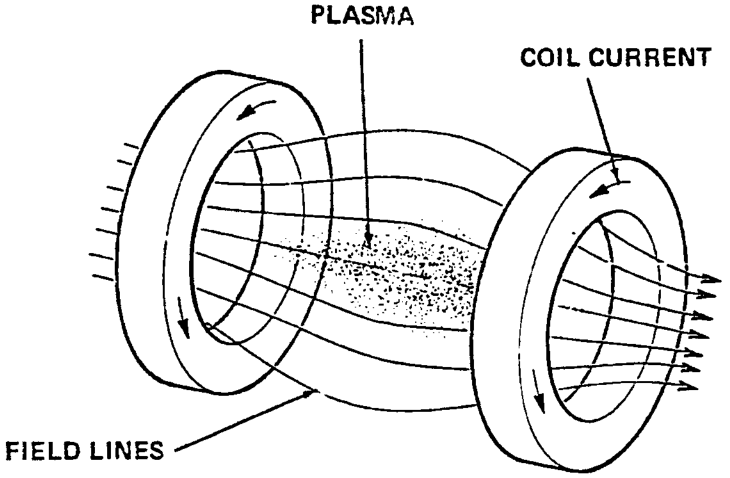
where n is the ion density and τ is the energy replacement time, or approximately the plasma confinement time.

Magnetic Confinement of Plasmas

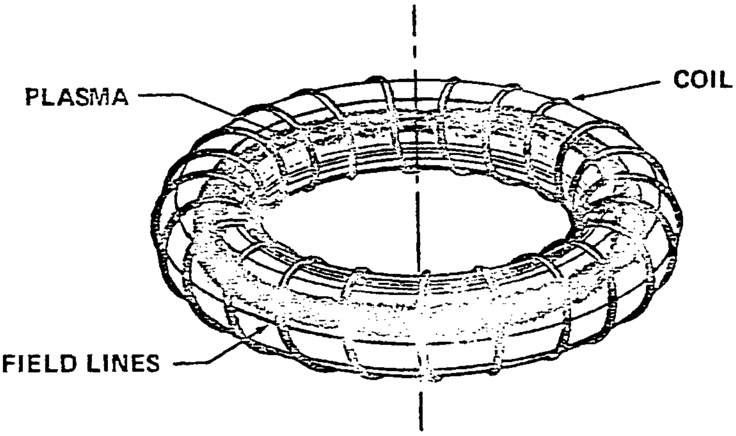
Magnetic confinement of plasmas takes advantage of the fact that in strong magnetic fields individual charged particles are confined to move along field lines in tight helical trajectories. Thus individual particles are confined to one dimensional motion along magnetic field lines. Two basically different approaches to magnetic confinement are shown in Figure III-4 and differ as to whether magnetic field lines, and hence the trajectories, lead directly out of the containment region as in the open systems, or whether magnetic lines remain largely within the containment region as in the closed toroidal system. In open systems magnetic mirrors, or regions where the strength of the magnetic field increases, are used to reflect particles and reduce the loss from the ends. All "magnetic bottles" are variants of these simple open or closed systems.

With increasing plasma density, particles occasionally collide with one another, and change their orbits somewhat. A collision may, in the case of mirror systems, allow the particle to escape through the mirror directly, or in the case of closed systems, allow the particle to take a small step toward the surface of its magnetic container. In the latter case, after many such collisions the particle is lost altogether. Thus, collisions are responsible for a slow leak from the magnetic

MAGNETIC CONTAINMENT CONFIGURATIONS



OPEN SYSTEM - SIMPLE MAGNETIC MIRROR



CLOSED SYSTEM - SIMPLE TORUS

Figure III-4

container, referred to as a classical loss. Since it is not possible to eliminate these collisions, they set an upper limit on confinement time--termed the classical confinement time. Classical confinement times in large enough systems are more than adequate for successful fusion reactors.

Until recently, all plasma experiments yielded loss rates considerably in excess of classical values, loss rates clearly unacceptable for a fusion reactor. Frequently these anomalous losses seemed to be associated with plasma instabilities and turbulence. There has been an enormous amount of research on the nature of plasma instabilities, their effect on plasma confinement, and upon ways to eliminate them or minimize their effects on confinement, during the past 10 years. As a consequence of this work, classical confinement times (or very near to classical) have been observed under a wide variety of plasma conditions, including plasmas of thermonuclear temperature and density. In several research devices observed confinement times would be adequate for a fusion reactor provided they scaled as expected as the size of the machine is increased.

The scientific, technical and size limitations of present-day fusion experiments preclude any of them from simultaneously achieving all three of the plasma parameters (temperature, density and confinement time) required for a fusion reactor. This achievement, which would demonstrate scientific feasibility, will require larger, more complex facilities than presently available. In addition it will be necessary to continue the development of relevant technologies at an expanded level in parallel with plasma experimentation.

Laser-fusion is based on a (deceptively) simple notion. Light from a powerful laser is to be used to compress and heat a particle of fuel to densities and temperatures at which thermonuclear burning occurs releasing energy far in excess of that necessary for the original compression and heating. Behind the simple notion, however, lies a myriad of complex physical phenomena which must occur each in its right place and at the right time in the sequence to achieve the required compression, heating and burning.

The phenomena are sufficiently complex that no analytical description of the whole process exists. They must be modeled on a digital computer. So far, the computer results are very encouraging. But it must be recognized that the crucial laboratory experiments, whose aim is to validate the computer models and results, are yet to be performed. Until the results of such experiments are in hand judgment must be reserved as to whether laser-fusion will turn out to be a relatively simple or a difficult problem.

It is widely recognized and accepted, however, that presently available lasers are inadequate for the job. The development of more powerful, more efficient, more reliable and more economical lasers is a necessary (albeit not sufficient) requirement for laser-fusion to become a reality.

Major Experimental Approaches

The present AEC fusion effort represents a mutli-line attack on a very complex problem. Today four general approaches are receiving major emphasis. These are magnetic mirror systems, steady state toroidal systems (principally the tokamak), pulsed high-beta* pinch systems (principally the theta pinch), and laser-fusion systems. Each of these concepts appears to have the potential of being extrapolated to a practical power reactor, based upon preliminary systems studies.

In addition to these main lines, a broad range of supporting research which spans the range from basic plasma studies to relatively large-scale confinement system research is conducted in national laboratories, universities, and industry. Technological development (magnets, beams, energy storage, diagnostics, etc.) is carried out in support of existing experiments and in preparation for next generation systems. Finally, a small but growing program in fusion reactor analysis and technology is supported both to provide guidance to the plasma research and to provide an understanding of the variety of problems which must be solved prior to the achievement of practical fusion power.

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* Beta is defined as the plasma pressure divided by the magnetic pressure. High beta refers to values approaching unity.

Steady State Toroidal Systems - The so-called tokamak concept is receiving primary emphasis in this general area of research. Tokamak plasmas in the U.S. and the U.S.S.R. have reached densities of about $3x10^{13} cm^{-3}$, ion temperatures of 600 eV, and confinement times of about 20 milliseconds, near the classical value for the magnetic fields, densities, temperatures, and sizes now being utilized. A reactor-grade tokamak plasma must have a density near $10^{14} cm^{-3}$, an ion temperature above 5000 eV, and a confinement time of about one second.

Research areas of current greatest importance relate to plasma confinement and stability, plasma purity and methods for heating the plasma. Work is being carried out on these various aspects of steady state toroidal systems at a number of laboratories including the Oak Ridge National Laboratory (with the ORMAK tokamak), Princeton (with the ST and the ATC facilities) and the University of Texas (with the Texas Torus).

Results in late 1972 and early 1973 from the ATC experiment at Princeton and the ORMAK experiment at Oak Ridge are particularly encouraging. At Princeton it was verified that a tokamak plasma can be heated by adiabatic compression without loss of stability and equilibrium of the plasma could be assured by a relatively simple engineering design. In the ORMAK experiment the plasma was taken much further toward the thermonuclear regime again without loss of stability.

The recently authorized PLT tokamak at Princeton is a significant step along the road beyond the present generation of tokamak experiments. It is estimated to cost $13 million and to be operational in 1975. If successful, it will provide plasma conditions close to those considered necessary to establish the scientific feasibility of tokamak systems.

Magnetic Mirrors - A number of mirror plasma experiments have already exhibited conditions approaching those needed for a reactor. Densities greater than $10^{13} cm^{-3}$ and, in other machines, confinement times of seconds have been achieved. The scientific questions important to mirrors are considered to be well defined, and many of them are being actively studied at this time.

The conditions for stable confinement in mirror systems are being approached in experiments at the Lawrence Livermore Laboratory and at the Oak Ridge National Laboratory. If the present scale experiments continue to show that adequate stability can be maintained as the plasma is made hotter and denser, then it will be necessary to verify that volume effects do not result in deleterious losses and this will require systems of still larger size, closer to those required for a reactor.

It has been recognized that the plasma which leaks out of the ends of mirror systems represents an undesirable energy drain. A few years ago a direct conversion technique to efficiently capture this loss was conceived. In simple terms this concept involved expanding the plasma flow to low density and then allowing the plasma to do work on an externally applied electric field, i.e., as in an MHD system. This concept has been studies on a small scale, and theory and experiment have been found to be in agreement. A larger experiment to more accurately model all of the relevant physics is now under construction to extend these results prior to testing the concept on a large plasma experiment.

Theta Pinches - The theta pinch program is presently centered around the Scyllac experiment at the Los Alamos Laboratory. Its eventual aim is to create and confine a <u>pulsed</u>, high density, toroidal plasma. Scyllac's predecessor, the Scylla IV, was a linear, open-ended system whose thermonuclear plasma (5 keV ions at 5 x $10^{16} cm^{-3}$) decayed classically in the radial direction but was dominated by end losses because of its short coil length (1 meter). One portion of the present Scyllac program involves assembly of a 5 meter straight section with magnetic mirrors to extend the Scylla IV results and to obtain a better understanding of the limits of the linear theta pinch geometry.

In the second half of FY 1973 the remaining ten meters of the Scyllac will begin to be converted to the full 15 meter torus for operation in mid FY 1974. Its principal task will be to demonstrate control of gross plasma instabilities and drifts. If Scyllac operates successfully in FY 1975, confinement will be limited only by the capacitor bank decay time of 250 microseconds, and the extension of theta pinches to the millisecond periods required to demonstrate scientific feasibility would have a high probability of success. Before embarking on a theta pinch feasibility experiment, however, a considerable amount of development of magnetic energy storage and separated shock heating systems will be necessary.

Laser-Fusion

The AEC Division of Military Application conducts a research and development program in laser fusion because of its potential for a number of military needs. However, the basic technology also has potential application to the production of electrical power.

The basic impediment to the demonstration of scientific feasibility of laser fusion has been the pulse energy available with current lasers and that required to obtain net thermonuclear energy release. To date laser outputs have not been sufficient to produce measurable target compressions. KMS Industries, one of two privately supported efforts in laser fusion, has a 1 kilojoule system operating and expects to commence target irradiation at this energy level in 1973. If they are successful in this effort and the experimental results confirm their theoretical projections, they could succeed in achieving scientific breakeven, i.e., that condition where laser energy equals fusion energy released. Even if this point is not realized, valuable information on the absorption and compression phenomena should be obtained. AEC researchers are developing 10 kilojoule laser systems which are virtually certain of producing the breakeven condition unless unexpected difficulties arise.

In addition, the lasers used for civilian power applications must be efficient in terms of the conversion of electrical energy to laser energy. The present workhorse of the program is the Nd:glass laser whose practical upper energy limit is believed to be near 10^4 joules and whose overall efficiency is of the order of 0.1%, which is inadequate for power generation. Efficient lasers with outputs of 10^5-10^6 joules are considered to be necessary for reactor operation, and relatively few choices are presently available, in part because of the early state of the research.

CO_2 lasers appear attractive in this regard in part because they have already been shown capable of efficient, high energy operation. That operation was with long pulses, however (tens of microseconds) versus nanoseconds (10^{-9} seconds) required for laser-fusion. Considerable development from the present few joule, one nanosecond levels will be required.

Pellet design is a second important consideration in laser fusion development. While most of the information in this area remains classified, it is known that rather sophisticated pellets have been developed which cost fractions of a cent, an essential factor in the ultimate goal of commercially viable systems. Still further improvements can be expected as laser system capability increases to the point where more meaningful tests can be performed.

Supporting R&D

The discussion above has focussed on the devices and programs that are the forerunners of the critical experiments on the scientific feasibility of fusion. A number of other areas of research and development are being actively pursued in the fusion program. These include basic plasma research, back-up magnetic confinement research, research device development, and technology development and analysis.

The research category includes both theoretical and experimental studies. Research experiments are aimed at a broad range of relatively basic problems and are conducted on a relatively small scale.

A number of relatively large confinement research programs are included in the category of back-up confinement research. Back-up confinement experiments are often sued to study specific questions which are difficult or impossible to effectively study in main-line systems and are not considered primary approaches to the goal of developing fusion reactors. A number of experiments at various laboratories contribute to this program.

Among the development programs that have contributed significantly to the main research program have been the development of ultra-high vacuum systems, high current ion and neutral beam sources, large-volume, high-field copper and superconducting magnets, sophisticated plasma diagnostics, and fast, high energy capacitors.

The most important development problems which must be faced in the next few year period include superconducting magnets, magnetic energy storage systems, and natural beam sources.

Fusion Reactor Technology

The physics problems of creating, heating and confining a fusion plasma are clearly basic to the feasibility of practical fusion power but many technological problems must also be solved before a practical fusion device is feasible. As a basis for identifying those problems the AEC initiated a series of fusion reactor design studies in the late 1960's. Those studies have been used to develop the technological program elements defined in the next section.

Reference CTR

As a basis for analyzing the impact of fusion power in this study a conceptual design of a full scale tokamak was chosen as a Reference CTR.[30] The principal features of that design, as developed at Oak Ridge, is shown in Figure III-5. The torus structure is divided into six sectors to facilitate construction and maintenance. The figure shows different sectors in various degrees of construction and installation. Note the massive steel reinforcing rings that contain the superconducting coils. The plasma is surrounded by a blanket region approximately one meter thick. Lithium flows through the blanket and acts both as a coolant and a source of tritium. A typical breeding ratio is 1:3 giving a doubling time for tritium of about a month. A set of tubes installed in the lithium blanket utilizes the heat generated in the blanket to boil potassium. The potassium vapor is led out to a potassium vapor turbine in the adhacent turbine hall. The design provides for a net electrical power output from the plant of 518 Mw. To start up the power plant, an initial fuel charge of deuterium and tritium will be needed. Thereafter, a continuous supply of deuterium and lithium will be required

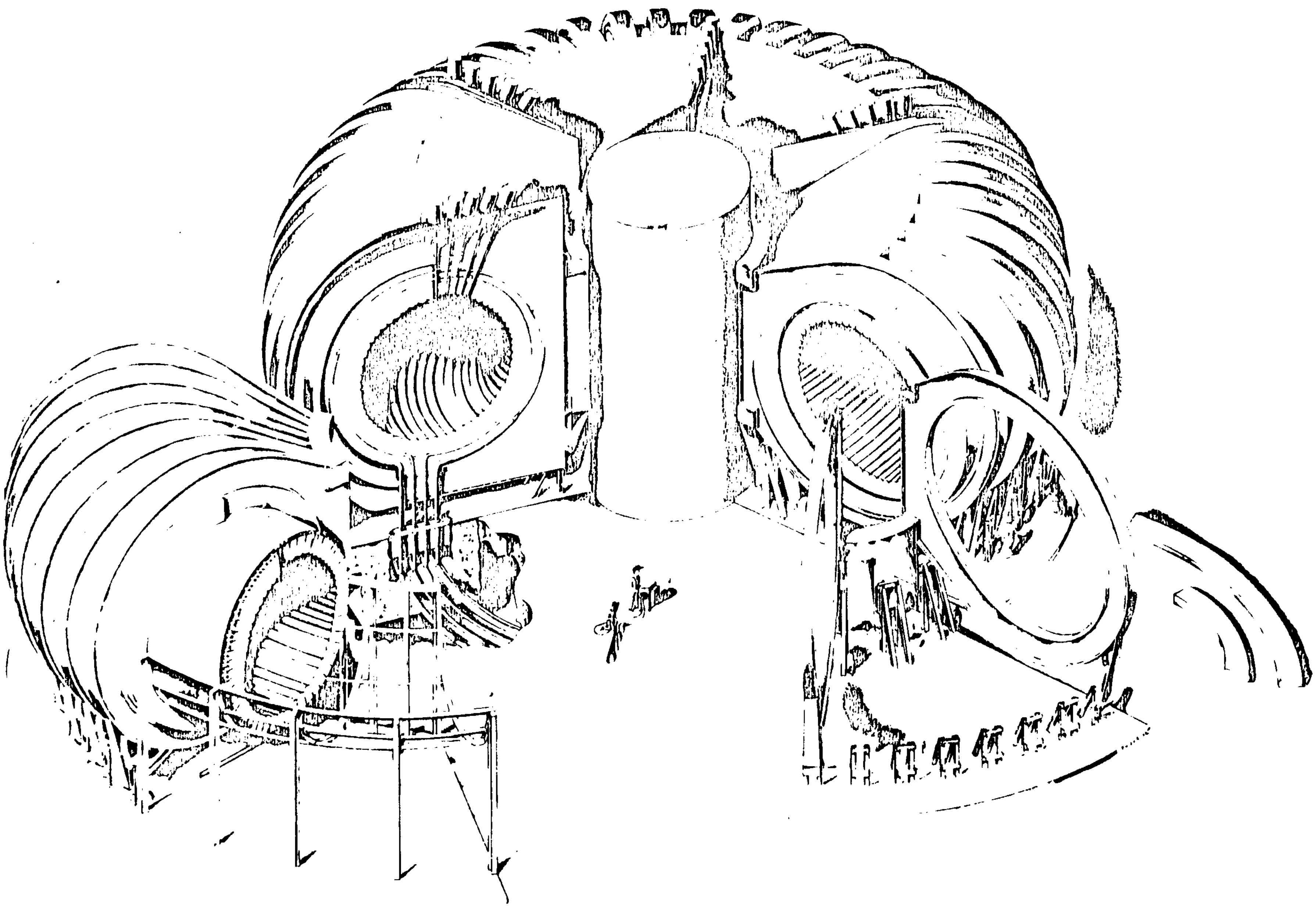

Fig. III-5. Isometric view of an ORNL full-scale Tokamak reactor in the latter stages of assembly. Two partially assembled sectors are shown in the foreground.

at the rate of about a kilogram per day. The blanket structure of the plant will become radioactive and will have a finite lifetime of the order of 10-20 years. It will then have to be shipped for reprocessing or storage.

Conceptual designs have also been made for laser fusion reactors. One such is shown in Fig. III-6.[37] A DT pellet is injected through a port, and is bombarded at the center of the 1 m diameter cavity by a laser pulse. The subsequent (D+T) burn releases 200 million joules (MJ) of energy, more than 150 MJ of which is deposited within the blanket lithium and structural materials.

Within ~0.5 ms the pressure pulses generated by the interaction of the pellet with the lithium at the wetted-wall will subside. Within the next few milliseconds, the cavity conditions are equilibrated and about 1.6 kg of lithium are vaporized from the protective layer at the wall. The cycle time is 1 sec.

The energy deposited within the blanket is removed by circulating the lithium through an external heat exchanger. The thermal power output is about 200 Mw.

PROGRAM RECOMMENDATIONS

The planning of R&D for a technology which is in a very early state of development is quite different from that for a near term technology. The large basic uncertainties involved discourage work on long term development problems and force attention to immediate research problems. It is difficult to justify work on the engineering aspects of a particular fusion reactor design before one knows what designs are possible or most desirable from the physics standpoint. On the other hand, in all potential designs one can see engineering and materials problems that are going to require lengthy programs to resolve. It must remain a matter of judgment (under considerable uncertainty) as to how much effort should be devoted at any time to the resolution of long term development problems relative to the piercing of current scientific barriers. This balance must be a central element in the continual reassessment of a program such as fusion.

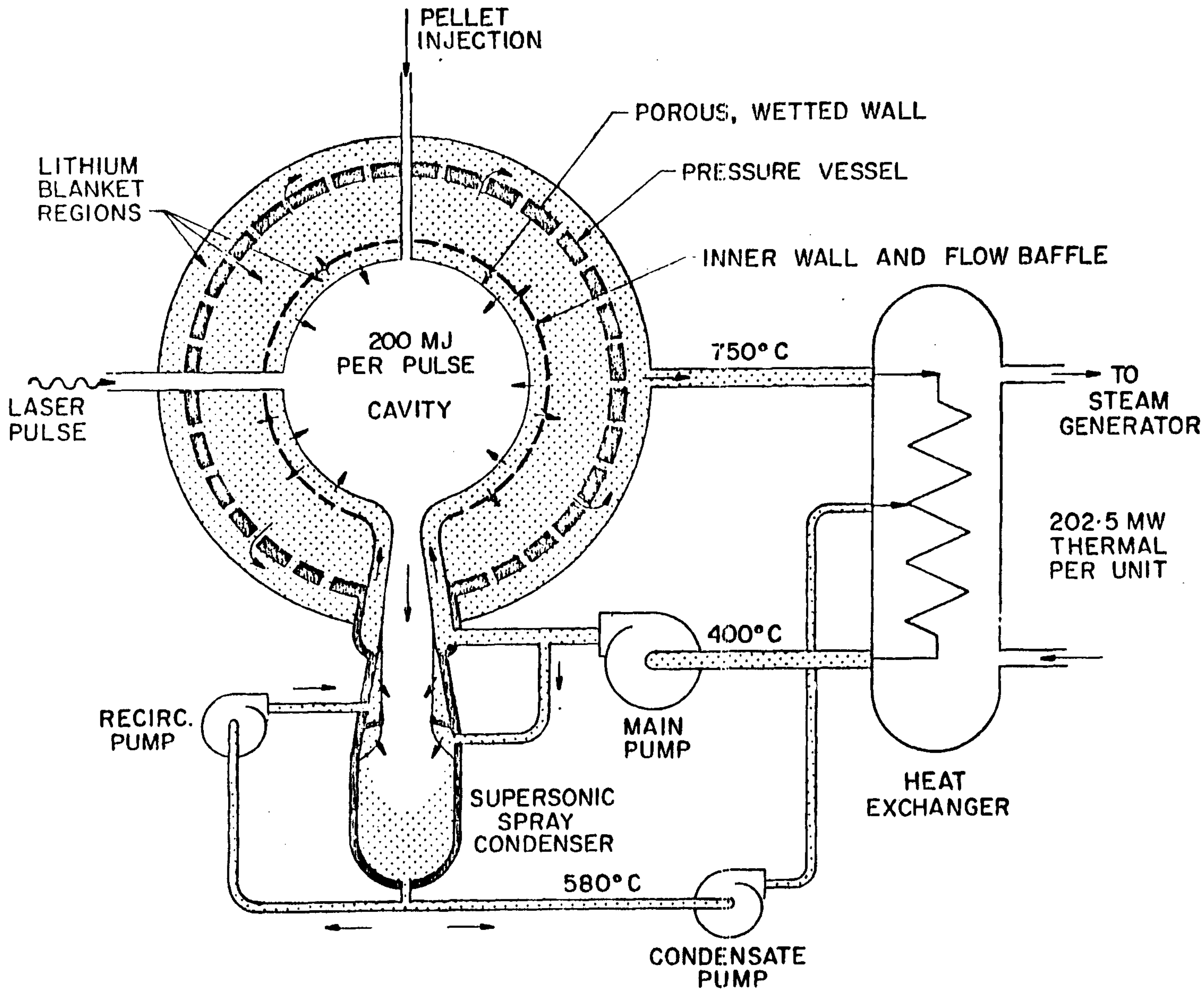

Fig. III-6. Schematic of a Laser-Fusion Reactor Design.

Device Development

Given the current situation in the three main approaches to magnetic confined fusion, all warrant continued development toward tests of scientific feasibility around 1980. Current AEC technical plans appear well designed toward that end.

For toroidal systems the next step beyond the PLT tokamak would be a full scientific feasibility experiment. Such as experiment is estimated to have a capital cost of about $50 million and would require 3-4 years to fabricate. Under the program assumptions adopted for this study, this experiment would not be authorized before FY 1977 and therefore would not operate before about 1981-1982. Among the major supporting activities which will be necessary for future generations of tokamaks are the development of large bore, high field superconducting magnets and quite possibly the development of higher current neutral particle beam sources.

A feasibility experiment for mirror systems is projected to have a capital cost of about $30 million and would represent a significant scale-up in magnet field intensity, plasma volume, and plasma temperature from the present Baseball II experiment. Before such an experiment is initiated, however, further advances are required in the production of neutral beams and superconducting magnet technology.

In pulsed systems, the Scyllac facility should provide a firm stepping stone to a feasibility experiment. Before starting such an experiment, however, an additional concept must be verified. At present the shock heating and compression characteristics of theta pinches are accomplished in a single step. It appears advantageous to modify this to a two step sequence in order to simplify the energy storage requirements. The required experimentation is projected to require about 3 years so that full scientific justification for a theta pinch feasibility experiment would not be possible before FY 1976. The capital cost of such an experiment is projected to be about $30 million.

Although it would be unwise to concentrate on only one of the three approaches at this point, with the passage of time budgets of the less attractive schemes should be transferred in part to the more attractive ones. By about 1975 enough additional physics may have been learned so that a significant concentration on one or at most two approaches could be effected.

An appropriate budget for magnetic confinement research is $30.1 million in FY 1974 which would include $4.3 million devoted to major device fabrication.

Laser Fusion

Although laser fusion avoids the difficult confinement problems which have challenged plasma physicists for many years in the CTR program, it presents different and equally complex problems in plasma physics and laser development. The most immediate objectives of the program are to verify experimentally the theoretical predictions of energy absorption and interface stability which relate to the laser beam-pellet coupling. KMS results should be revealing in this regard in the near future. It is likely that some refinement in computer codes will be required based on the early experimental results. The AEC program in this area seems adequately funded at the present time.

The critical component in a commercially viable laser fusion system will be the laser. Neodynium glass lasers do not appear satisfactory for power reactor systems. It is thus necessary to develop a laser which produces several hundred kilojoules of energy at wavelengths as low as or lower than the neodynium laser over nanosecond intervals. It must have a high repetition rate, reasonable life and maintenance requirements and sufficiently high electrical to light conversion efficiencies to make the system economically viable. New laser media are being discovered regularly, and it does not seem unreasonable that a sustained effort in a relatively immature field such as lasers will produce promising results within the next decade.

Pellet development is also essential to a commercial system, but much progress appears to have been made already. Irradiation experiments should provide further guidance as to the additional refinements which may be necessary. The development of optics to provide uniform irradiation and protection of the laser from back scattered radiation must also be pursued.

Reactor design, while substantially less complex than for magnetically confined systems, must provide for fatigue failure associated with severe pulsing conditions. Other design considerations, such as radiation damage and energy removal, are similar to magnetic systems except that they are uncomplicated by the need for large superconducting magnets. Experimental and demonstration reactors for laser driven systems will likely be smaller and less costly than those for magnetic confinement systems, but this could be offset by laser costs. The present funding level of the Federal program provides for a substantial investment in laser facilities. Once these are completed a slight reduction may be possible until such a time as experimental reactor development commences. Military applications may, however, justify investments over and above those deemed appropriate for power purposes.

Supporting R&D

Work in the research category is basic to the development of fusion. The current allocation of about 20% of the total program funds to this area is appropriate. In recent years the center of gravity of supporting research has been shifting from the national laboratories to the universities and to industry. Such broadening is to be encouraged in all appropriate areas of the program.

Work should be expanded considerably on the development of superconducting magnets and magnetic energy systems and neutral beam sources. These activities will have a major impact on the speed with which scientific feasibility experiments can proceed. In addition, advanced normal-conducting magnet systems warrant more serious attention. A number of other technologies which will require development work include high current switches, r.f. energy sources, direct energy converters, plasma diagnostics and feedback control systems. A funding level of $10.4 million ia appropriate for this work.

Fusion Reactor Technology

More attention must be paid to understanding and beginning to resolve some of the technological problems connected with practical fusion power systems.

Superconducting magnet systems will be required for magnetically confined plasma systems and will represent a significant fraction of the total capital cost. In addition to the development of magnets for feasibility experiments, there is a strong incentive to develop new, ductile, high-field, low cost, easily fabricated superconducting materials. This and a back-up program on very low-resistance materials for pulsed applications also appears desirable and should be supported under fusion reactor technology.

Increased effort also should be devoted to pulsed cryogenic energy storage, radiation damage studies, tritium containment and the many problems associated with coolants and blanket design.

The level of support for these activities should be increased to $5 million.

Program Summary

Table III-16 summarizes the program elements discussed above. The total budget of $55 million is that which is deemed necessary to make adequate progress toward the demonstration of scientific feasibility by around 1980 and, at the same time maintain a balanced program in terms of the long run. It must be recognized that, given the early stage of development of fusion technology, any plan that can be specified at this time is subject to major reprogramming as the program evolves and as the relative merit of various approaches change. The total amount required through FY 1980 will be on the order of $700-800 million. Although such matters are obviously highly speculative, at this point an estimate of the total cost to commercial feasibility around the year 2000 is $5 billion if success is achieved at the critical junctures along the way.

IMPACT OF IMPLEMENTATION

The successful completion of the development program outlined above would lead to the commercial availability of fusion power plants around the year 2000. It should be emphasized that such an accomplishment requires the successful resolution of a very large number of scientific

Table III-16

SUMMARY OF FUSION PROGRAM

Program Element	Current R&D Objective	First-year Cost $ Million	Long-term Cost $ Million/9 Years
Confinement Research	Demonstrate scientific feasibility		
Operations		25.8	427
Major Device Fabrication		4.3	81
Supporting R&D			
Plasma Research	Understanding of plasma behavior	9.5	116
Development	Develop superconducting magnets, energy systems, beam technology	10.4	168
Reactor Technology	Develop superconducting materials, energy storage, radiation damage studies, etc.	5.0	211
	Total	$55.0*	$1003/9 years

* Laser Fusion funding not included - Program funded under Military applications.

and technical problems along the way. It does not, however, count on improbable break-throughs.

If a growth pattern similar to that projected for the LMFBR is assumed, fusion could be producing 18% of the electricity generated in the year 2020. This corresponds to a third of the capacity installed between the year 2000 and 2020. For simplicity it is assumed that the fraction of generation corresponds to the portion of installed capacity. Table III-17 indicates the installed capacities assumed.

Resource Effects

The effect on the consumption of resources of the introduction of fusion power is readily derived from the perturbed energy system and is shown in Table III-18. If fusion power is as successful as would be indicated by the sort of implementation assumed here, its rate of implementation in the year 2020 would be very large. Thus the effects calculated would be increasing quite rapidly.

As shown in the Table, the reference implementation of CTR reactors would consume about 77 tons of Li per year. The initial charge of Li would be about 900 tons for each 1000 MWe reactor. The known and inferred reserves of lithium in this country are about 100,000 times the estimated 2020 consumption rate. This amount can be multiplied by another factor of 50,000 if extraction from seawater is considered feasible. In any event the supply of fuel seems to present no difficulty, even in the long term.

Many other relatively rare materials such as niobium, titanium, and beryllium may also be required, depending on the specific design, but no severely limiting materials supply problem is apparent.

Environmental Effects

At the present time the environmental effect which would appear to be of greatest concern is the production of tritium. Prevention of tritium leakage from a fusion reactor is an important and difficult requirement. The tritium inventory of the reference CTR is 6 kg, or 58 million curies. Assuming that tritium leakage is to be discharged

Table III-17

Installed Capacity for
Central Station Power Plants
(in 1000 MWe Units)

Year	Type of Plant		Reference Energy System Projection	Reference Energy System Projection Modified to Include Fusion
2000	Fusion		0	0
	Light Water Reactor		407	407
	Breeder Reactor		422	422
	Other		807	807
		Total	1636	1636
2010	Fusion		0	247
	Light Water Reactor		432	389
	Breeder Reactor		926	834
	Other		1126	1014
		Total	2484	2484
2020	Fusion		0	644
	Light Water Reactor		443	365
	Breeder Reactor		1739	1430
	Other		1446	1189
		Total	3628	3628

Table III-18

IMPACT OF IMPLEMENTATION OF FUSION POWER IN THE YEAR 2020

Based on fusion replacing 18% of electric generation and 23% of the residential-commercial space heat requirements (see text).

Impact Area	Percent Change from Reference Energy System
Resource Consumption	
Nuclear	-18
Coal	-15
Oil	-3
Natural Gas	-7
Other	77 metric tons Li/year and possible significant use of Nb, Be, Ti, He, Ph, Va and Mo.
Environmental Effects	
Air Pollutants	
CO_2	-11
CO	-1
SO_2	-14
NO_x	-8
Particulates	-5
Hydrocarbons	-1
Radioactive Materials	
Tritium	-10[a]
Krypton-85	-18
Rad Waste	-18 with production of 11×10^6 curies of Nb-93m/year.

[a] Based on release of 0.0001% of inventory per day, total release of 2.8×10^6 curies/year.

from a 200-foot high stack, to keep the radiation dose from tritium below 1 mrem/yr at ground level downwind of the stack requires that tritium leakage be kept below one millionth of the plant inventory per day. Experience with the Molten Salt Reactor Experiment has shown that tritium diffuses rapidly through metal walls at high temperatures and suggests that it may be difficult to control leakage of tritium from the blanket and other high-temperature components of a fusion reactor.

The primary source of radioactive waste from a fusion reactor will be the activated structural material of the blanket, which will have a finite useful lifetime within the reactor owing to radiation damage. Approximately 9000 Ci/MW-yr of long-lived radioactivity would be produced in the niobium structure of the Reference CTR. If vanadium were substituted for niobium, this activity would be reduced by a factor of 1000-10,000 depending upon the type and concentration of alloying material.

Studies of the afterheat produced in the Reference CTR indicates that it is possible to evolve a design that is virtually unaffected by a loss-of-coolant accident. The inventory of volatile radioactive material is probably the most important factor to be considered in appraising the hazards from other accidents. For a fusion reactor this means that the tritium inventory, particularly the active inventory in the liquid metal system, is the most vital consideration because it will be the only volatile activity present. By holding the tritium concentration in the lithium to 1-10 ppm and isolating the lithium and tritium handling equipment in a single, well sealed and monitored compartment, this potential accident hazard can be kept very low.

Other Factors

The national security aspects of fusion power tend to be positive. There is no dependence on foreign sources of fuel and, furthermore, a potential for exportation of technology. Some reliance on foreign sources of materials such as nickel and chromium will be inherent to fusion as well as many other power sources. Although fusion reactors do not utilize fissionable materials which may be subject to diversion for clandestine purposes, tritium inventories may present a safeguard problem.

It is too early to have any confidence in estimates of the cost of fusion power. The estimates that have been made, however, are not discouraging in this regard.

I. HYDROGEN AND OTHER SYNTHETIC FUELS

INTRODUCTION*

The larger fraction of today's energy needs are served by the general-purpose fuels, oil, and natural gas. In view of anticipated domestic shortages of these energy sources, the possible role that synthetic fuels may play as general-purpose fuels in both the near and long term is of considerable interest. Methane, gasoline, and other oil products derived from oil shale or coal have been the subject of other intensive investigations, and research and development options for this class of fuels are discussed elsewhere. The discussion here will focus on another class of synthetic fuels; those that may be derived from both fossil and non-fossil sources. Synthetic fuels are of interest primarily because they may be derived from the more abundant solar, nuclear, or thermonuclear resources and do provide a convenient fuel form for transport, storage, and ultimate utilization. Thus, they provide promising alternates for supplying the long-term needs for gaseous and liquid general-purpose fuels.

Synthetic fuels, as considered in this study, consist of hydrogen obtained from water and synthetic fuels containing hydrogen such as methanol, ammonia, and hydrazine. The production of hydrogen may be carried out by electrolysis or, perhaps, by the thermal decomposition of water using any of the more promising clean energy sources. It should be recognized that, in the near term, hydrogen and fuels derived from hydrogen can, and most likely will, be made more economically by the direct conversion of fossil resources or possible from urban and agricultural waste products.

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* This section is based in part on the Panel report - References 38 and 39.

Because of low transport costs for gaseous and liquid fuels as compared with electricity, synthetic fuels may be produced at remote, well-regulated plants, and such production would not contribute to the primary pollution problems that exist in urban centers. The synthetic fuels, especially hydrogen, may be consumed with very little or no air pollution in a variety of energy conversion and utilizing devices for both stationary and motive power. This low pollution characteristic of hydrogen energy systems is particularly attractive for urban applications.

Specific applications of hydrogen, and synthetic fuels derived from hydrogen, include central station energy storage, used as general-purpose fuels for heating and industrial processes, and for automotive and aircraft propulsion. Hydrogen is at present an important chemical for oil refining and desulfurization. The main obstacles to its use in other applications at the present time are its high cost relative to oil products and natural gas and, for motive applications, difficulties in storage of the fuel as a gas or liquid. Safety considerations are important and must be addressed in any development program dealing with specific applications.

For central station electric storage, hydrogen could be produced by the electrolysis of water during off-peak periods, stored, and subsequently used to fuel a gas turbine or a fuel cell to produce electricity during periods of peak demand. In this mode of operation the system could provide an alternate to pumped storage systems for which available sites are quite limited.

Hydrogen, methanol, and ammonia have been used successfully in automotive engines. For the near term, methanol would be a relatively clean fuel and would be more compatible with existing storage and distribution facilities. In the long term, as storage and delivery systems are developed, hydrogen might be preferable from the environmental viewpoint.

CURRENT STATUS OF SYNTHETIC FUEL TECHNOLOGY

The current status of synthetic fuel technology will first be discussed in terms of the sequence of activities required to deliver the fuel form to a consuming sector. These activities are production, storage, and transportation. The status of utilization technologies, safety, and economics will also be reviewed. For reference purposes the comparative characteristics of synthetic fuels are shown in Table III- 19. The characteristics of methane and gasoline are also included in the table.

Production

Perhaps the most critical factor influencing the commercial viability of an energy system based on synthetic fuels resides in the production system, particularly in terms of the cost, environmental effects, and primary resource consumption. The principal processes that are currently used for producing hydrogen use water electrolysis and the partial oxidation or reforming of fossil fuels. Other processes which are now in the research and development phase use thermochemical, radiolytic, and biological production techniques. A combined process involving first a thermochemical reaction between chlorine and water, followed by the electrolytic separation of hydrogen and chlorine has also been proposed.

Hydrogen may, in turn, be converted to other fuel forms to provide a more convenient material for special applications. The production of ammonia, methanol, and hydrazine from hydrogen is discussed below following the review of hydrogen production processes.

Water Electrolysis - Water electrolysis is accomplished by the passage of a direct current between two electrodes immersed in an electrolyte (usually a potassium hydroxide solution). Hydrogen is formed at the cathode and oxygen is formed at the anode in direct proportion to the current passing between the electrodes.

Ideally, about 18 kWh/lb H_2 would be required for the electrolytic process at the standard pressure and temperature conditions. Inefficiencies in the process, attributable to ohmic losses at the electrodes

Table III-19

Comparative Characteristics of Synthetic Fuels

Fuel	Heat of Combustion Btu/1b	Heat of Vaporization (at boiling point) Btu/1b	Density			Boiling Point ^oF
			Liquid $1b/ft^3$	H_2[a] lbs H_2/ft^3	Gas(STP) $1b/ft^3$	
Hydrogen (H_2)	51,600	194	4.4	4.4	.005	-423
Ammonia (NH_3)	8,000	590	42.6	7.8	.043	- 28
Hydrazine (N_2H_4)	7,200	540	62.4	8.9		236
Methanol (CH_3OH)	8,600	474	49.7	7.1		149
Methane (CH_4)	21,500	220	25.9	6.5	.041	-259
Ethanol (C_2H_5OH)	11.600	360	49.7	6.5		173
Gasoline (C_8H_{18})	19,100	140	43.8	7.0		257

[a] Density of hydrogen in the fuel.

and in the electrolyte, increase the typical energy requirement for current plants to about 24 kWh/lb H_2.

The economics of electrolytic hydrogen are determined by the capital cost and utilization of the electrolysis plant and by the cost of electrical power. The capital cost of current large-scale plants is about \$95/lb H_2/day. At a fixed charge rate of 15% and a 90% plant factor, the capital charge is equivalent to 4.3¢/lb H_2 or 84¢/10^6 Btu, assuming no credit for by-product oxygen. At an electric power cost of 5 mils/kWh, the power cost in terms of hydrogen produced is about 10¢/lb H_2, resulting in a total cost, excluding labor, maintenance, and overhead costs, of 14.3¢/lb H_2. The cost of electrical power depends, of course, on the type of generating plant providing the power and on the rate structure. Power may be obtained at a very low cost during off-peak demand periods and at a higher cost during periods of peak demand on the electric generating system.

Although water electrolysis is already a relatively efficient process it does appear that further improvements may be achieved through research and development. It may be possible to reduce the energy requirements to around 13 to 15 kWh/lb H_2 with an attendant decrease in the portion of the cost of hydrogen attributable to the input electric power. There is relatively little R&D in progress on water electrolysis at the present time. Some work is being done in industry on lowering cell fabrication cost and on improving their performance and lifetime.

Thermochemical and Radiolytic Production - Thermochemical production of hydrogen involves the decomposition of water via the application of thermal energy. The decomposition may be accomplished in a single direct chemical reaction requiring extremely high temperature (greater than 1500°C), or it may be carried out via a sequence of chemical reactions whose net result is the production of hydrogen and oxygen. The potential advantages of a direct thermal decomposition process over the electrolytic process is the avoidance of the intermediate conversion step to electricity. Although thermochemical cycles also are limited in efficiency by the laws of thermodynamics, higher temperatures, and thus higher efficiencies, may be attainable than are reached in steam-electric generating plants. Several thermochemical processes have been proposed and are under study. It has not yet been demonstrated that a thermochemical process may be competitive with electrolysis; however, neither can the possibility of such an advantage be ruled out. The major uncertainties regarding these processes involve the basic thermodynamic and kinetics data for proposed reactions.

Radiolytic production of hydrogen involves the direct absorption of energy from fission fragments and gamma or other nuclear radiation, by water to produce hydrogen and oxygen which must then be separated.

Biological Production of Hydrogen and Other Synthetic Fuels - Biological processes have been in use for the production of synthetic fuels in a limited manner for many years. Primarily examples are the generation of methane from sewage and the fermentation of grains and sugars to produce alcohol. It is also possible to use photosynthetic organisms in a photochemical fuel cell to prdouce hydrogen. The energy requirements for an aqueous system of this type would be supplied by light, using a stabilized photochemical apparatus capable of generating reductants from water ferredoxin or a similar electron carrier, and a ferredoxin-coupled hydrogenase. The critical characteristics of this system that will determine whether it may be economical is the overall conversion efficiency of light to the output energy form.

Hydrogen Production from Fossil Fuels - Most of the current hydrogen production is via steam reforming of natural gas and naptha. Hydrogen may be produced at a cost of about 5¢/lb when the price of natural gas is $40¢/1b^6$ Btu. In the longer term, as gaseous and liquid hydrocarbon resources are depleted, production directly from coal appears to be more desirable. Two methods for converting coal to hydrogen are the steam-oxygen (Synthane) process and the CO_2-acceptor process. When coal is reacted with steam at 450 psi and 1600 to 1800^oF, the principal gaseous products are CO, CO_2 and H_2. In addition, small amounts of CH_4 are produced. The CH_4 yield increases with pressure and becomes a major product at 1000 psi. The coal-steam reaction is highly endothermic and a large input of heat is required.

In the steam-oxygen process for production of hydrogen from coal this heat is supplied by adding pure oxygen to the steam; the oxygen-coal reaction producing CO, CO_2 and heat. The CO produced in both the coal-steam and coal-oxygen reactions is then reacted with additional steam in a shift reactor to produce more hydrogen and CO_2. The CO_2 is removed by scrubbing the final gas.

In the CO_2-acceptor process, lime (CaO) is introduced with the coal being reacted with steam (no air or oxygen is added). The CO_2 in the reaction product gas is removed by the lime as rapidly as it is formed to produce calcium carbonate ($CaCO_3$). In the absence of CO_2, the shift reaction occurs in the main reactor, thereby minimizing or eliminating entirely the need for an external shift reactor and CO_2 scrubber. The necessary heat to support the coal-steam reaction is supplied by both the shift reaction and the absorption of CO_2 on the lime.

Hydrogen production is a major process in all of the coal gasification schemes that are now under development as sources of methane. The most advanced hydrogen production process that uses coal and is commercially available is the Lurgi steam-oxygen process. The objectives in the further development of these processes are a scale-up in unit size and improved conversion efficiency.

Ammonia and Methanol - Ammonia is produced by direct catalyzed synthesis from hydrogen and nitrogen (2000 to 5000 psi and 200 to 500^{o}C). The basic process has been in commercial use for many years and is considered to be a highly developed technology. The only significant future change that is anticipated is the use of new sources of hydrogen. The present low cost of ammonia is dependent to a great extent on the use of low cost natural gas. As natural gas is depleted and costs increase, hydrogen production from steam-naptha reforming and partial oxidation of various petroleum fractions will become more competitive.

Methanol is produced by reacting synthesis gas (composed of carbon monoxide, carbon dioxide, and hydrogen in the proper proportions) at various temperatures and pressures in the presence of a catalyst. Essentially all methanol manufactured in the U.S. is based on natural gas. Carbon dioxide is usually added to the feed to balance the excess hydrogen in natural gas.

Storage and Transportation

Synthetic fuels are of interest for the most part because they may be more conveniently stored and transported than electricity, which would be the most viable long term alternative when oil and natural gas resources are depleted. None of the synthetic fuels discussed here, however, is quite as easily stored and transported as those general-purpose fuels that we are now dependent upon.

The energy storage characteristics of hydrogen, methanol, and ammonia compared with those of gasoline and methane are apparent from the data given in Table III-19. Hydrogen may be stored as a pressurized gas, as a liquid, or in a chemical compound as a metal hydride. Most metal hydrides have a higher hydrogen atom density than liquid hydrogen and thus are quite competitive with that mode of storage on a volume basis although there is a weight penalty associated with the metal in the hydride compound. Furthermore, many hydrides may be decomposed at or near room temperature simply by adding the heat of decomposition, so that the need for cryogenic or high pressure systems is avoided.

Hydrogen gas is distributed by pipeline in refineries and petrochemical plants. Studies of long distance pipeline transmission indicate that it will cost about 2.6 times as much to transport hydrogen as compared with natural gas at the same operating pressure. By increasing the pipeline pressure from the usual 750 to 2000 psia this factor could be reduced to about 1.5. The increased cost of hydrogen transport is attributable to its lower heating value and increased pumping power requirements.

Pipeline transport of liquid hydrogen is far too costly to be competitive with other methods of energy transport except for special purposes and over short distances. However, with high capacity superconducting or cryogenic electric transmission lines, the simultaneous transmission of liquid hydrogen through the cryogenic conduit could be a viable concept.

The use of ammonia in the production of fertilizers has reached a scale where large interstate pipelines are in operation along with extensive barge, rail, and truck distribution systems. Because of the seasonal nature of the demand for agricultural chemicals, large storage complexes have also been developed.

Methanol has long been a basic petrochemical used in tonnage quantities and distribution by all means has been fully developed. Among the synthetic fuel candidates under consideration here, methanol is the most compatible with existing heating oil and motor fuel transport and distribution systems.

Current R&D work on the storage and transport of synthetic fuels in liquid and gaseous form is directed at marginal improvements in existing technology.

The metal hydrides appear to offer a promising storage technique for mobile as well as stationary applications. Several ternary alloy systems have been evaluated but the search has by no means exhaustive.

Use of Synthetic Fuels

The present usage of hydrogen, ammonia, and methanol is almost exclusively in the industrial sector. Of the 2.06 trillion cubic feet (5.8 million tons) consumed commercially in 1968, 42% was used for ammonia synthesis, 38% in petroleum refining and 20% for other uses including synthesis of methanol, naphthalene, cyclohexane, benzene, aniline, aldehydes, and hydrochloric acid, and for the hydrogeneration of unsaturated fats and oils.

Hydrogen is used in two ways in petroleum refining: (1) in hydrotreating (using catalytic reforming) for desulfurizing petroleum feedstocks, for hydrogenating olefins and other unsaturated hydrocarbons and for producing cyclic compounds such as cyclohexane, and in treating lube oils and kerosene-base jet fuels, and (2) in hydrocracking heavy petroleum fractions to produce lighter grades, principally gasoline. In fact, about half of all petroleum currently processed in the U.S. is so converted to gasoline. Use of hydrogen in petroleum refining is expected to increase rapidly in the future and to surpass the amount used for ammonia synthesis before 1980.

The coal gasification processes that are under development for the production of high-Btu gas require large quantities of hydrogen. In this case hydrogen is required to react with CO and, if an external source of economic hydrogen is available, it could be used for this purpose rather than consuming coal to produce the hydrogen. In this case coal would be partially oxidized, perhaps with by-product electrolytic oxygen, to CO, then converted to methane. An alternative process, hydrogasification, may be used wherein hydrogen is reacted directly with carbon at high temperatures to produce methane.

Use of hydrogen as a metallurgical reductant <u>in lieu</u> of carbon (coke) has long been known to be feasible; however, only very limited use has been made of this technology so far. Since the production of iron (89 million tons in 1968) far overshadows the production of all other metals combined, hydrogen reduction of iron ore is of greatest significance in this area. Several processes have been developed; however, none are yet economically competitive with the conventional blast furnace.

Over two-thirds of all ammonia consumed in the U.S. is used directly or indirectly as fertilizer in agriculture; the remainder is used in petrochemical synthesis, inorganic chemicals and plastics manufacture, as a refrigerant, and in a variety of smaller uses. The natural gas requirement for the projected 1985 ammonia production will be about one trillion ft^3. In terms of hydrogen usage, this production rate would require about 12,000 tons/day of hydrogen capacity.

Many studies have been performed of the "hydrogen energy economy" in which hydrogen would play a major role as a general-purpose fuel for residential and commercial uses, for aircraft and automotive transport systems, and as a storage medium for central station electric systems. Both aircraft and automotive engines have been operated successfully on hydrogen. Such end uses would be stimulated more by advances in hydrogen production and delivery technologies than by further development work on end use technologies.

PROGRAM RECOMMENDATIONS

The emphasis in a research and development program should be placed on the production, delivery and storage technologies that are critical in opening up the synthetic fuels as a viable option for general-purpose energy application. Although the future role of hydrogen, and synthetic fuels derived from hydrogen, in the nation's energy economy requires additional study, it is clear that hydrogen is an important material in oil refining, coal gasification, and central station electric storage applications. In addition to work on production and storage systems, research on general safety problems is warranted.

Production

The program for the production of synthetic fuels should emphasize electrolytic, thermal decomposition, and biological techniques for hydrogen generation.

For electrolytic devices the objective is to reduce energy requirements and production costs. One promising area for R&D appears to be in increasing the cell operating temperatures up to about the 350°F level. Specific tasks include research to find satisfactory separator, gasketing, and insulating materials, the development of improved power conditioning equipment, and the investigation of high current density devices such as flow through electrodes. A vigorous development effort should point toward a 10 MWe modular unit that would form the basic building block of a 100 MWe demonstration plant to be built at some future time.

Research on thermochemical and biological hydrogen production processes should address the basic thermodynamic, kinetic, and biological data that are required to perform realistic process designs and evaluations.

It is estimated that a program with the objectives outlined above, but not including the large demonstration plant would involve a total expenditure of about $17 million over a 6-year period, starting with a $1 million budget in the first year.

Storage

In view of the advanced state of development of storage techniques for liquid hydrogen, ammonia, and methanol, any further research and development activity should include the investigation of alternative methods of storing hydrogen. The objective of such work should be to provide safe and convenient systems for both small portable storage applications and large-scale storage systems such as may be required for central station electric storage.

A promising alternative for both small- and large-scale storage is the metal-hydride system. Work in this area should include an extensive survey of alternate materials and determination of the thermodynamic, and mechanical properties of selected materials.

A total of about $3 million would be required over a 5-year period to accomplish this work. About $300 thousand would be needed during the first year.

Miscellaneous

Detailed studies of the various applications for synthetic fuels are required to determine how they may best be employed within the nation's energy system and to define any safety problems that may be limiting so that the required research may be performed. Some component development work should be done on fuel cells and hydrogen-oxygen turbines for power generating applications, however, specific programs for such work are discussed in the section on Advanced Cycles for Power Generation. Demonstration programs will ultimately be required for specific applications; however, such projects are not within the scope of the programs that are outlined here.

The system studies and safety research could be performed over a 5-year period with a total budget of about $3 million starting with a support level of some $200 thousand in the first year.

Program Summary

Table III-20 presents a summary of the program elements discussed above including estimated funding levels for the achievement of the objectives outlined.

IMPACT OF IMPLEMENTATION

Although the general R&D program outlined in the previous section does not deal with any specific applications, several have been selected for impact analysis in order to identify some of the potential benefits of the successful implementation of hydrogen energy systems.

The following implementation cases were considered and analyzed in terms of the year 2000 Reference Energy System:

1. Hydrogen, generated with off-peak electric power available from the reference mix of generating facilities is used for automotive or aircraft propulsion. Each of these uses is considered separately.
2. Hydrogen is produced and used as in case 1, except that all of the electric capacity used to produce off-peak hydrogen is converted to nuclear generation.
3. Hydrogen is produced from coal and used in the automotive sector.
4. Hydrogen is produced by electrolysis at remote-sited nuclear plants, distributed to urban areas, and reconverted to electricity in gas turbines or fuel cells. It is assumed that 20% of the electrical energy delivered in the year 2000 reference case is distributed in this manner.

The estimated perturbations on resource consumption, cost and environmental effects are summarized for these cases in Table III-21.

TABLE III-20

Summary of Synthetic Fuel Program

Program Element	Current R&D Objective	First Year Cost $ Million	Long-term Cost $ Million/Year
Production	Increased efficiency and reduced cost	1.0	17/6
Storage	Development of metal hydrides	0.3	3/5
Systems Analysis	Study specific hydrogen energy systems and safety aspects	0.2	3/5
	Total	$1.5 million	$23 million/6 years

TABLE III-21

Impact of Hydrogen Energy System Implementation,
Percent Change from Reference Energy Systems

Resources	Perturbed year 2000 Reference off-peak generation of hydrogen for transportation systems		Perturbed year 2000 All-nuclear off-peak electric generation of hydrogen for transportation		Perturbed year 2000 Gasification of coal to hydrogen for transportation	Perturbed year 2000 Gas turbine electricity from nuclear hydrogen
Coal	+30		-73		+27	-28
Oil	- 7		-20		-11	- 5
Natural gas	+ 9		+ 2		0	- 8
U^{235}	+21		+110		0	+78
U^{238}	+23		+120		0	+83
Environmental effects	Automotive utilization (or)	Aircraft utilization	Automotive utilization (or)	Aircraft utilization	Automotive utilization	Central station electric emissions
(a) Fossil fuel						
CO_2	+10	+11	-34	-34	+ 6	-16
CO	-13	-17	-15	-20	-14	- 1
SO_2	+30	+29	-55	-56	- 1	-29
NO_x	+17	+14	-31	-34	0	-16
Particulates	+ 6	- 0.2	-16	-22	- 2	- 8
Hydrocarbons	- 3	-32	- 8	-36	- 4	- 2
Aldehydes	+ 3	-15	- 6	-25	--	- 4
(b) Radioactive						
T	+23	+23	+120	+120	0	+84
Kr	+23	+23	+120	+120	0	+84
Solid high-level waste	+23	+23	+120	+120	0	+84
Population exposure	+23	+23	+120	+120	0	+84

J. ELECTRICAL TRANSMISSION AND SYSTEMS

INTRODUCTION*

As shown in Chapter II, electrical energy consumption is expected to continue to grow even faster than total energy use. The reference electrical energy production in the year 2000 is more than five times that produced in 1969. Among the technologies considered in this study, and thus not included in the Reference Energy Systems, many are means of producing electricity. This is as true in the long term (e.g., fusion and centralized solar energy) as it is in the short term (e.g., geothermal energy and nuclear breeders). The basic reason for this is clear. Electricity provides a convenient channel for new technology; the electrical link in the energy system allows any energy form convertible to heat to be applied to a number of end uses. Many exotic energy forms such as nuclear fission and fusion, although capable of producing heat, cannot do so at the small scale necessary for most uses.

Efficient and inexpensive electrical transmission can also introduce a significant element of flexibility into the system. It could facilitate the utilization of resources at large distances from load centers. It could also provide important freedom in the siting of large power plants.

In addition to the reduction of cost and increasing efficiency, a further challenge to R&D in transmission is presented by the figures presented in Table II-8. The lion's share of land use projected for the energy system is for transmission line rights-of-way. This, and the visual impact associated with it, is the primary environmental problem faced by transmission. Current means of solving this problem, by placing transmission lines underground, are expensive--in many cases prohibitively so.

In addition to the specific technical problems of transmission and distribution, problems related to overall transmission networks and systems are becoming of increasing concern. The rapid growth in size

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* This chapter is based in large part on the report of a study group chaired by F. F. Parry, Department of the Interior (see Reference 40 of the bibliography). See also References 41-45.

and complexity of electrical power systems is creating control problems of a difficulty not previously encountered.

CURRENT STATUS OF TRANSMISSION AND CONTROL TECHNOLOGY

UHV AC Overhead Transmission

With a single exception, all significant electrical transmission in this country is by overhead AC lines. A major element in the technological development of the electrical sector has been the increasing capacity, related to increased voltage, of AC transmission lines. Although most current systems are operated at 345 and 500 Kv, the largest blocks of power travel over 765 Kv lines. In 1967 a major program for transmission at above 1000 Kv (ultra-high voltage, UHV) was initiated. This program has included the investigation of insulators, corona effects, tower design, effects of weather, and the safety problems of high electrostatic fields. Attention has also been directed to associated transformers, lightning arrestors and gas-capacitors.

If one were to identify a single problem as the most severe limiting factor in the extension of transmission line voltages, it would be the problem associated with the electrostatic field between the conductors and ground. While this problem has been significant in the design of 700 Kv class transmission lines, it becomes a major difficulty above 1000 Kv. In addition to noticeable discomfort of people and animals, induced currents can reach levels above let-go currents when persons make contact with metal structures or vehicles. Corona, radio and television interference and audible noise are also more of a problem at higher voltages. The problems of land-use and visual effects are probably at least as severe per unit of power transmitted for UHV lines as for lines of lower voltage.

DC Transmission

At equivalent voltage levels, it is easier to transmit DC power than AC power. Direct current lines operate without voltage drops due to series inductance and electromagnetic induction between lines. Even more important, DC voltage eliminates the continuous flow of charging currents in cables, thus removing I^2R losses due to these currents. AC dielectric losses are also eliminated in DC cables. On the other hand, because of residual polarization effects, DC cable insulation must be rated at twice the operating DC voltage due to polarity reversal that occurs when the direction of power flow is reversed. The net effect of these variables is that the total capacity of the DC system is approximately 1.5 to 2 times that of the AC in the overhead case and 4 times that of the AC in the underground case. When systems are of great length, these ratios can be increased to 4 and 6, respectively.

The basic drawback of DC transmission stems from the fact that all electrical generating equipment, distribution systems and electrical appliances are based on AC. Thus the advantages of DC systems in themselves are counteracted by the need for AC-DC conversion equipment at the terminals of DC lines. The only major DC transmission in the United States is by the overhead Pacific Northwest-Southwest Intertie. This 850 mile line, which operates at $\pm$ 400 Kv is in fact the largest DC transmission system in the world.

Another role that a DC line can play is a link between AC systems. The advantage of the DC link is that it can control power flow from one AC system to the other without at the same time transferring undesirable system instabilities. DC links may also have economic advantages over AC ones.

The practical development of high power DC systems has been limited by the capability of rectifiers. Mercury-arc rectifier valves have recently attained a power rating of 270 Mw (150 Kv, 1800 A) per converter group, but appear resistant to further development. Recent developments in solid-state converters and innovative plasma valves, however, indicate that significant improvement in rectifiers is still possible. Another limitation on the flexibility of DC systems has been the lack of a commercial high voltage DC circuit breaker.

Underground Power Transmission

Underground transmission techniques that are already in use or being developed within the United States fall into four categories:

1. The conventional cable in which a copper conductor is insulated by oil impregnated helically wound paper tape. Its most common form is the pipe type system in which the three-phase conductors are enclosed within an oil-filled steel pipe. At present, pipe type cables are in commercial service up to 345 Kv with a maximum capacity of approximately 450 Mw (with natural cooling). Increased capacity can be attained with forced cooling or by use of new insulating tapes.
2. The extruded solid dielectric cable. Here a solid dielectric insulating material, normally a polyethylene derivative, is extruded around a copper or aluminum conductor. The process is continuous and in principle should lead to inexpensive cables. In fact, many problems involving unpredictable and inexplicable breakdown of the dielectric have inhibited their large scale applications. Presently such cables up to 138 Kv, but with capacity below 200 Mw, have been installed on a restricted basis within the United States.
3. The compressed gas insulated cable. Presently this is a rigid system in which three separate-phase conductors are laid side by side and separated from one another according to the surrounding thermal characteristics. The conductor is surrounded by an outer sheath of extruded aluminum tubing. The diameter depends upon operating voltages and varies from 8-1/2" at 138 Kv up to 20" for 500 Kv. The central conductor is supported and maintained concentric with the outer sheath by solid insulators located at intervals along the transmission line. The most popular solid insulating material is epoxy; sulfur hexafluoride (SF_6) has been used almost exclusively as the insulating gas. The continuous power carrying capability of a cable operating at 500 Kv is almost 2,200 MW. At the present time only naturally cooled gas-spacer cables have been designed and installed, but calculations have indicated that forced cooling could double the capacity of

given installation. So far no detailed design or development has taken place.

4. Cryogenic cable. These are of two types: cryoresistive, and superconducting.

In a cryoresistive cable the copper or aluminum conductor is cooled to a low temperature to reduce the resistivity of the metal and hence the ohmic losses. This reduction in power loss is partially offset by the refrigeration that is required to absorb the heat leaking into the cold environment from the outside and the residual losses which appear as heat dissipated at the low temperature.

Two types of cryoresistive cable systems have been proposed. In one, which operates at temperatures of approximately $80^{\circ}K$, stranded flexible aluminum conductors are insulated with Tyvek tape in a manner similar to a classical oil-paper cable. The three phases are contained within a cryogenic enclosure through which flows liquid nitrogen as the coolant and impregnant. The second type of cryoresistive system consists of three rigid phase conductors mounted within a single vacuum envelope. The vacuum provides both thermal and electrical insulation between the phase conductors and between the conductors and the enclosure. The refrigerant is liquid nitrogen which flows through the conductors. Both types of systems have gone through experimental stages and are approaching demonstration project status.

Superconducting systems are designed to exploit the characteristic feature of a superconducting metal--its resistance becomes identically zero at a particular, very low "transition" temperature. For materials of interest, these temperatures are generally below $10^{\circ}K$; for all current materials the only feasible coolant is helium (probably liquid). Although in DC systems the ideal of zero resistance can be attained, for AC there remains some small hysteretic losses.

As in the cryoresistive case, the penalty for reduced resistance is increased insulation and refrigeration costs.

Superconducting transmission systems are still at an early state of development. Although lower operating costs have been projected for such systems, the complexity of current designs and the amount of development still required reduce the confidence with which such estimates can be made. The projected installation and maintenance problems appear to be severe.

Microwave Transmission

Two approaches have been suggested for the transmission of power by microwave radiation. In one the microwave energy is transmitted through a transmission line consisting of a closed waveguide. In the other it is radiated from a large aperture antenna as a focused beam, bounced off an orbiting reflector and received by another large aperture antenna. In both approaches systems are required for conversion to microwaves before transmission and reconversion, ostensibly to AC, after transmission.

Only relatively low frequency waveguide power transmission systems can be constructed at present. In order to have acceptably low losses in such systems they must be unacceptably large. Neither microwave generators nor reconverters of adequate performance have been developed for this purpose.

In principal, power could be transmitted by means of charged particles travelling through an evacuated pipe. This concept, based on the principle of linear accelerators, is highly speculative at this time and has received very little attention.

Controls and Control Systems

Electric power systems are growing in complexity as well as in size. There are an increasing number of diverse types of generating sources being placed in operation and under development. These include pumped hydro, once-through fossil-fired units, gas combustion turbines, nuclear reactors, MHD, fuel cells and possibly fusion reactors. Each of these has its own unique operating characteristics and constraints. The integration of many such units of large capacity into existing systems are rapidly compounding, and making more complex and more critical the control problem which must be faced by the system designer and ultimately by the system operator.

Plant control systems are essentially the same as those which have been used for the past 10-20 years. These are fundamentally set-point analog control devices using the well known techniques of feedback and feedforward. It is quite common that these controls do not represent an integrated system approach to the problem, but rather an accumulation of devices which are available and which can be interconnected to perform a reasonable task. Some efforts have been made to automate the operations of plant start-up and control, using digital or analog computer techniques. Rather than representing a completely unique approach to the problem, these computers are used to operate equipment through the basic existing control systems, providing a reasonably safe contingent mode of operation at the set-point level in the event of computer failure. Present plant control systems have two significant limitations in performance: (a) inadequate stability when subject to transient conditions, and (b) less than optimum response when commanded to accept additional or reduced load.

In addition to the control of individual generating plants is the need for controlling electric power systems, some of modest size and others of the large interconnected type. Essentially, a large interconnected system consists of several smaller systems, each of which must be controlled both independently and in conjunction with the larger system.

Some systems are now operating on a hierarchical basis. At the top level of hierarchy in such a system is the power pool control center. These centers provide criteria for economic dispatch and security within the present capabilities of technology. Dispatch instructions are then forwarded to control points of satellite stations which are responsible for providing directions to individual generation plants and units. Individual plants are then responsible for control of basic parameters peculiar to their operation. The three-level hierarchy is now used in several major installations with a complete closed-loop continuously solving the problems of economic dispatch and system security. Unfortunately, manual intervention is still common especially at the plant level where very often the controls either are not automatic or, if so, are inadequate to respond properly to the demands placed upon them.

Energy Storage

The time variation of the electrical load presents a challenge to the economical operation of central station electric generation. Most generation technologies are capital intensive and are thus most economically operated in a continuous mode. This is particularly true of new central station technologies, for example, breeder reactors, solar energy and fusion. Inexpensive energy storage (and reconversion to electricity if necessary) would allow the installation and operation of central station plants at a level closer to the average demand (all "base loaded") rather than the peak demand.

The only widely used energy storage technology is pumped water storage and hydro-turbines. Potential sites for such storage are rapidly being exhausted over large regions of the country. Storage of energy has been proposed in the form of compressed air, flywheels, superconducting magnetic fields, etc. Preliminary research has been carried out on batteries for central station use and on hydrogen, produced by electrolysis of water and stored as hydrides.

PROGRAM RECOMMENDATIONS

Traditionally a large portion of R&D devoted to transmission has been carried out by private industry. This should continue to be the case. The program elements described below represent the outlines of a balanced program with an appropriate federal share of individual projects ranging from 20-40%. The total amount of funding for the projects described below is $66 million for the first year.

With some exceptions the program outlined here is similar to that developed by the Electric Research Council.[41] The program elements refer to areas in which increased or entirely new funding is required.

Analytical Studies

As shown above, there are a number of potential technological approaches to increasing the capacity of transmission systems. Each has quite individualistic characteristics in terms of costs, environmental effects, system impact, etc. A coordinated set of planning studies should be carried out to better understand the requirements and relative benefits of alternative systems. The need for a national policy on utility corridors should also be studied along with general problems of large interconnected systems.

UHV AC Overhead Transmission

The program proposed by the Electric Research Council R&D Goals Task Force[41] represents a reasonable approach to the development of UHV AC overhead systems. This program aims at development of 1100 Kv lines by 1980, 1300 Kv lines by 1985, and 1500 Kv lines by 2000. Such problems as audible noise, induced voltages and currents in objects under the lines, TV and radio interference, contamination flashover, and the difficulty of obtaining right of way may make alternative transmission systems more attractive in the future, however.

DC Transmission Systems

The most urgent task relative to DC transmission is the development of terminal equipment. Specifically, the plasma valve requires development to the stage of system application. At the same time it is necessary to initiate new R&D programs to lower the cost and increase the efficiency of solid-state converters. The EHV circuit breaker programs require continued support. The development of a completely miniaturized 250-500 MwDC terminal station for use in urban areas would be of great importance. Some work is also warranted on the cables themselves concentrating on the development of extruded dielectric cables.

The successful development and application of these DC components requires more adequate test facilities than currently available and, as soon as possible, demonstration of DC elements in an AC network. To prove the reliability and flexibility of the DC elements they should be operated in a variety of modes and under a variety of realistic conditions.

Subsurface Transmission

The two major difficulties with underground transmission are high cost and low capacity. The development of extruded dielectric cables has the potential of reducing costs. Both costs and capacity can benefit from the development of gas spacer cables with emphasis on flexible and compact forms. The specific requirements of submarine cables require analysis and R&D because of their importance to off-shore power plant siting. An integral part of all of these development programs must be attention to installation and repair problems.

Research and development should continue on cryoresistive and superconducting transmission concepts. This should include hardware development (with attention paid to cost, ease of installation, reliability and maintainability) and basic supporting research on superconducting materials.

One possible means of decreasing the cost of underground transmission is through the use of utility corridors. Studies need to be performed on this concept. When considering utility corridors, however, one must take great care in insuring public health and safety and in insuring the reliability of the various utilities that use the corridor.

Control Systems

Significant benefits can be derived from the extension of modern control theories and the application of modern control techniques to the electric utility industry. Work in this area would comprise analytical development (e.g., mathematical modeling of elements of the system, stability analysis, cost benefit studies) and component development (e.g., digital unit controls and relays).

A National Simulation Laboratory is needed to provide facilities to study in the most realistic and objective way possible the behavior of a power system, especially the transient behavior following a major disturbance. The simulation laboratory would contain digital, analog, and physical scale model simulation adequate to represent the major portion of the generation, transmission, and loads of the largest interconnected system in the US. It is anticipated that a continuing effort will be made to improve and expand the simulation accuracy and capability. The simulation laboratory would be available to utilities, groups of utilities, and manufacturers and would be of significant use to governmental regulatory bodies.

Energy Storage

The development of inexpensive and reliable energy storage technologies for central station use would be of great utility. Systems studies are required to evaluate on a comparative basis possible new storage technologies. At the present both battery storage and hydrogen storage appear worthy of support. The latter is included in the recommended program on synthetic fuels (in the previous section).

Fundamental Studies

At the present time the reliability of utility equipment is less than predicted or desired and the failures most often involve phenomena that are inadequately understood. Not enough is known about the physical, chemical and electrical processes involved in the failure or other malfunction of a variety of electrical equipment and systems. Fundamental research needs to be done on failure modes. A few specific examples are: failure of insulation in high voltage apparatus such as transformers; corona discharges around imperfections evolving to insulation breakdown and equipment failure; contamination flashover of outdoor insulation in which complex physical, chemical, and electrical phenomena that result from wet contaminant on insulating surfaces lead to breakdown of the insulation; electromechanical effects in apparatus that lead to vibration, noise, and material fatigue. This task defines a need for fundamental research to support all of the program elements in the area of electrical transmissions and systems.

Program Summary

Table III-22 recapitulates the program elements discussed above.

THE IMPACT OF TRANSMISSION R&D

The future development of the transmission system in this country is dependent on a large number of other characteristics of the energy system. The size of newly installed electrical generation units is an example. But here, as in other examples, available transmission technology will have an influence on optimal unit size. This sort of interaction between evolving transmission and generation technology makes it difficult to predict the impact of any specific development in transmission.

Thus, the basic rationale for work in transmission described in the introduction must serve as a measure of potential impact. According to the projections given in Chapter II, electrical production will continue to increase faster than total energy production. The impacts of current electrical transmission--in terms of visual effects and land use--are severe enough. Multiplied by a factor of five (by the year 2000) they become intolerable. As shown above, a number of technological avenues are open to reduce those impacts and to increase the security of the transmission network despite its growth in complexity and size.

Table III-22

SUMMARY OF PROGRAM IN TRANSMISSION AND CONTROL

Program Element	Current R&D Objective	Program Cost[(a)] First Year Cost $ Million	Program Cost[(a)] Long Term $ Million/years
Analytical Studies	Study interconnected systems and benefits of alternative technologies.	1.2	4/3
UHV AC Overhead	Develop 1100 Kv line by 1980, 1500 Kv by 2000.	11.2	78/7[(b)]
DC Transmission			
Conversion Equipment	Develop plasma valve and advanced solid-state converter.	2.0	14/7
Auxiliary Equipment	EHV DC circuit breaker, etc.	2.1	15/7
Miniaturized Terminal	Develop 250-500 Mw miniaturized terminal.	5.7	40/7
Undergound Cable	Develop extruded dielectric cable.	2.3	16/7
Test Facilities	Prepare facilities for testing cables and components.	4.3	30/7
Demonstration	Demonstrate DC elements in an AC system.	4.3	30/7
Subsurface Transmission	Develop extruded dielectric and gas spacer cables; develop submarine systems, superconducting transmission.	3.5	30/7
Control Systems			
Development & Analysis	Develop modeling techniques, digital controls, etc. Analyze security needs.	6.3	44/7
Nat'l Simulation Lab.	Provide facilities for simulation studies of power system behavior.	14.3	100/7
Energy Storage		2	30/7
Fundamental Studies	Research on physical-chemical bases of failure modes.	10	70/7
	TOTALS	$69 million	- $501 million/7 years

(a) A significant portion of these costs are expected to be borne by industry.

(b) This program may be decreased in future if competing technologies are successful.

K. TRANSPORTATION

INTRODUCTION*

The direct fuel requirements for the transportation sector account for about 25% of the total energy consumed in the U.S. and about 55% of the U.S. petroleum consumption. When the energy requirements for automobile manufacture and repair, and for road building and maintenance, are included, a much greater fraction of the total energy demand can be attributed to transportation. In view of projected shortages of domestic petroleum, new transportation technologies that can improve the efficiency with which people and goods are moved and reduce the attendant environmental impact are of major importance. It is recognized that certain policy decisions and institutional factors can influence transportation efficiency, perhaps even more effectively than new technologies; however, the focus in this study is on technology.

The different modes of transportation, and the different vehicles used in each mode, use quite different amounts of energy to accomplish their purpose. The automobile typically provides 30 passenger-miles per gallon of fuel (PM/G) while aircraft provides about 16 PM/G. Small cars achieve about 48 PM/G, transit buses 59 PM/G, intercity buses about 128 PM/G, and trains approximately 100 PM/G. For freight service, trains provide 190 ton-miles per gallon (TM/G), aircraft about 4 TM/G, pipelines 300 TM/G, and trucks up to 60 TM/G.

The total petroleum demand for transportation may be reduced by reducing demand, substituting more efficient systems for less efficient ones, or by improving the efficiency of given systems. Alternatively, a different fuel form derivable from more abundant energy resources may be substituted for petroleum. Such substitutability is feasible now to a certain extent and could be enhanced by the development of new technologies such as the electric car and hydrogen-fueled automobiles and aircraft. The development of processes for the economical production of synthetic gasoline from coal would also relieve the projected shortage of conventional fuels for transportation. Technologies

* This section is based in part on the two panel reports - see References 46 and 47.

relating to the production of alternative fuels are discussed in the sections on Clean Fuels from Coal and Synthetic Fuels.

In the near term, within five years, it appears possible to demonstrate as much as a 30% reduction in fuel consumption by standard automobiles without substantially affecting performance or losing any of the gains made in controlling emissions.

Some alternate heat engines offer fuel economy advantages over the current gasoline-fueled spark ignition engine while others offer the possibility of simplified emission controls, provided that certain technical problems can be successfully resolved through R&D. Some of these advanced engines, for example gas turbines, steam engines, Stirling engines, and closed Brayton cycle engines, burn fuel continuously rather than intermittently, and thus, have a multi-fuel capability that is not easily attained in the conventional spark ignition engine. They could use a variety of liquid and gaseous fuels, and in some cases, could even use stored heat. The stratified charge engine, including the prechamber combustion version, is another promising technique for reducing emissions from a gasoline fueled engine. Looking further into the future, if ground transportation vehicles are to make substantial use of electricity, a high-performance battery will be required.

Technologies may also be defined which would achieve advances in the efficiency of mass transport and freight transport systems. The implementation of new and more efficient transport systems will depend ultimately, of course, on competitive market forces and on policies that are established.

CURRENT STATUS OF TRANSPORTATION TECHNOLOGY

The state of development of transportation technologies will be discussed in two major categories: automotive, which includes private vehicles, buses, and trucks: and heavy-duty transportation which includes railroads, aircraft, and vessels. The major fraction of research and development in the automotive field is being directed toward emission control systems that can be used with the conventional gasoline-fueled spark-ignition engines. At present it appears that catalytic converters along with exhaust gas recirculation and possibly thermal reactors are the most promising methods for meeting the 1976 EPA standards; however, both the cost of these control systems and the reduction in fuel economy that they will cause may be large. Other areas where development work is in progress are fuel economy, alternate engine concepts with fuel diversification, and electric propulsion.

Automotive Fuel Economy

Improved fuel economy can be achieved by reduction of vehicle weight, reduction of aerodynamic drag, reduction of rolling resistance, and improved matching of the engine to the load. Most of these approaches require little further development and will undoubtedly be implemented as fuel prices rise. Alternative engine concepts that offer improvements in fuel economy will be discussed separately.

The weight of an automotive vehicle is an extremely important factor with respect to fuel economy, especially on an urban driving cycle. The implementation of smaller vehicles and the use of lighter weight materials for body, panels and other components would result in improved fuel economy. One of the most promising features of the Wankel engine is its lighter weight for a given horsepower output than a conventional engine.

It is known that aerodynamic drag becomes the dominant power consumer at speeds above 40 to 50 miles per hour. The drag coefficient of a typical automobile could be reduced by 50% by using a teardrop design. Between the mid-30's and the late 60's a series of technical articles were published on this subject for truck and auto applications; however, few of the techniques proposed have been employed in the design of production models. It is estimated that a 5% energy saving may be achieved using known technology and that 20 to 30% savings could be achieved in practice with a moderate level of development work.

The dominant power loss at low speeds is rolling resistance, most of which is friction on the loaded tires. Newer tire designs, in particular the steel-belted radial ply tires, provide substantial improvement. Reductions in rolling resistance of 15% on ice and 45% on sand are claimed. This may be translated into a 10% improvement in fuel economy on an average road. There seems to be little need for additional development work here since the major obstacle to greater implementation of this type of tire is a limited production capability rather than any technical deficiencies.

Fuel economy may also be improved by better matching of the propulsion system to the vehicle road demand. The power trains on current vehicles are optimized for low manufacturing cost and ease of operation. The consequence of these practices is that the gasoline engine frequently operates at varying part-load and part-speed points that are off the optimum design points for minimum specific fuel consumption. It is estimated that a saving of 10 to 15% may be realized by a re-optimization of automotive power trains. An alternate approach to achieving the same objective involves the use of a supercharger or turbocharger with a smaller base engine. The small engine would be efficiently utilized for routine load demands and the supercharger would assist the engine in negotiating peak-power demands.

Alternative Automotive Engines

New automotive engine concepts under development have the promise of either reduced emissions with conventional fuels, improved performance, or improved compatibility with novel fuels. The novel fuel concepts are of interest both as a means of reducing emissions and relieving the demands on conventional automotive fuels. The Stratified Charge Engine and Light-Weight Diesel have the potential of providing alternatives to the less efficient 1976 Internal Combustion Engine (ICE) in the early 1980's. The Advanced Gas Turbine could be available by the mid-1980's and promised reduced emissions although with some fuel consumption penalty. The Rankine (steam cycle), Stirling, and Closed-Cycle Brayton engines are external combustion systems with two significant advantages over all other engines; very low emission levels and excellent compatibility with novel fuels such as methane, propane, methanol, ethanol, hydrogen, and ammonia. Electric vehicles would provide complete independence from petroleum and may be more efficient than any of the other alternatives.

Following is a discussion of the current state of technology for these engine concepts.

Stratified Charge Concept - The stratified charge engine uses a fuel injection system to produce a rich mixture in the vicinity of the spark plug. The average air-fuel ratio in the cylinder is varied with the engine load as compared with the conventional engine where the air-fuel ratio is held relatively constant.

The prechamber combustion system is a version of the stratified charge concept. In this system a rich mixture representing a portion of the total fuel charge is ignited in a small prechamber. Very small quantities of oxides of nitrogen are formed in this prechamber combustion because of the richness of the mixture. The combustion products pass through an orifice into the main chamber where the balance of the combustion is carried out with a lean mixture. The combined hydrocarbons and carbon monixide from the prechamber are also reacted in the main chamber, leading to very low overall emissions and good fuel economy.

Exploratory development has been in progress for five to seven years on the stratified charge concept. The basic exploratory work has been technically sponsored and funded by the Defense Department for the whole period with increasing EPA participation and funding in 1970-1972. This exploratory phase is scheduled for completion by the end of 1972. Future program plans involve the engineering development of this engine for Army trucks and are directed toward initiation of engine production late in 1976. The feature of precise control of combustion offers lower fuel consumption at substantially reduced emission levels. To meet 1976 standards, cycle compromises and after-treatment are still required but dependency on auxiliary equipment is less.

Diesel - The diesel engine uses fuel injection and operates at a high compression ratio. It is more efficient than the ICE and produces less emissions but is somewhat heavier. A light-weight diesel of 200 hp size currently wieghs a little over 1,000 lbs, for a specific weight of 5 lbs/hp while gasoline engines for cars are in the 3 to 4 lbs/hp range. Current R&D efforts on the diesel are giving special attention to reducing weight and increasing power. Higher powered diesel engines are well-advanced in engineering development and have specific weights of 3.1, 3.6, and 4.2 lbs/hp in sizes of 640, 480, and 320 hp, respectively. Extrapolation of this demonstrated technology from the nominal 500 hp size to passenger car 150 to 200 hp appears to be straightforward. Diesel engines are or can be made low on smoke, HC, and CO emissions. NO_x emissions still pose a problem with respect to the 1976 standards. Combustion control (intracylinder turbulence and flow) is well-managed and may be subject to reoptimization for further NO_x reduction. It is anticipated that emission requirements can be met by diesel engines with less complex aftertreatment than is required with conventional gasoline engines. Further, the light-weight diesel engine could probably meet emission requirements without the 20 to 25% penalty expected for conventional gasoline engines.

The diesel engine operates on kerosine type fuels, so the demand for low- or no-lead-gasoline at higher octanes from refineries would be relieved if this engine was implemented to a greater extent.

Gas Turbine - The gas turbine is the most common version of the Brayton cycle engine. It is employed on all jet aircraft and turboprops, some experimental automobiles, high-speed boats, and in power plants to generate electricity during peak demand periods. In view of such widespread applications, the technology is highly developed. Demonstration gas turbine automobiles have been built and operated. The difficulties encountered in applying the gas turbine to automobiles include high cost and high specific fuel consumption. The 1975 hydrocarbon and carbon monoxide emission standards can be easily achieved, but the 1976 nitrogen oxide standard cannot be satisfied with existing gas turbine technology.

The current research and development work on this automotive engine concept is directed toward reducing NO_x emissions, reducing fabrication costs, and improving performance. Conceptual designs have been completed for engines with improved fuel economy using a single shaft with heat recovery. Improved combustors and generators are also under development. The gas turbine is adaptable to a wide variety of fuels.

Rankine Engine - Steam engines operating on the Rankine cycle were popular in the early days of the automobile but could not compete in performance with the ICE. Several types of advanced Rankine cycle engines operating on steam and organic working fluids are under development for automotive application. The current problems with this concept include high-weight and bulk, freezing of the working fluid, poor fuel economy, and large condensor sizes. The Rankine cycle engine is an external combustion system and has a multifuel capability.

Prototype automotive engines will be operated during 1973 and further R&D requirements will be defined as a result of those tests.

Stirling Cycle Engine - Seven types of Stirling engines have been developed and used for small stationary power sources over the last century. Stirling-cycle devices such as refrigerators (cryogenic), have been highly successful. The Stirling engine has been developed in sizes up to 400 hp per cylinder and a production line has been set up for a 200 hp commercial vehicle engine. Development work on truck-size engines is also being carried out.

The most recent research involves an engine which is compact and light weight (less than 4 pounds per horsepower). Its exhaust emissions, with the possible exception of NO_x, are below the 1976 standards; it performs much like a standard engine, and has excellent fuel economy; however, it is expensive.

The engine design is a major departure from earlier Stirling engines (employing rhombic drive). It is most easily described as a four cylinder in-line engine that has been pulled into a circle so that the first and fourth cylinders are adjacent. The crankshaft is replaced by a swashplate on an axle parallel to the center lines of the cylinders. The cylinders are interconnected to permit the working gas (nine grams of hydrogen) to flow from one to the next. The piston in each cylinder plays a dual role, as the power piston and as the displacer piston of the more familiar rhombic drive version.

The Stirling engine is better than the diesel engine in terms of fuel consumption. Its advantage is especially significant in applications where a large amount of running time is spent at reduced output, or at idle.

The efficiency has been found to vary only between 40 and 34% from full power to 1/10 power. The low-fuel consumption is partly a consequence of the unusually wide temperature differences over which the closed gas cycle engines can function, the good cycle efficiency, and the practicality of a high degree of regeneration or recuperation over the temperature differential. It is, however, due also to the fact that efficiency can be kept high over a wide range of power outputs, and that starting is easy and idling for long intervals is not necessary.

Closed-Cycle Brayton Engine - The closed-cycle Brayton engine operates in similar fashion to the open-cycle Brayton or gas turbine engine but the working fluid is cooled and recycled rather than being exhausted to the atmosphere. About a dozen closed-cycle Brayton engines have been in operation in medium-size fixed generating plants for periods of up to 15 years. The engines have demonstrated a tolerance to varying grades of fuels and the ability to operate at a nearly constant efficiency over widely varying power outputs. The closed-cycle Brayton engine has proven to have excellent starting characteristics, thus making long idling unnecessary.

In the past several years, a great deal of development work has been done on closed-cycle Brayton engines suitable for space-flight applications. These engines have been designed for operation in the 20 hp range at 30% thermal efficiency and an unattended continuous-operation lifetime of five years.

NASA has also started design work on a 140 hp version for use in space stations. Several characteristics of the closed-loop Brayton developed for space-flight applications which may make it attractive from a transportation standpoint are as follows:

... The high density of the pressurized working fluid makes it possible for the rotating machinery to be of small size.

... Rapid reaction to changes in power demand are possible, since the temperature and compressor rotations and working fluid linear velocities do not change substantially with load.

... Closed-cycle turbines should be able to make use of open-cycle gas turbine production technology, tooling and equipment.

... Fuel consumption is quite low (lower than the Rankine).

The closed-cycle Brayton is extremely attractive from an environmental standpoint. It is expected that the Brayton engine could satisfy 1976 emission standards; however, lower cost systems must be developed for automotive applications before the engine may be marketed.

Electric Vehicles - Electric propulsion is currently used for subways and some rail lines and for industrial lift trucks and golf carts. All electric vehicles require electric power conversion systems, drive motors, and controls. Some form of storage is required for vehicles that do not operate on an electrified rail or guideway. The storage requirements depend on the degree to which the vehicle operates independently of the electric power source. A hybrid vehicle operating primarily on an electrified roadway but with sufficient battery storage to operate independently for short-time periods is feasible at the present time. Lead acid, nickel cadmium, or other well-developed battery systems could be employed in such a vehicle.

It is not feasible with existing battery technology to operate an electric vehicle in the independent mode with performance anywhere near that of conventional automobile. Advanced batteries of high-energy density and specific power, such as the sodium-sulfur and lithium-sulfur systems, are under development and promise to provide competitive performance capabilities.

Drive motors and control systems for electric vehicles are well developed but are still expensive and not generally adaptable to mass production techniques.

Heavy-Duty Transportation--Aircraft and Rail

Current research and development activities for aircraft and rail propulsion systems has similar objectives to the automotive work; namely, increased efficiency and reduced emissions. This work may be broken down into three general categories: engine development, aircraft development, and alternate transport modes.

Engine Development - Aircraft gas turbine development programs are currently directed toward higher inlet temperature capability and higher efficiency. Specific development efforts include new turbine blade cooling schemes, ceramic and high temperature alloy turbine blades, increased pressure ratio, and reduced engine size. New combustor designs are being investigated for smoke reduction. Aircraft gas turbine technology may be applied to stationary power generation and ground vehicle propulsion with some modifications. Other power cycles such as the closed-cycle Brayton, Feher, and Stirling cycles are being studied for heavy-duty ground transportation systems such as rail and large trucks. For a technical description of these systems refer to the section on Advanced Cycles.

Aircraft Development - Several technical studies have been performed to determine the economic feasibility of incorporating technological advances in the future subsonic civil transport aircraft. Specific advances that have been identified are supercritical aerodynamics, active controls, and composite structures. A major benefit of applying these technological advancements is structural weight reduction. Supercritical aerodynamics permits design for lower loads and hence reduced structural weight, stability augmentation permits designs for smaller tail surfaces and reduced weight, and advanced structures utilizing filamentary materials and honeycomb concepts also result in lower weight. Additional weight benefit is gained by resizing the vehicle for lower weights gained by applying the advanced technologies. These structural weight benefits of course manifest themselves as reduced gross take-off weight (GTOW) which is directly proportional to the engine thrust requirements, and hence, fuel requirements.

Alternate Transport Modes - System studies have been performed of improved urban and intercity mass transport systems including tracked air cushion and magnetic suspension vehicles. The air cushion vehicle operates by forming a pressurized cushion of air under it, contained by a flexible skirt around the periphery of the craft. Vehicles of up to 200-ton size are in ferry and military service and prototypes of larger vehicles are under test. This vehicle concept could provide a more efficient mode of freight transport than cargo aircraft. Lighter-than-air vehicles, employing the latest structural technology, have also been proposed as a promising option for freight transport.

Economical nuclear powered aircraft and ships would free a large portion of the transportation sector from reliance on petroleum fuels. An extensive nuclear aircraft development program was terminated because of the large airframe size requirements and safety concerns. Recent growth of airframe size might make such systems more feasible. Nuclear powered ships are, of course, in operation primarily in military applications.

PROGRAM RECOMMENDATIONS

The development program for transportation systems should focus on improving the efficiency with which people and goods are moved and relieving the dependence on petroleum fuels.

The state of technology on automotive fuel economy is well advanced but this technology has not been implemented for economic reasons. Implementation of several energy conservation techniques could be promoted through a fuel economy vehicle demonstration similar to the DOT experimental safety vehicle program. It is estimated that an initial annual expenditure of $5 million and a total expenditure of $15 million over a four-year period would be required for such an effort.

A continuing research and development program for alternate automotive engines should include the gas turbine, Rankine cycle, and lightweight diesels for the near term, and battery concepts for the longer term. The Stirling and stratified charge engines are also promising but the current industrial development effort appears to be adequate. A $20 million initial annual funding level would be required for this program. The total expenditure for heat engine development is estimated at $68 million over a six-year period and for batteries would involve a $250 million expenditure over some 15 to 20 years. The engine program would essentially be a continuation of the current automotive engine development effort but would stress fuel economy as well as emission levels.

A modest program for the evaluation of alternative transportation modes, such as the lighter-than-air vehicle, seems warranted. In order to perform such an analysis a general transportation system model is required. At the present time no comprehensive model exists which can predict the modal split in the transport of people or goods as a function of price, trip time, and convenience. The development of such a model and its application to general transportation studies would require a funding level of about $5 million during the first year.

Program Summary

Table III-23 gives a summary of the program elements and estimated funding levels discussed above.

Table III-23

Summary of Transportation Program

Program Element	Current R&D Objective	First Year Cost $ million	Long-term Cost $ million/year	Notes
Fuel economy	Demonstrate fuel economy vehicle	5	15/4	
Alternate engine	Develop 3 alternative heat engines and battery-driven vehicles	20	250/15	Includes gas turbine, Rankine, and diesel engine as well as electric battery
Alternative transport modes	Develop planning model and perform studies	5		
	Total	$30 million	$265million/15 years	

IMPACT OF IMPLEMENTATION

The development and implementation of the fuel economy measures that involve vehicle design could begin to contribute to reduced fuel requirements in automobiles during the late 1970's. By 1985 fuel requirements could be reduced by about 30% in automobiles of current size and weight. Still further economies could be realized with smaller vehicles and improved engines.

The more efficient alternative engines such as the stratified charge, Stirling, and Rankine systems could contribute to an additional reduction in fuel consumption. These technologies could be implemented in the late 1970's and could make a significant impact on transportation fuel requirements in the early 1980's. In comparison with the ICE, emission control would be greatly simplified with these alternative engines and improvements of 20% in fuel economy might be achieved. The economic impact cannot be accurately determined at this time.

With respect to environmental impacts, the standards may be more easily satisfied by application of these technologies but no credit may be taken at this time for further reductions below the standards that have been published and that have been assumed in the Reference Energy Systems.

The development of a high performance electric automobile appears to be further off but would facilitate the substitution of the abundant coal and nuclear fuels used to produce electricity for the oil products that are now employed for transportation. The impact of the electric automobile in the year 2000 Reference Energy System is indicated in Table III-24. In this analysis it was assumed that all automobiles were electrically driven.

TABLE III-24

Impact of Electric Automobile

Percent Change from Reference Energy System

	Electric automobile--Year 2000	
Sector replaced	automotive	
% of sector replaced:	100%	
Resources		
Nuclear	+19	
Coal	+11	
Oil	-25	
Natural gas	+4	
Environmental effects	Centralized sources	Decentralized sources
CO_2	+19	-18
CO	+19	-27
SO_2	+19	- 3
NO_x	+19	- 4
Particulates	+19	- 4
Hydrocarbons	+19	-10
Radioactive materials	+19	

L. URBAN AND RESIDENTIAL ENERGY UTILIZATION

INTRODUCTION*

The most severe energy supply and environmental problems are encountered in the densely populated urban areas. At the same time it is apparent that opportunities exist in these areas for the more efficient utilization of energy in the residential and commercial sectors. Total energy systems, which produce electricity and utilize low-grade waste heat for other purposes are one means of obtaining more complete utilization of the energy content of fuels. On a larger scale, urban energy systems, in which the electrical and thermal energy needs of a city are handled in an integrated manner, provided the same benefit. Improved construction techniques and appliance design can serve to reduce the energy requirements of all consumers. Many opportunities exist in architectural design and building site planning to reduce space heat and air-conditioning needs. The proper use of insulation, lighting glass panels, and other construction materials, and consideration of the orientation of the building with respect to sun and shade, will undoubtedly receive more attention as energy conservation measures as fuel prices increase.

Total energy systems may be installed in individual buildings or building complexes for the on-site generation of electricity. Fuel-burning internal combustion engines or turbines are employed to drive electric generators and the "waste" heat from the prime mover is used to provide for space heating and cooling as well as water heating. The principal feature of the total energy system from an energy conservation viewpoint is that about one-half of the "waste" energy can be reclaimed for useful purposes.

Urban energy systems, as defined in this discussion are equivalent to large total energy systems that serve an entire city or a region of a city. Conventional power plants may be used in this manner to produce steam or hot water in the condenser for distribution to nearby buildings to provide space heating and cooling. When the condenser temperature is increased above that used in a conventional power plant producing only

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* This section is based in part on the panel report - Reference 48.

electricity, the amount of electricity produced from a given amount of fuel is, of course, reduced. Nevertheless, the energy content of the fuel may be used more effectively by providing both electricity and steam or hot water at a useful temperature.

The efficiency of energy utilization in the residential sector may be improved in two general areas. Reduction of the heat loss, or gain, through the structure may be accomplished by increasing the thermal impedence of the structure itself. Such a reduction provides for more efficient heating and cooling within the residence. The other area where energy may be used more efficiently involves the appliances that are used within the residence.

The major factor in residential energy consumption is space heating. The combustion efficiency of gas- and oil-fueled heating equipment for residential application is typically in the range from 70 to 80% when new. The combustion efficiency may be decreased 10% or more in use unless the heating surfaces are regularly cleaned and the amount of combustion air is properly regulated. Some of the heat from the combustion gases discharged into the flue or chimney is recovered by heat transfer from the flue, but this heat is usually not available in the right places. Economizers with powered fans for installation in the flue pipes of furnaces or boilers are available on the market, but have not gained wide acceptance.

A somewhat more complicated and costly device could be attached to the furnace or boiler outlet that would recover most of the sensible heat and some of the latent heat from the combustion products. A device based on sensible heat recovery only could achieve a 10% fuel saving, and could pay for itself in five years.

CURRENT STATUS OF TECHNOLOGY

The current status of technologies for total energy systems, urban energy systems, and improved energy utilization efficiency in the residential sector is discussed below.

Total Energy Systems

The total energy concept has been applied for some time. Since 1958 over 600 systems ranging in size from .2 to 20 megawatts have been installed in the U.S. More recently, however, the number of new total energy plants installed annually has decreased sharply along with reductions in the level of promotional activities by the gas industry due to growing shortages of natural gas. Most of the existing systems serve industrial or commercial developments and just 55 of the total are residential applications, probably because of the low electric load factor in residences. The aggregate electrical energy generation of presently installed total energy plants is between 0.1 and 0.2% of the total electrical energy generated at this time. The use of a significant number of smaller total energy systems has been discontinued after a few years service because of high maintenance costs, poor reliability in electrical service, inadequate supervision, and other causes. Approximately 550 systems are currently in use.

The typical total energy plant ranges from 0.5 to 2.0 megawatts in capacity and most often has 1 to 3 prime movers per plant. About 70% of the plants utilize reciprocating gas engines and an additional 15% employ gas-fired turbines as the prime movers. There is no technical reason preventing wider application of oil-fired prime movers.

Nearly all total energy plants are custom designed and most of the components are made to order by producers of equipment designed for other applications, e.g., construction equipment or transportation. The mechanical engineering firms who design total energy plants often choose components, systems, and controls that emphasize reliability at some expense in thermal efficiency. As a result, actual performance of many total energy plants has been below achievable levels.

By way of contrast many total energy systems do function efficiently, can meet exhaust pollution regulations, and are designed for automated operation so that a full time operator is not needed. These systems receive regularly scheduled preventive maintenance and are provided with electronic performance monitoring and alarm systems. Further, typical total energy systems have one or more standby engine-generator sets which are capable of handling half of the maximum electrical demand of the installation.

A recent study showed that properly designed systems using available components could achieve energy savings in the 25 to 35% range over conventional energy systems for the sites considered. (These sites were six of the HUD BREAKTHROUGH housing sites comprising 300 to 500 dwelling units each.) Electric energy can be generated by a total energy plant for 1.0 to 1.5¢/kWh in some of the more favorable supply areas for gas. However, in general, documentation of total owning and operating costs, maintenance and repair costs, plant thermal efficiency, utilization of waste heat, and reliability of utilities, is fragmentary and is an insufficient basis for general conclusions. There is a modest amount of relevant research and development in total energy and related fields in progress and the major activities are outlined below.

A total energy plant is being installed in a BREAKTHROUGH apartment complex of 500 dwelling units at Jersey City. It comprises five diesel-engine generator sets aggregating 3 megawatt capacity. The installation will be extensively instrumented by the National Bureau of Standards to measure the thermal efficiency of the major components and the overall plant; the stability of the electric service; the reliability of the utility services; the ability to control noise, air pollution, mist, and odor; the nature and frequency of repair and maintenance; the diversity of the various energy requirements; and a detailed record of all owning and operating costs.

A thermal storage system using eutectic salts is being studied. Materials have been identified which are suitable for energy storage use at temperature levels from 40° to $190^{\circ}F$, thus providing the ability to store either a "cooling effect" or a "heating effect." These studies include attempts to achieve optimization of heat transfer and to resolve persistent technical problems with the recrystallization characteristics of these salts with time. Such storage systems would provide better load characteristics for all types of heating and airconditioning systems including total energy installations.

At least two U.S. manufacturers have developed prototype absorption air-conditioning equipment with a coefficient of performance of 1.0. These are not yet commercially available and their first cost is expected to be about 15% higher than conventional equipment. Most of the turbine research and development in progress is directed toward vehicular propulsion or high-capacity electric power generation units (20 megawatts and higher). Some of the automotive turbines in the size range from 400 to 600 hp could be adapted to total energy systems.

The Department of Housing and Urban Development is sponsoring economic feasibility studies of total energy systems in comparison with conventional energy systems for residential developments in the range 300 to 3000 dwelling units. The parameters being analyzed include number and density of dwelling units, fuel costs, conventional utility costs, climatic conditions, availability of commercial power, environmental impact, and fuel requirements.

Several options to expand the function of total energy plants are currently being explored by U.S. industry. In face of the growing shortage of natural gas, a major turbine manufacturer and others are developing fuel gasification processes for converting coal or residual fuel oil on-site for turbine use with resulting overall costs competitive with conventional plants.

Another interesting opportunity is the utilization of waste heat to generate fuel gas from residential solid and sanitary wastes in an anaerobic digestion process. A proposal using available technology to construct a demonstration plant in the 20 to 40 megawatt capacity range which combines both gasification and anaerobic digestion has recently been received by the Department of the Interior.

Urban Energy Systems

Analytical research on urban energy centers is being conducted under the sponsorship of the Department of Housing and Urban Development. The program includes a determination of the least costly method of providing an urban energy center for new cities or large urban areas having an acceptable postulated growth pattern. For example, would it be most economical to build a large central dual-purpose plant connected to the regional electrical grid and gradually enlarge the heat distribution system as the demand develops over a period of years; or would it cost less to establish local energy plants and eventually connect their infrastructure to a central station? The analytical research also includes a study of common trenching techniques for all utilities and the associated institutional problems.

There is an experimental and analytical program on dual-purpose water desalting plants supported by both the Atomic Energy Commission and the Department of the Interior.

A summary of the present and past use of district heating systems in the U.S. offers some perspective on the probability for growth of dual-purpose urban energy systems under the existing technological and institutional constraints. A report to the 1968 World Power Conference included the results of a survey on the use of heat-electric operations by 22 large district heating companies in the U.S. The chief results were as follows:

... Eleven of the 22 companies made some use of dual-purpose plants.

... The electric generating capacity of the extraction and back-pressure portions of the turbines was 2,447 MWe.

... The electric generating capacity of the extraction and back-pressure portions of the turbines was equal to 0.76% of the total maximum electric power supplied during the year 1966 by the public electric distribution systems (auto producers excluded) in the U.S.

... The total electric energy generated by the extraction and back-pressure portions of the turbines in 1966 was 2326 GWh.

... The net electric energy generated by the extraction and back-pressure portions of the turbines in 1966 was equal to 0.3% of the total net generation for the year or for the fisal year of the public electric distribution systems (auto producers excluded) in the U.S.

The statistics in this report indicate that the total delivery of steam for all the district heating systems increased about 5% in 1970. The number of new customers averaged about 380 per year for the year 1968-70, representing about a 40% increase over the rate applicable to the preceding decade. Revenues were correspondingly higher in the years 1968-70. However, only five systems out of 34 added new plant or distribution facilities in 1970.

In addition to the district heating company systems in U.S. cities, there are several thousand district heating systems serving industrial installations, commercial projects, college campuses, hospitals, and other institutions.

Experimental programs are in progress to study several uses of "waste" heat from power plants including agriculture, aquaculture, and sewage treatment.

Residential Energy Utilization

The construction techniques required to reduce heat transfer and infiltration losses in buildings are well known. Increased insulation, Thermopane, and storm windows provide for reduced thermal losses and require no further development.

There is very little development work in progress on more efficient appliances. Fluorescent lights and integrated circuits are efficienct devices and are available on the market.

Considerable study is going into the determination of energy utilization habits in typical households. This work should indicate where opportunities exist for energy conservation.

Heat pumps may be employed for heating and cooling to provide increased efficiency of fuel utilization. Electric heat pumps and air-conditioners are available with coefficients of performance between 1 and 3. The coefficient of performance is defined as the ratio of the thermal energy transferred between a heat source and sink to the amount of energy input to drive the device. Heat pumps are high capital cost devices compared with conventional heating systems but will have an economic advantage as fuel prices increase. Development work is in progress on engine driven Rankine cycle and gas operated heat pumps that will have higher coefficients of performance than those systems that are available now.

Thermal energy storage devices, such as those using the eutectic salts discussed previously, may be usefully employed with heat pumps and with other residential heating and cooling systems to smooth the normal daily variations in demand on those systems.

PROGRAM RECOMMENDATIONS

The research and development program emphasizes encouragement of more efficient energy utilization technologies in urban and residential applications. More efficient systems are currently available, but only at a higher price than conventional systems. Utilization of these systems can be encouraged through studies that identify areas where proper economic analysis, in which capital and operating costs are weighed for the entire life of the system, would lead to greater implementation of energy conservation techniques and through regulation. Important as this general area is, the amount of improvement that can be brought about by new technological R&D is small, given the background of institutional problems and the currently funded programs.

Following are specific development program elements in this area.

Energy Conversion

Demonstration of total energy system components, thermal storage techniques, and more efficient heating, ventilating, and air-conditioning components including heat pumps, is warranted. Integrated systems employing these components should also be demonstrated. The demonstration program should emphasize further reductions in cost and improved reliability. A major effort of this type would require a funding level of about $4 million in the first year.

Energy Recovery and Conservation

A balanced program to promote the implementation of more efficient systems for residential and commercial use would include the demonstration of standard utility cores which recover waste heat for supplemental heating and discharge waste heat outside of the building during the cooling season. More efficient appliances and improved construction standards would also be developed and demonstrated. New architectural concepts including site planning would be considered for purposes of energy conservation in developing construction standards. About $7 million would be required for this program during the first year.

Program Summary

Table III-25 presents a summary of the program elements discussed above including estimated funding levels for the achievement of the objectives outlined.

IMPACT OF IMPLEMENTATION

Implementation of total energy systems and urban energy systems produce similar benefits. The impact of these systems on the 1985 Reference Energy System are summarized in Table III-26. It is assumed that 5% of the electrical production is from such integrated systems operating at 30% efficiency in the conversion of fuel to electricity and that half of the waste heat is used for commercial space heating and air-conditioning.

TABLE III-25

Summary of Urban and Residential Utilization Program

Program Element	Current R&D Objective	First Year Cost $ million	Long-term Cost $ million/year
Energy conversion	Demonstrate more efficient total energy system components, thermal storage systems and HVAC equipment.	4	100/10
Energy conservation	Develop and demonstrate energy conservation programs.	7	200/10
	Total	$11 million	$300 million/10 years

Table III-26

Impact of Implementation of Urban and Total Energy Systems

Percent Change from Reference Energy System - 1985

Sector replaced: Electrical (5%)
Space heat (10%)
Air-conditioning (10%)

Effect on Resources	Percent change
Nuclear	-5
Coal	-3
Oil	+3
Natural Gas	-2
Environmental Effects	
CO_2	Neg.
CO	Neg.
SO_2	+0.2
NO_x	+0.5
Particulates	-0.1
Hydrocarbons	+0.1
Radioactive materials	-5

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Chapter IV - CONCLUSIONS

A. SUMMARY OF R&D PROGRAMS AND IMPACTS

In Chapter II, Reference Energy Systems were described which projected the future of the U.S. energy system under conditions of minimum change from current policies and minimum introduction of new technology. The specific problems revealed by that sort of laissez-faire projection were summarized in Section F of Chapter II. In Chapter III, eleven technological areas were discussed in which research and development could lead to new options in the evolution of the energy system. Before analyzing the potential impacts of those new technologies, let us summarize the R&D programs that have been described above. Such a summary is presented in Table IV-1.

In the discussion in Chapter III an estimate was made of the impacts on resource consumption and environmental effects of the implementation of each technology. These impacts were based on perturbations of the Reference Energy Systems. Such impact estimates are innately uncertain, depending as they do on evaluations of the probability of the success of future R&D and on a number of assumptions related to implementation in the market place. In most cases, the degree of implementation assumed was based on optimistic assumptions on both counts. It is of interest to summarize the impacts relative to the problems defined earlier in the report.

Oil Supply

One measure of the short term fossil fuel supply problem is the projected rate of oil importation. In Figure IV-1 the impact of various new technologies on oil consumption is compared with oil importation projections, made by the National Petroleum Council. It should be noted that the impact of each new technologies is plotted separately. Based on the degree of implementation shown in the figure these new technologies can have only a small impact on this problem in the near term. The sum of the impacts in 1985 amounts to about 10% of

TABLE IV-1 SUMMARY OF R&D PROGRAM

Program	Major Areas of R&D Activity	First Year Funding $ Millions	Long Term Funding[a] $ Millions/Years
Fossil Fuel Extraction	Oil and gas stimulation, oil shale development, conversion of biological waste and underground coal mining.	27.5	1060/10[b,c]
Solar Energy	Space conditioning for buildings; thermal and photovoltaic central station power generation.	12.7	370/10
Geothermal Energy	Resource appraisal, development of exploration and production techniques.	20.8	600/10
Clean Fuels from Coal	Coal and combustion cleanup and conversion technology.	162	3230/8
Advanced Power Cycles	Combined cycle, MHD, fuel cells and comparative studies.	34	622/10
Alternative Breeder Reactors	Molten salt and gas cooled breeders.	12[d]	70/5[d]
Fusion[e]	Confinement research, supporting R&D, technology development.	55[e]	1000/9[e,f]
Hydrogen Uses	R&D on production and storage of H_2.	1.5	23/6
Electrical Transmission	Advanced AC and DC methods, subsurface transmission, control systems, energy storage.	69[g]	501/7[g]
Transportation	Increased fuel economy alternate engines and transport modes.	30	265/15
Urban and Residential	Total energy systems and energy conservation technologies.	11	300/10
	Total First Year Funding	435.5	8041/10[h]
		$563[i]	6000/10[j]
		1,000[k]	14,000/10[k]

TABLE IV-I SUMMARY OF R&D PROGRAM (Cont'd)

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a) Many programs contain elements of different duration. These long term estimates provide only a rough estimate of funding requirements and assume private expenditures will equal or exceed present levels.

b) Assumes continued funding by industry in drilling technology (on and off-shore), advanced oil recovery and refining exclusive of this amount.

c) Assumes industry investment in oil shale mining and retorting demonstration facilities with federal assumption of different cost between market price of oil from shale and crude oil.

d) Includes only funding to maintain Molten Salt Breeder Reactor and Gas Cooled Fast Reactor programs in a reliable backup mode. Light water breeder reactor was not evaluated in detail but the current program was viewed as appropriate. LMFBR development and demonstration not included.

e) Refers only to magnetic confinement approach. Laser fusion was judged to be adequately funded under the military program. In future years this should be reviewed.

f) Rough estimate of total cost to commercial feasibility is $6 billion over 30 years. Excludes laser fusion funding.

g) Represents total program, federal share of which is 20%-40% in specific projects.

h) Excludes Fission R&D (except for Alternate Breeders); health effects research.

i) Expenditures for fission and other items not in program recommendations. (Based on current level of funding.)

j) Fission, health effects, conservation technologies -- project 10-year funding.

k) Total Energy R&D requirements projected over 10-year period.

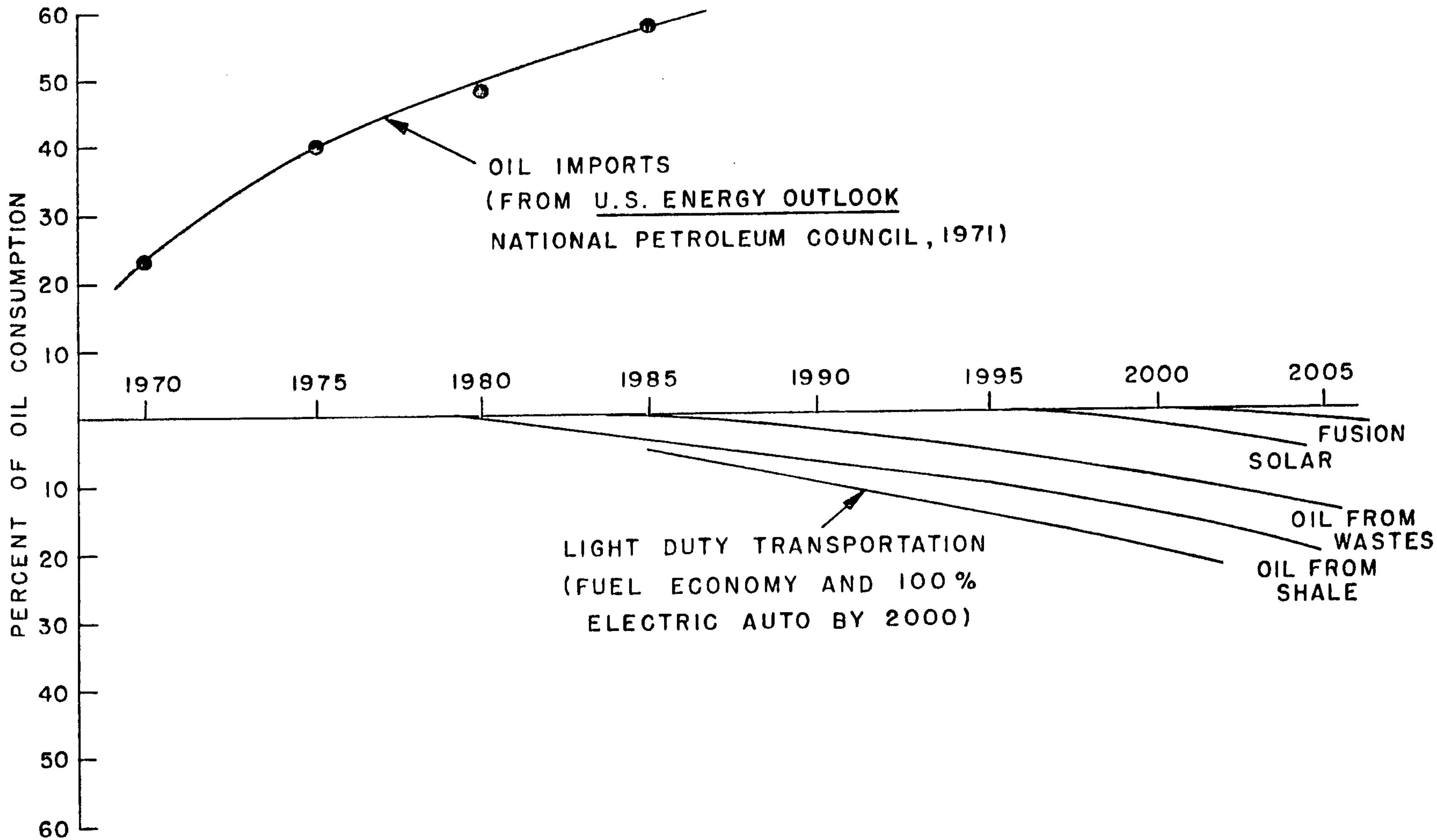

Figure IV-1. Potential Impacts on Oil Importation total consumption. By the year 2000, however, these technologies have the potential of supplying or replacing a total of 45% of total oil demand. Even at that point in time neither fusion nor solar energy could play a large role in displacing oil, but beyond the year 2000 their utilization could increase rapidly.

Gas Supply

In the case of natural gas, the new technology with the greatest potential impact is coal gasification to high-Btu gas. This technology was explicitly considered in the Reference Energy Systems. Figure IV-2 shows the fraction of future gas consumption expected to be supplied by gasified coal and by importation. These are used to indicate the potential impact of two other technologies discussed in Chapter III, namely, stimulation of gas by nuclear explosives and conversion of waste to methane. Although extrapolation beyond 1977 is uncertain, the only new technology with potential short-term impact in this area is nuclear stimulation. Public concern about possible environmental problems of this method, however, may severely limit its applicability.

Electrical Supply

Figure IV-3 shows the potential contribution that several technologies can make to electricity supply. Note that the reference total electrical demand could be increased significantly if electrically powered automobiles were to be used appreciably. The figure indicates the perturbation for the introduction of the electric auto starting around 1985 and achieving 100% by 2000. As the figure shows, only geothermal energy has potential of contributing to electrical supply in the intermediate term. As shown in Section E of Chapter III, the use of advanced topping cycles can have an impact on the amount of fuel used to produce electricity. The nuclear contribution grows rapidly during this period, of course, and warrants separate discussion.

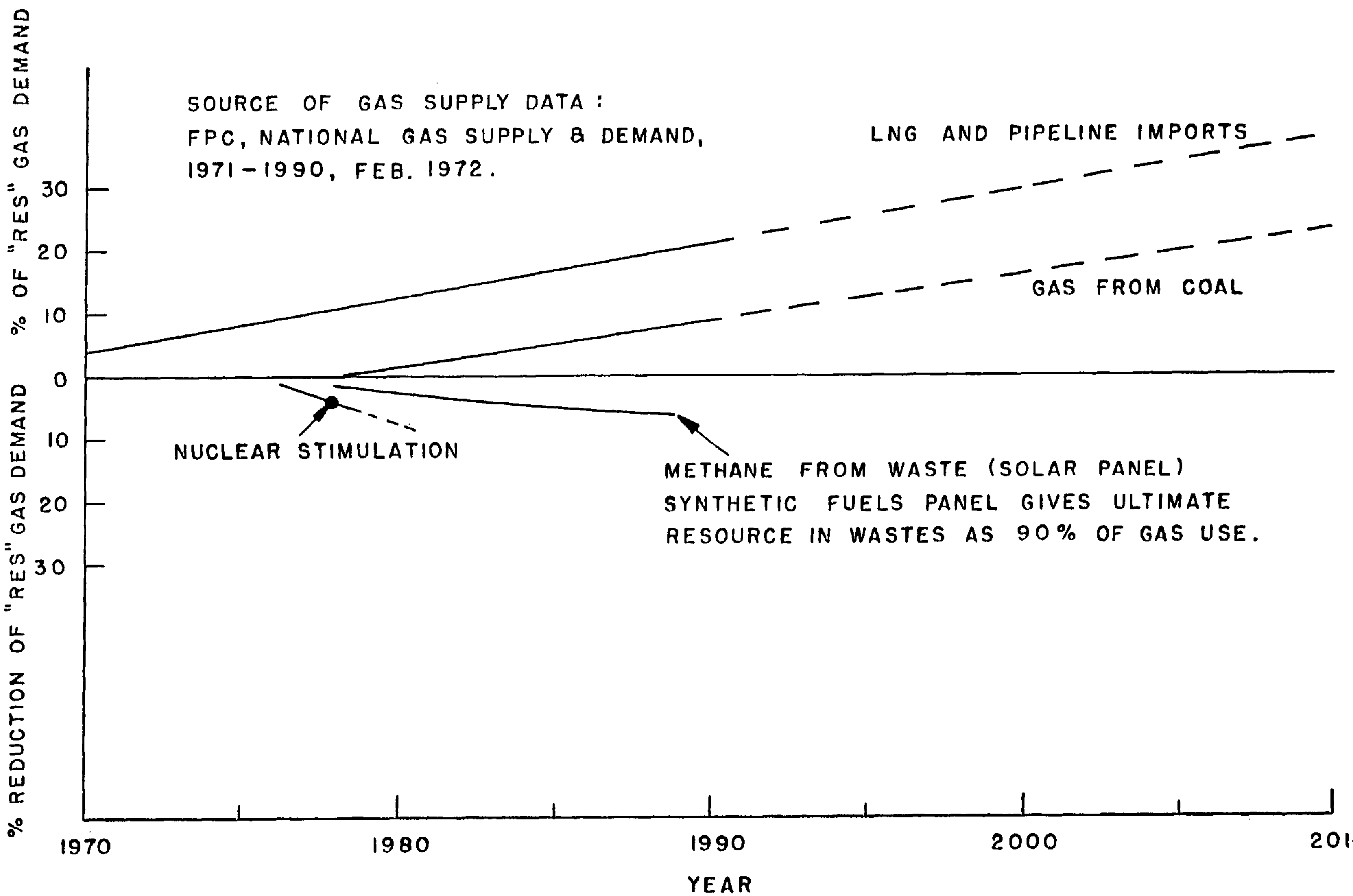

Figure IV-2. Potential Impacts on Gas Supply

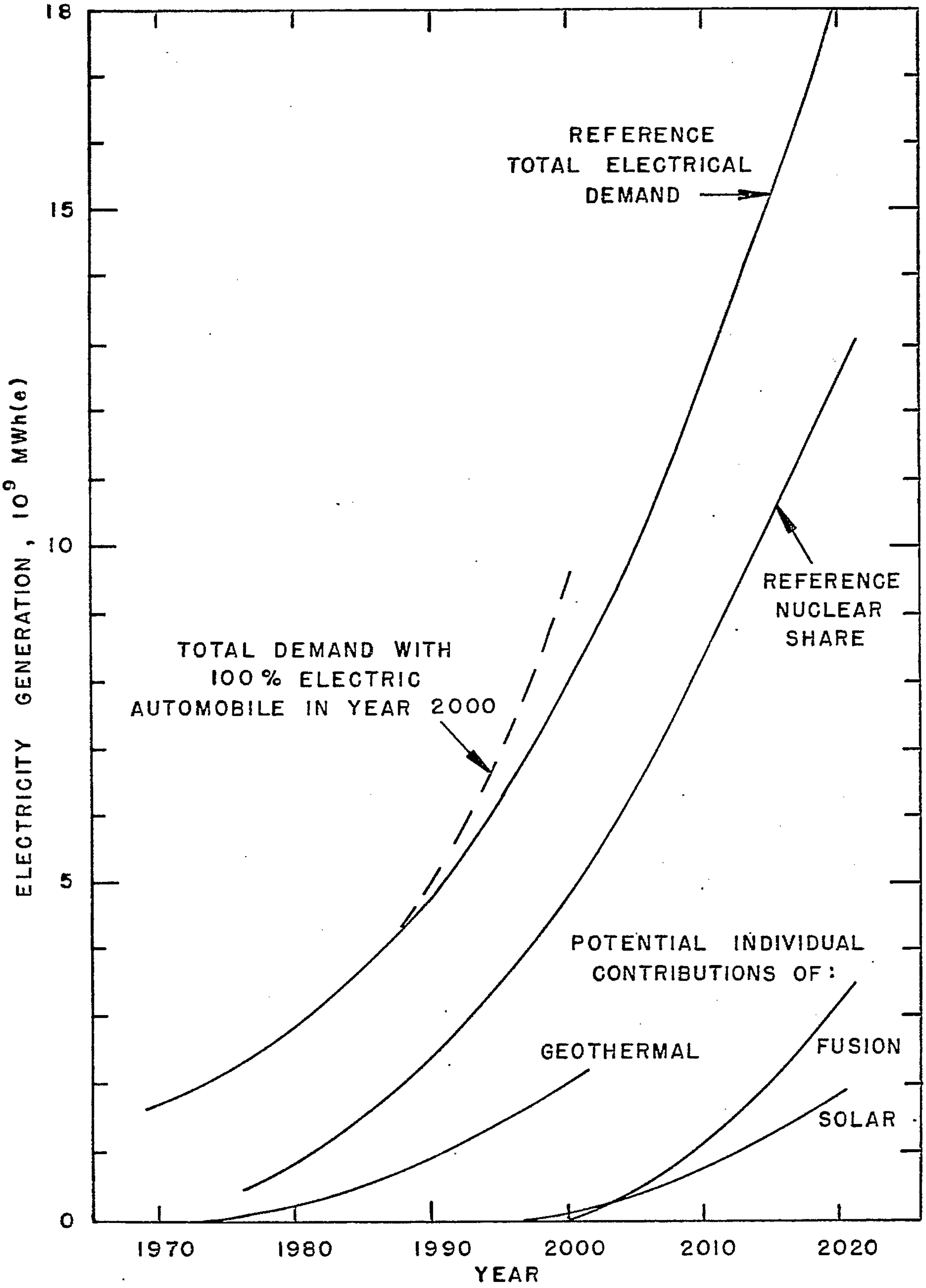

Figure IV-3. Potential Impacts on Electric Supply

Nuclear Energy

Although the main line of fission reactors, light water burners and liquid metal cooled breeders, were not explicitly considered in this study, a few comments should be included.

As is clear from the reference projections and the problems discussed in Chapter II, the fastest growing component of the energy system between now and 1985 will be light water reactors. Although there is no longer a need for Federally-supported R&D for the basic technology of this type of reactor, there is an important need for continued safety research. The problems of long term safe disposal of high level radioactive waste is also of major concern and must continue to receive priority attention until an acceptable solution has been demonstrated. In these areas, the regulatory responsibility of the government requires a continuing authoritative evaluation program beyond the development of technological solutions. These activities, particularly in safety research, are crucial in protecting the near term development of the nuclear component of the energy system.

The gas reactor program is potentially important both in the intermediate and long term. A commercial demonstration of the High Temperature Gas Reactor (HTGR) is scheduled for startup in late 1973 at Fort St. Vrain, Colorado. This reactor could provide improved thermal efficiencies, increased siting flexibility by virtue of its air cooling capabilities and lessened concern over safety as a result of its graphite core. Unanticipated problems can be expected as occurred with the water cooled reactors, but these will likely be resolved in a continuing R&D program. This program also provides a base for component development that can be used in the Gas Cooled Fast Reactor (GCFR), a breeder backup to the LMFBR. The incorporation of a gas turbine in a closed loop helium cycle for energy extraction offers even higher efficiencies for both the HTGR and GCFR. HTGR's could become an attractive reactor option for nuclear plants ordered in the late 1970's and the 1980's, particularly if the breeder is delayed in reaching commercialization.

The medium-term development of nuclear power hinges on the success of a breeder reactor. Although the Liquid Metal Fast Breeder reactor has been selected as the type to be brought to commercial utilization, in Section G of Chapter III it was recommended that the overall security of the breeder program depends on continued interim support of backups to the LMFBR. In both the main line effort and the backup efforts strong safety research programs are necessary if these new technologies are to move expeditiously and with public confidence into their commercial roles.

B. THE BALANCE OF TECHNICAL OPTIONS

The value of flexibility and variety in available energy technologies should be clear from an analysis of current problems of the national energy situation. It should also be clear from the previous discussion of potential impact of new technologies. The variety of needs for energy in this country in the near and distant future cannot be met by only one or two new technologies. Fortunately, as this assessment has shown, there is a large number of places within the system where new technologies, if properly developed, can make significant contributions.

Breadth of technical options is also dictated by our lack of knowledge of environmental and health effects of energy-related residuals. For example, by no means are all of the environmental implications of the use of solar energy clear. But, in principle, they are sufficiently different from those of both fossil and nuclear energy that having solar energy as a real option must be considered an advantage.

Thus the breadth of technologies discussed in Chapter III is not incidental; a diversified balance of technical options is vital to the best future development of the system.

C. POLICY ALTERNATIVES AND REQUIREMENTS

It is important to emphasize again the limited purview of this study. Only technological means of influencing the beneficial development of the energy system were considered. Although the study was carried out in full cognizance of other means of institutional and policy natures, such alternatives were not analyzed explicitly. The summary of potential impacts of new technologies given above, however, clearly indicates the limited impact that R&D programs can have in the near term. Detailed analysis is not required to prove that; it follows from the basic time lags involved in R&D and in implementation. Thus, for the most part, we are forced to look to non-technological approaches to solve the near term problems of the energy system. Many of these approaches, including modifications in tax laws, changes in price regulation and import quotas, and encouragement of conservation can be effective in the short term. Although it is necessary to extend these policies into the medium term, they do not solve the medium and long term problems. For example, an increase in the regulated price of natural gas (or deregulation) will increase production of natural gas, but has little impact on the long term problem of gas supply.

This leads to another type of policy action more closely linked to the R&D programs discussed in Chapter III. In many instances the question of industrial participation was mentioned. A number of factors discourage private industry from supporting the initial stages of research in new technologies. As a technology develops from the early research stage to commercial use, increased involvement of private industry operating in a competitive mode is required. However, because of Federal patent policies and industrial concern for the protection of proprietary information, there is often a reluctance on the part of private industry to collaborate on even the later stages of development. Unfortunately, this is particularly the case for the more experienced companies in a given technological area. The question of how to best encourage private industrial involvement is one which should be addressed in general but which should also be dealt with in each specific development program.

D. FUTURE ANALYSIS

In the course of this study it was very clear that the questions being dealt with were of major importance to the nation and, at the same time, it was clear that the conditions under which the study was performed even if the best under the circumstances, was not entirely satisfactory. The determination of R&D strategies in the energy field is too important and too complex to be carried out under ad hoc conditions. First of all, the sorts of comparative engineering-economic evaluations necessary for intelligent decisions cannot be produced in a short-term effort. Secondly, the analytical tools required to assess the role of new technologies in the future evolution of the energy system require long term development.

Ideally, one would like to base this kind of assessment on fundamental societal goals from which requirements on the energy system and thus on R&D can follow. In this study it was possible to approximate this concept only remotely. The concept implies two requirements. The assessment must be a continuing, multidisciplinary, activity with long time horizons, and it must be situated in an effective location within government.

In many, of not all, of the technological areas under review continuing evaluation efforts were recommended. These are required to optimize the effectiveness of the individual R&D programs. Similarly, a continuing overall assessment activity is required to assure the effectiveness of the kind of broadly based and well balanced R&D program in energy that this country requires.

Finally, the realization of the potential which advanced technology affords is compromised if government's ability to plan and manage its R&D efforts is not properly coordinated internally and externally. The present Federal energy structure is highly fragmented and as a result programs in some areas such as solar, geothermal, energy conversion and coal mining are either underfunded or lack direction. Fission and fusion have benefitted from centralization of these efforts in the Atomic Energy Commission in this regard, even though it can be argued that centralization of the decision making authority can compromise some elements of a program. It is generally acknowledge that the light water reactor safety program, the gas reactor program and to a lesser extent the molten salt reactor and fusion programs have suffered as a result of the major commitment to the LMFBR. Adequate funding and a more open dialogue as these programs evolved over recent years could have avoided these difficulties. The problem here seems to be related more to our failure to appreciate the seriousness of our energy problem soon enough and the need to support a range of options rather than the concept of centralized control.

On balance it is believed that the Federal effort would be improved if, as a minimum, overall planning and management responsibilities for each major program area were centralized in a lead agency. Creation of a single agency with overall energy R&D responsibility, while offering many advantages, may be more difficult to achieve politically and less responsive to external inputs from the technical community, Congress and the public. This decision is one which must ultimately be made by those elected to govern and not this panel. In any event a rapid escalation of funding in the energy R&D area seems essential and this will require the close cooperation of both the legislative and executive branches of government to achieve and the involvement of industry, universities and government laboratories in well planned and managed programs to produce the required results.

Appendix A

Energy Advisory Panel to the Office of Science and Technology

The members of the Energy Advisory Panel that provided the overview evaluation of energy technologies (and their affiliation at the time of the assessment) were:

Professor Manson Benedict
Massachusetts Institute of Technology

Dr. Solomon Buchsbaum
Bell Telephone Laboratories

Gerald L. Decker
The Dow Chemical Company

Dr. Edward J. Gornowski
Esso Research and Engineering Company

Professor S. William Gouse
Carnegie Mellon University

Raymond Q. Huse
Public Service Electric & Gas Company (N.J.)

Professor Donald L. Katz
University of Michigan

Professor Robert W. Rex
University of California, Riverside

Louis H. Roddis
Consolidated Edison Company of NY, Inc.

Professor David J. Rose
Massachusetts Institute of Technology

C. M. Sliepcevich
University Engineers, Inc.

Dr. Chauncey Starr
University of California, Los Angeles

Professor H. H. Woodson
University of Texas at Austin

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U.S. DEPARTMENT OF COMMERCE
Technology Administration
National Technical Information Service
Springfield, VA 22161 (703) 605-6000