COMMERCIAL OBJECTIVES, TECHNOLOGY TRANSFER, AND SYSTEMS ANALYSIS FOR FUSION POWER DEVELOPMENT*

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Fusion is an essentially inexhaustible source of energy that has the potential for economically attractive commercial applications with excellent safety and environmental characteristics. The primary focus for the fusion-energy development program is the generation of central-station electricity. Fusion has the potential, however, for many other applications. The fact that a large fraction of the energy released in a DT fusion reaction is carried by high-energy neutrons suggests potentially unique applications. These include breeding of fissile fuels, production of hydrogen and other chemical products, transmutation or "burning" of various nuclear or chemical wastes, radiation processing of materials, production of radioisotopes, food preservation, medical diagnosis and medical treatment, and space power and space propulsion. In addition, fusion R&D will lead to new products and new markets.

Each fusion application must meet certain standards of economic and safety and environmental attractiveness. For this reason, economics on the one hand, and safety and environment and licensing on the other hand, are the two primary criteria for setting long-range commercial fusion objectives. A major function of systems analysis is to evaluate the potential of fusion against these objectives and to help guide the fusion R&D program toward practical applications. The transfer of fusion technology and skills from the national laboratories and universities to industry is the key to achieving the long-range objective of commercial fusion applications.

KEY WORDS: fusion; fusion systems analysis: fusion applications; fusion technology transfer; fusion planning.

COMMERCIAL OBJECTIVES

Electricity Production

The application of fusion that has received the most study is the production of electricity in a central-station power plant. Commercial objectives for fusion electricity production have the following aims: (1). Make fusion economically competitive with other forms of central-station power for the 21st century. (2). Exploit the safety and environmental advantages of fusion in plants that offer a very low risk to the public and to plant workers, as well as provide a very low risk of losing plant investment costs. (3). Make the R&D costs for fusion an acceptable fraction of the potential benefit.

The key aspects of economic performance are low capital cost, short construction and licensing time, high availability, and low operating costs. These aspects are directly related to requirements on component performance, lifetime, repair time, and safety characteristics that affect licensing. Stringent requirements must be set in all of these areas. The most important areas involve component failure rates and repair times, because high availability must be maintained in fusion plants, which are capital-intensive. Another key objective is to provide a range of unit electrical power ratings in economically attractive plants.

The safety and environmental objectives stress inherent safety under all credible accident conditions. Inherent safety offers many potential benefits,

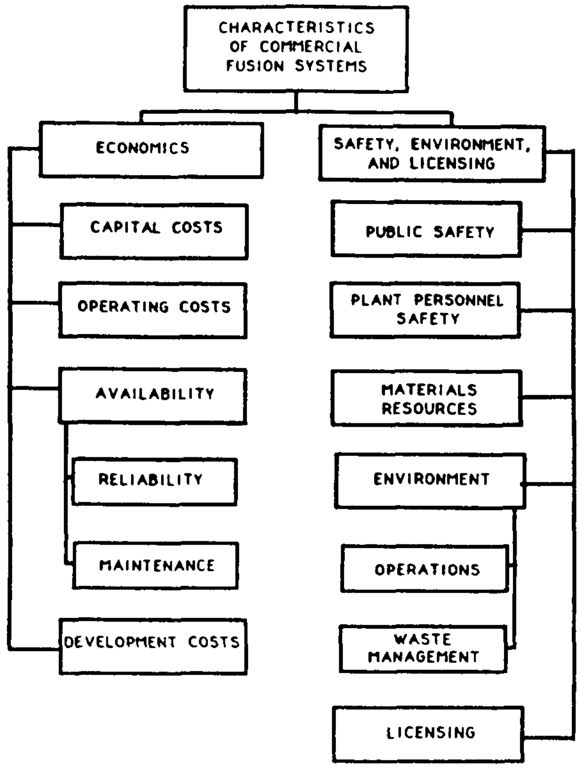

Fig. 1. Characteristics of commercial fusion systems.

Table I. Economic Objectives, Attributes, and Target Values for Electricity Production

Program Element and Subelement	Objective	Attribute	Planning target
Economics	Minimize cost of product	Cost of electricity (mills per kilowatt-hour) evaluated by levelized costing, zero escalation, and inflation, in 1985 dollars	30–40
	Maximize investment protection	Cost of recovery from any fusion-core component or subsystem failure or accident, expressed as percent of original direct capital cost	5–15
		Time required for recovery from any accident (months)	3–9
Capital costs	Minimize capital costs	Total direct cost to construct plant ($\$/kW_e$) for a nominal 1000-$MW_e$ plant	~1000
Operating costs	Minimize operating costs	Cost to operate plant, expressed as percent of cost of electricity	< 5
Availability	Maximize availability	Percent of total time plant is available for full-power operations	~85
Development costs	Minimize development costs	Total projected development cost before first commercial order ($\$10^9$)	~20

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including ease of licensing; elimination of high-cost, engineered safety systems; reduction in backfitting; lower cost for the balance of plant; and public acceptance. Inherent safety must be accompanied by very low normal emissions of hazardous materials.

The commercial objectives are set for a hierarchy of characteristics, as shown in Fig. 1. These objectives are given, along with attributes and target values, in Tables I and II.

Fissile-Fuel Production

An application of fusion that may have economic potential is the cogeneration of both electricity and fissile fuels for later consumption in fission converter reactors (e.g., LWR or HTGR) that produce electricity or process heat. Fissile-fuel production has the following aims: (1). Make fusion-bred fuels economically superior to mined and enriched uranium in the early decades of the 21st century. (2). Provide a source of affordable fissile fuel to support the domestic and international demand for nuclear power for the indefinite future. (3). Provide the technological basis and operating experience required to advance fusion technology to a level such that fusion electric-power generation will become an attractive alternative to conventional nuclear power.

The key aspects of economic performance are low capital costs, high fissile-fuel breeding, high availability, low operating costs, and low fuel-cycle costs. These aspects are directly related to requirements on component performance, lifetime, repair time, and safety characteristics. The most difficult problem areas are component failure rates and repair times. High availability is required in fusion plants because they are capital-intensive. For fissile-fuel breeding, the requirements on fusion performance

Table II. Safety, Environment, and Licensing—Objectives, Attributes, and Target Values

Program element and subelement	Objective	Attribute	Planning target
Public safety	Maximize public safety	Risk to public from accidents, expressed as percent of existing risk from all accidental sources	< 0.1
		Risk to public from routine operations, expressed as percent of existing risk from all routine sources	< 0.1
Plant-personnel safety	Maximize plant-personnel safety	Risk to plant personnel from occupational hazards and accidents, expressed as percent of risk from nonoccupational hazards	<10
Materials	Maximize use of domestically available, abundant, or recyclable materials	For those elements for which fusion is the driver in domestic demand, recycle, expressed as percent of wastage per cycle	1–5, depending on element
		Procurement of no more than stated percent from nondomestic sources	< 20
Environment	Minimize thermal effluent from facility	Waste thermal effluent from facility, expressed as percent of gross thermal power	< 70
	Minimize long-term activation	Percentage of radioactive waste generated that qualifies for near-surface disposal, as defined in 10CFR61 or relevant extensions thereof	> 99%
		Dilution of used material to meet standards, expressed as factor increase in volume of disposed radioactive materials	<10
Licensing	Minimize licensing time	Time frame during which licensing process is completed	Prior to or during construction

(relative to fusion-electric applications) are relaxed, because the fusion energy is multiplied severalfold in the blanket and because an additional product, fissile fuel, is produced. However, safety/environment/licensing issues may be similar to those encountered for fission plants.

Synthetic-Fuel Production

Fusion energy could be a source of electricity and high-temperature process heat for the production of synthetic fuels. Hydrogen production by thermochemical water splitting or by high-temperature electrolysis has received limited study. The hydrogen produced can be used as a feedstock material to produce other fuels, such as methanol.

The advantage of fusion as the heat source for synthetic-fuel (synfuel) technologies stems from the deep penetration of the 14-MeV neutrons produced in the DT reaction. This penetration allows thermal decoupling of the high-temperature blanket from the fusion core. Such decoupling is not possible with combustion or fission heat sources.

The economic performance required of a fusion reactor for synfuel production is equal to or better than that required for central-station electricity production. Thus, most of the objectives defined for electricity are equally applicable to synfuels. The most important environmental objective is to keep the product (hydrogen or organic fuel) free of tritium contamination. The high mobility of tritium and its affinity to replace hydrogen in organic compounds will make achieving the required product cleanliness very difficult.

Other Applications and Spinoffs

The three fusion applications described above are those that have been most extensively analyzed. Plausible conceptual designs have been developed for fusion systems to produce these products, and preliminary economic evaluations indicate that fusion has the potential to compete with alternative sources of these products in the planning time frame for commercial fusion applications. Other potential applications include transmutation of high-level wastes produced in fission reactors, production of radionuclides for commercial and medical applications, and production of special nuclear materials for military applications.

Preliminary analyses have been made of the use of fusion to transmute or "burn" actinide wastes from fission reactors in order to reduce the amount of waste and its long-term toxicity. The prime concerns are economic feasibility and technical complexity.

An application area where fusion may have a significant advantage over alternative sources is the production of radionuclides. Fusion produces about five times more net neutrons per unit of thermal power than does fission, and these neutrons are of much higher energy (14 MeV, compared with 3 MeV for fission). This means that fusion can be a more prolific source of transmutation products than fission. Preliminary analysis of the production of cobalt-60 and other isotopes by fusion indicates that fusion reactors could easily satisfy future market requirements.

Finally, initial studies indicate that fusion reactors can potentially produce tritium and plutonium for military applications much more efficiently than can fission reactors. Many other potential fusion applications exist that have not yet been evaluated.

An important benefit from fusion is the "spinoff" of knowledge and technology to other fields. As the space program has amply demonstrated, when high-technology research and development is undertaken, products and applications result that are of significant benefit outside the immediate program. Fusion has already produced a positive benefit from spinoffs (see Table III). Additional spinoff benefits from fusion science and technology programs are expected.

TECHNOLOGY TRANSFER

The DOE Magnetic Fusion Program Plan contains the following technology-transfer objective:

> The technology transfer objective is to provide a range of options for private sector investment and commercial development of fusion. The establishment of the scientific and technological base for fusion requires industrial participants both to provide expertise in conventional components and to gain experience with the unique aspects of fusion science and technology. The necessary degree of industrial experience is best gained through the technical participation of industrial personnel in the state-of-the-art developments produced by the fusion program. A noteworthy aspect of this objective is that, through it, the fusion program will also serve as a stimulus to United States technological growth and the further training of scientists and engineers in industry.

Table III. Spinoffs from Fusion Science and Technology Programs

Field	Spinoff
Computers	Cray timesharing-system software
Metal forming	Magneform system
Isotope separation	Plasma-separation process
Defense	Neutral- and charged-particle beams; high-power, high-frequency microwave sources and microwave transmission components
Welding	Refractory-armor materials and tiles, homopolar resistance welding
Magnets	Superconducting magnets for energy storage, materials processing, and medical applications

Table IV. Industrial Roles and Functions

Roles	Functions
Advisor	Support-Services Contractor
	Advisory Committees
Direct participant	Research and Development
	Materials Supplier
	Component Supplier and Manufacturer
	Subsystems Contractor
	Prime Contractor, Project Manager
	Facilities Operator
	Customer
Sponsor	Research and Development

This section describes how this DOE objective can be achieved. Industry has played and will play a variety of roles in the development of fusion energy. The more useful roles fulfilled by industry can be separated into three main categories. These categories, along with the principal functions performed in each category, are listed in Table IV. Each of these roles and the corresponding potential functions will be described. A technology transfer plan for industrial contributions in fusion is shown in Fig. 2.

Industry as Advisor

The advisory role is filled frequently by corporate officials, who are asked to help assess various stages of program development and may serve on management boards of development projects. The principal benefit expected from the advisory role is the development of appropriate program goals. (This role is discussed below.)

Support Services

Industry acts as a support-services contractor when it assigns individuals or small groups of individuals to work in direct support of a manager at DOE or at a national laboratory. In such an arrangement, the customer benefits by acquiring immediately needed skills and having a long-term personnel commitment. Industry benefits by acquiring knowledge, contacts, and income.

Advisory Committees

Utilities, as well as industry, can provide members of their technical staffs to serve on technical committees assigned to carry out specific tasks. This participation serves to facilitate development of program goals and provides useful feedback regarding program direction.

Industry as Direct Participant

A number of studies have been conducted to examine the characteristics of research programs that led to the successful commercialization of new technologies. A common characteristic among those technologies was the early involvement of the ultimate user. Therefore, it is important both to the user and to the national program to include early participation of the user at all phases of the program.

To become major participants in the fusion program, industrial executives must understand and identify with near-term program objectives. The program objectives must be developed in conjunction with the ultimate users, if they are expected to become involved early. One near-term goal, essential to the success of fusion, is the resolution of environmental and safety issues, which have proven to be a major stumbling block for fission.

Direct participation requires a corporate commitment of financial and manpower resources to

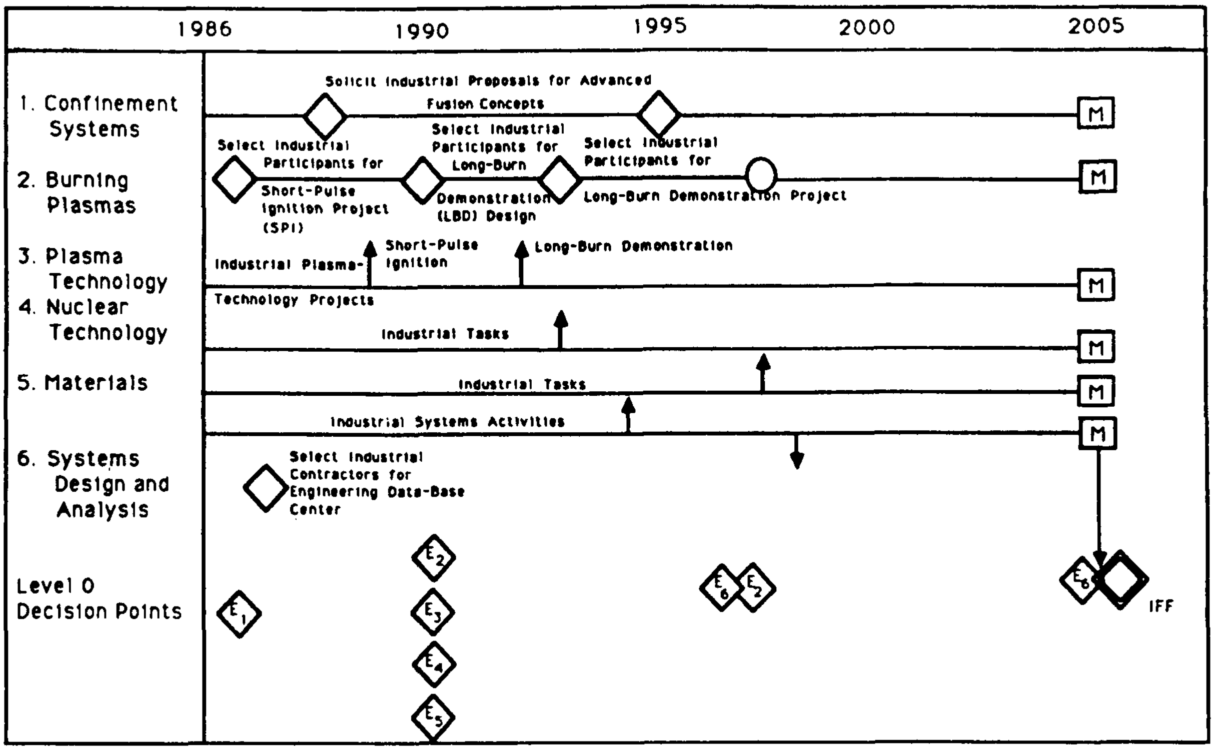

Fig. 2. Logic diagram for technology-transfer plan.

perform fusion work. This type of participation can take a variety of forms; the more notable functions, listed in Table IV, are discussed.

Research and Development

Private companies with unique ideas should be able to compete for funding when, after peer review, such support is technically warranted. The fusion program should make full use of novel ideas and approaches conceived in all sectors of the society, including individuals, national laboratories, universities, and private companies.

Materials Supplier

Materials used for commercial application will require a well-documented history for quality-assurance/quality-control (QA/QC) purposes. As the program enters the commercialization phase of fusion development, detailed engineering specifications will be needed.

Component Supplier and Manufacturer

Industry acts as component supplier or manufacturer when it supplies an off-the-shelf component or when the customer has build-to-print requirements. Industry also frequently designs and manufactures components to customer-supplied specifications. Increasingly, manufacturers will have to take on the job of fabricating fusion-specific components, subsystems, and (eventually) complete reactor systems.

Subsystems Contractor

Industry acts as a subsystems contractor in situations where the customer has defined a scope of work and has assigned to a company the responsibility for performance. This is a most desirable form of industrial participation. The customer benefits by having corporate commitment to the project, and industry benefits by being able to fully exercise its managerial and technical skills through a task assignment where it can bring to bear its background and experience.

Prime Contractor, Project Manager

Industry acts as prime contractor or project manager when it is directly responsible to a customer (e.g., DOE, a national laboratory, or eventually, an electric utility) for defined aspects of management, engineering, fabrication, and installation of a product, such as a fusion device or power reactor. An architect-engineer usually represents the client for engineering, procurement, and construction. However, the manufacture of the steam-supply system is usually carried out by separate companies. The industry roles that will emerge for fusion can only be developed by having experienced companies participate in the program. Preparing companies for these roles should be an important component in the fusion program.

Facilities Operator

Many companies are in the business of operating manufacturing plants, chemical plants, communications networks, and other sophisticated operational activities. To compete in the marketplace, these companies must also mobilize and manage the personnel logistics and training required for facilities operation. Industrial companies can operate fusion equipment that they or others fabricate. This can be an important learning experience and can help prepare the companies for more important roles in the future and for direct participation in the development of fusion power. This is particularly true for those fusion experiments that involve technology development.

Customer

It is important for potential customers to interact with the developers of fusion to ensure that the final product is one that is acceptable for commercial use. Customers must be fully knowledgeable about the scientific and technological questions to be addressed in determining design trade-offs. Companies that deal with customers must be prepared to stand behind their products and services with performance guarantees.

Industry as Sponsor

Sponsorship includes contributions of direct funds, labor, or both. This form of participation has existed since the 1950s, albeit on a small scale, and is continuing now. Industrial sponsorship of fusion R&D includes the direct support of university research by utilities. Indirect utility support has also been provided through the Electric Power Research Institute (EPRI).

SYSTEMS DESIGN AND ANALYSIS

The systems design and analysis area supports major fusion program evaluation and decision points and guides fusion research and development toward practical products. The objectives of the activities in this area should be: (1) to ensure the development of practical fusion applications, (2) to complete preconceptual designs of major fusion facilities, (3) to analyze critical issues and optimize development paths, (4) to identify and implement necessary safety, environmental, and licensing features for fusion development, (5) to plan and execute necessary research and development for remote technology equipment, and (6) to evaluate the potential of alternative (non-DT) fuel cycles. The major systems activities are characterized in Fig. 3.

Systems design and analysis activities provide the fusion program with important tools, data, and perspective. Activities include the identification and resolution of critical issues that involve the interaction of plasma physics and technology, the maintenance of an engineering data base, and the setting of subsystem objectives based on identification of desired economic and safety/environmental characteristics of commercial fusion applications.

A recent accomplishment of these activities is the preconceptual design of the proposed short-pulse ignition experiment. The integrated physics and engineering effort involved in that high-field design showed that a low-cost, short-pulse ignition experiment was possible. This conclusion had not been widely accepted by the fusion community a few years earlier. The systems activities have also provided a key basis for international collaboration through the International Tokamak Reactor (INTOR) program. Guidance from systems studies also has had a major impact on programmatic directions in such areas as steady-state current drive and high-beta tokamak operation. Design studies of reactors based on advanced fusion concepts have also guided research programs for these concepts.

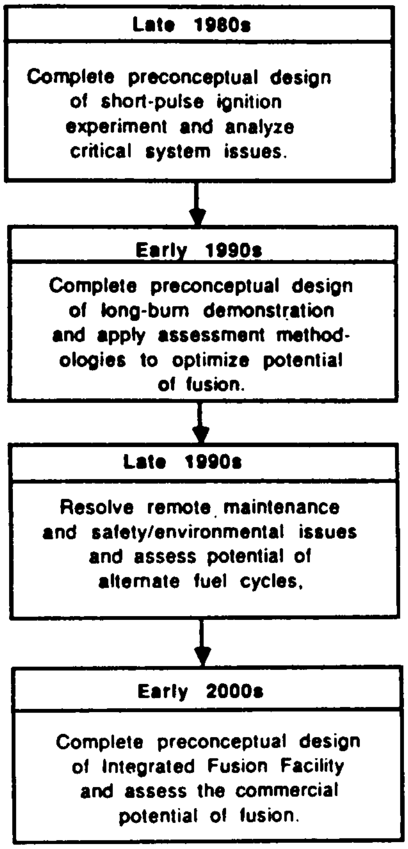

Fig. 3. Characterization of tasks for systems design and analysis.

Commercial fusion facility designs are important, particularly at this early stage of fusion development, to help identify necessary R&D program goals. The design studies are essential for guiding fusion R&D, and they provide a focus for the fusion program—namely, the development of useful products. The designs highlight the importance of good safety and environmental features, combined with acceptable costs.

Through design studies, system requirements are identified and the research and development needed for the fruition of fusion applications is forecast. For any given confinement scheme, the design activities ensure that all subsystems can be integrated within the constraints imposed by materials, technology, and physics to produce a system that is economically attractive and technologically feasible, while simultaneously maximizing safety and minimizing environmental effects. Depending on the confinement scheme being considered, these studies range from simple scoping analyses to detailed, multiyear preconceptual designs using sophisticated models.

Systems studies will provide important programmatic guidance in the preconceptual design of the device to produce a long-burn demonstration. The long-burn demonstration links broad national and international interests in fusion development. There is a spectrum of possibilities for long-pulse ignited devices, with a substantial variation in cost and technology requirements. The fusion program must find the most attractive design concept.

Another important function of systems activities is to search for development paths that have test-facility requirements that minimize the cost and risk of fusion development and compress the schedule. Test facilities should be capable of relatively rapid construction and very reliable operation. This is a very difficult issue, requiring contributions from people who have special expertise in global systems analysis.

Systems design and analysis covers a broad array of conceptual studies and facility designs, defines and maintains a listing of subsystems and component objectives for commercial and integrated test fusion reactors, relates these objectives to the objectives of specific science and technology programs, and assists in the optimization of program-implementation strategies. Systems design and analysis also treats the programs required (1) for developing remote technology equipment and (2) for developing fusion concepts based upon non-DT fuel cycles.

The systems design and analysis area should include the following program elements: (1) applications, economics, and technology transfer, (2) fusion test facilities, critical issues, and development pathways, (3) safety, environment, and licensing, (4) remote technology, (5) alternative fuel cycles.

A further breakdown of these program elements (discussed below) into subelements is given in Table V. A logic diagram is shown in Fig. 4.

Applications, Economics, and Technology Transfer

This program element includes activities in commercial-reactor preconceptual design, development of a range of fusion applications, development and application of methods to analyze the economic potential of fusion applications, and studies of factors affecting availability of facilities. It also provides for studies to identify the appropriate roles and timing for industrial participation in fusion R&D activities and the process of transferring the technology to industry. The milestones for this element are

Table V. Systems Design and Analysis Program Elements and Subelements

Program elements	Subelements
Applications, economics and technology transfer	Commercial-reactor preconceptual design
	Applications studies
	Economics analysis
	Availability analysis
	Technology-transfer studies
Fusion test facilities, critical issues, and development pathways	Fusion test facilities preconceptual design
	Critical-issues analysis
	Engineering-data-base assessment
	Development-pathways analysis
Safety, environment, and licensing	Safety
	Environment
	Licensing
Remote technology	Program plan
	Concepts
	Equipment development
	Applications
Alternative fuel cycles	Confinement systems and burning plasmas
	Plasma technology
	Nuclear technology and materials
	Systems design and analysis

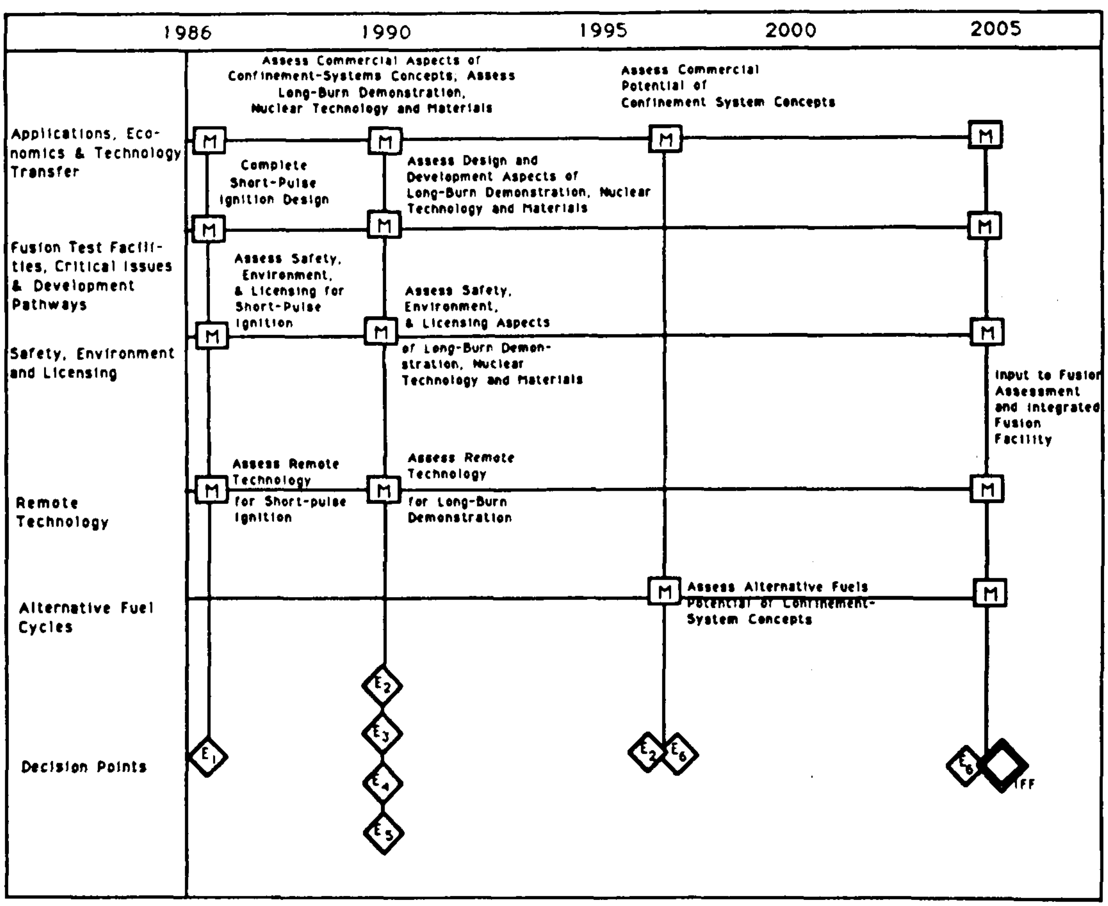

Fig. 4. Logic diagram for systems design and analysis.

to use the methods and data from these studies in reaching major program decisions.

Fusion Test Facilities, Critical Issues, and Development Pathways

This program element includes, in part, preconceptual designs of fusion test facilities, such as the short-pulse ignition experiment, the long-burn demonstration, and the integrated fusion facility. Milestones are established to provide the data to support those program decisions (see Fig. 4). This program element also provides for ongoing analysis of critical issues, including the assessment of systems issues arising from physics/technology interfaces identified in design studies. This element also provides for the establishment and maintenance of an engineering data base for component fabrication and design standards and includes development-pathways analysis, to develop and apply methodologies for estimating the time, risk, and cost impact of alternative technical options for fusion power development.

Safety, Environment, and Licensing

This program element is focused on the identification of critical fusion safety and environmental issues and on providing (1) experimentally verified methodologies for analysis, assessment, and resolution of these issues; (2) a technical basis for safety and environmental improvements in fusion reactor designs; and (3) a technical foundation and recommended strategies for licensing of commercial fusion reactors. The major milestones are timed to provide information to be used in making major program decisions.

Remote Technology

This program element includes activities aimed at developing the necessary design inputs, equipment, and procedures to support availability goals for a sequence of more ambitious test facilities, leading eventually to commercial plants. While substantial advances in remote technology can be anticipated independently of the fusion program, many aspects will be unique to fusion. The major milestones in this area are to provide the necessary remote-technology readiness needed for the decisions to build major fusion facilities (such as the short-pulse ignition experiment, the long-burn demonstration, and the integrated fusion facility) and to provide special-purpose equipment for these facilities.

Alternative Fuel Cycles

This program element includes the analysis of the potential of fusion fuel cycles other than the primary deuterium-tritium (DT) option. Operation with a fuel cycle other than DT could potentially reduce significantly the constraints on fusion-reactor design by eliminating the requirement for a tritium-breeding blanket. However, substantially improved values of beta and density-confinement-time product are necessary, compared with those required for DT operation. In addition, devices of larger size, stronger magnetic field, or both may be required. A variety of R&D activities important to the assessment of alternative fuel cycles is required. The results of these activities are not projected to influence a major program decision until the late 1990s.

APPLICATIONS, ECONOMICS, AND TECHNOLOGY TRANSFER

This program element consists of the following five subelements: (1) commercial facilities preconceptual design, (2) applications studies, (3) economic analysis, (4) availability analysis, (5) technology-transfer studies.

Issues, Objectives, and Attributes

The issues associated with the program element for applications, economics, and technology transfer are as follows: (1) The full range of potential commercial applications for fusion science and technology must be identified. The most likely application and the one that has received the most study is the generation of electricity; however, a number of other potential applications must be considered. (2) Preconceptual designs of potential commercial facilities must be performed now (and updated frequently), so that systems-related issues important to the design of attractive end products likely to affect near-term R&D programs will be appropriately identified. (3) Fusion research and development is carried out primarily in national laboratories and universities at present, but the skills required to commercialize fu-

Table VI. Objectives and Attributes for Applications, Economics, and Technology Transfer Program Element

Objective	Attribute	Planning target
Maximize number of fusion applications,	Number of potential applications with competitive economic and safety/environmental features	At least three
Maximize attractiveness of commercial fusion applications	Number of designs that meet economic and safety/environmental targets for each application	At least three
Optimize industrial participation in fusion program	Preparation of technology-transfer plan	Complete plan
Develop skill in projecting fusion economics	Preparation and standardization of economic models	Complete models
Maximize plant availability	Development of model and data base to analyze plant availability	Complete model and data base

sion must eventually be based in industry. (4) Perspective is required on the potential economics of fusion applications because fusion must compete with other technologies in the commercial marketplace. Plant availability is a critical factor in economic analysis. (5) Data, approaches, and methodologies are needed to establish a basis to achieve acceptable availability in fusion facilities.

The objectives, associated attributes, and proposed planning targets required to resolve the above issues are listed in Table VI.

Program Logic

The logic diagram for this program element is shown in Fig. 5. The program logic is discussed below.

Commercial-Reactor Preconceptual Design

This design effort includes conceptualization of commercial fusion facilities. Design activities are carried out for all fusion confinement concepts. The insights gained from these design activities are used to guide the science and technology programs and to assist with major program evaluations. Studies may be performed at varying levels of detail, as appropriate. For example, concepts with no direct experimental basis would be limited to scoping studies to assess their potential; preconceptual designs based on physics scaling and general reactor modeling would be carried out for concepts with some small-scale experimental verification, and concepts having a major experimental base would undergo detailed preconceptual engineering design.

Fusion Applications Studies

These studies are carried out in three areas: (1) continued assessment of the supply, demand, and cost of electricity from fusion; (2) investigation of fissile-fuel and nuclear-materials breeding; and (3) exploration of other nonelectric fusion applications.

The study of fissile-materials production would provide a basis for the technical evaluation of using fusion as a source of neutrons for such applications. An updated evaluation of fast fission hybrids should be made that incorporates the new safety and fuel-cycle ideas developed in recent years as part of the fission-suppressed hybrid designs. These ideas could lead to a significant improvement in the attractiveness of fast fission designs. Low-Q fusion reactors should be included in hybrid-system designs. These evaluations would contribute to the decision on a reference fusion breeder design. In parallel with the design of the reference fusion breeder, fuel cycle and reprocessing studies and deployment and development studies should be performed. The results of these studies would provide the basis for an evaluation of the technical, economic, safety, and environmental characteristics of the fusion breeder for input into the integrated fusion facility decision and the overall assessment of fusion.

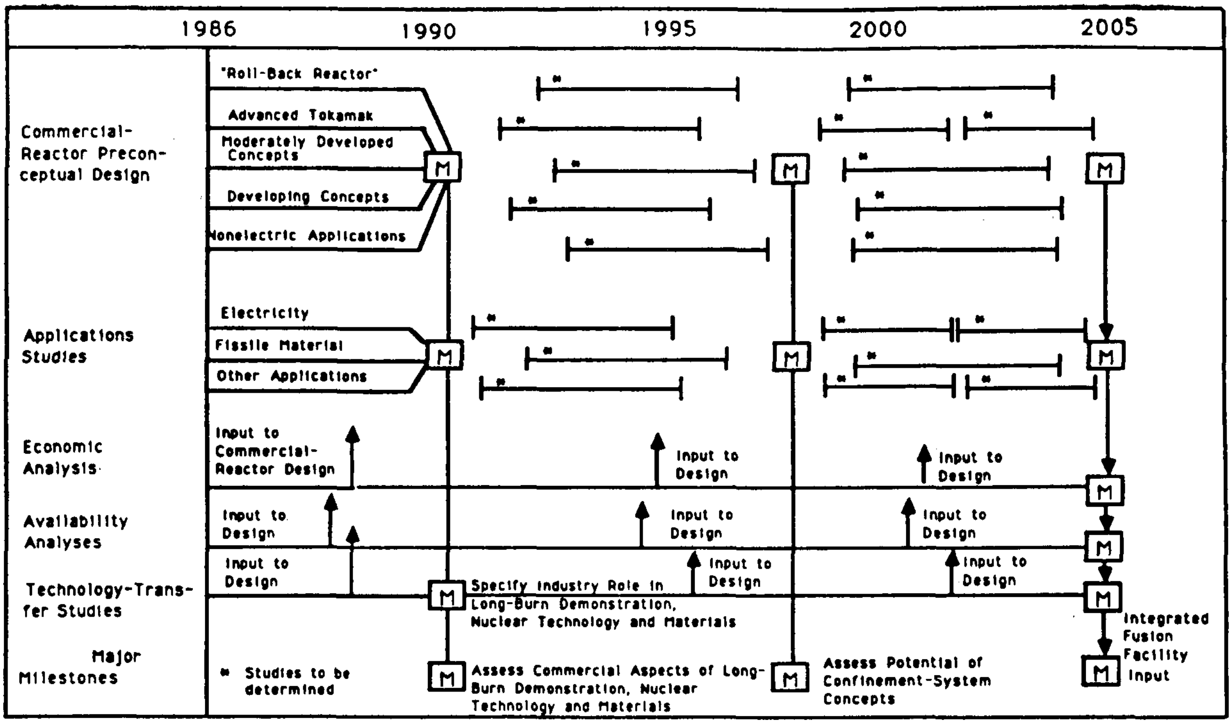

Fig. 5. Logic diagram for applications, economics, and technology transfer.

The other potential applications of fusion should be studied to provide a thorough assessment of the capability of fusion to produce a wide variety of products other than electricity and nuclear fuel. Fusion has the potential to produce hydrogen and other nuclear materials and chemical products, to "burn" nuclear and chemical wastes, to produce useful radioisotopes for food preservation and medical applications, to perform radiation processing of materials, and to provide space power and space propulsion. Still other applications may be possible. These studies will provide a preliminary assessment of the many potential applications of fusion and identify potential new ideas. These new ideas will be compared with applications that have already been evaluated. The results of small-scale experiments to verify the nuclear and chemical processes required for some applications will be considered in these studies. This task will culminate in an assessment of the potential of fusion to produce useful products in addition to electricity and fissile fuel. This assessment will produce valuable information for the overall assessment of fusion and for the decision whether to proceed with an integrated fusion facility.

Economics Analysis

This task consists of (1) developing and applying methodologies for estimating the costs of fusion products, (2) maintaining a cost data base, and (3) assessing the impact of development costs on fusion economics.

Availability Analysis

This task consists of (1) developing and applying methodologies to predict the availability of commercial fusion facilities and fusion test facilities, (2) establishing and maintaining a component reliability/maintainability data base, and (3) recommending design and/or operational modifications to improve facility availability.

Technology Transfer

This activity consists of studies to analyze and apply procedures for identifying appropriate industrial roles in fusion R&D activities. Results of these studies will be available as input to major program decisions and for incorporation into agreements on international collaboration.

FUSION TEST FACILITIES, CRITICAL ISSUES, AND DEVELOPMENT PATHWAYS

This program element consists of the following four subelements: (1) fusion test facilities preconceptual design, (2) critical-issues analysis, (3) engineering-data-base assessment, (4) development-pathways analysis.

Issues, Objectives, and Attributes

The issues associated with this program element are as follows: (1) Timely preconceptual design studies of required fusion test facilities must be available to support major program decisions and discussions on international collaboration. These studies are also critical to development-pathways analysis. (2) Many critical technical issues involve the interaction of plasma physics and one or more technology components and, thus, would not necessarily be addressed by the component-development or science programs. (3) A continuing formal effort is required to optimize the technical program, because a large number of optional technical pathways exist, each with its associated cost, schedule, and risk.

The objectives and associated attributes required to resolve these issues are listed in Table VII.

Program Logic

The logic diagram for this program element is shown in Fig. 6; program subelements are discussed below.

Fusion Test Facilities Preconceptual Design

Preconceptual design activities are carried out for test facilities having a fusion plasma core. The activities include support for the short-pulse ignition experiment and a long-burn demonstration, as well as possible engineering or materials test reactors or other integrated fusion facilities.

Preconceptual design studies typically are performed to identify promising embodiments of a given confinement concept to satisfy the fusion test facilities missions and objectives. Each study evaluates candidate options at a scoping level, makes a choice among the options that becomes a baseline design, and then develops the physics and component engineering of all the major systems and subsystems to a depth sufficient to establish feasibility, R&D needs, and performance. Companion activities are performed that include establishment of design and construction schedules, safety and environmental

Table VII. Objectives and Attributes for Fusion Test Facilities, Critical Issues, and Development-Pathways Program Element

Objective	Attribute	Planning target
Design fusion test facilities	Number of designs completed or under way	At least four
Minimize cost of fusion test facilities	Capital cost of any individual test facility, expressed as percent of annual magnetic-fusion budget	Less than 20%
Maximize resolution of systems-based critical issues	Number of design studies formally reviewed and critical issues analyzed	All
Minimize cost, schedule, and risk of fusion-energy development	Preparation of methodology for performing development-pathways analysis	Complete model
Maximize excellence of engineering in fusion facilities	Establishment and maintenance of engineering data-base from fusion and fusion-related experience	Establish engineering-data-base center

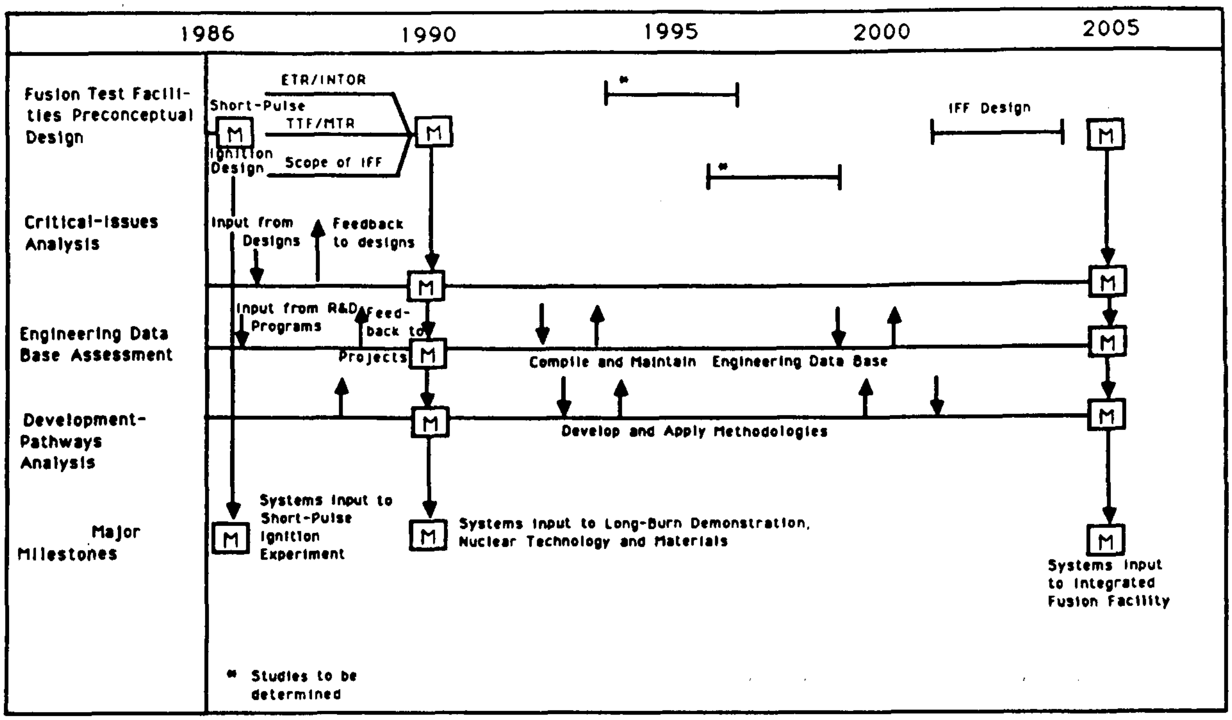

Fig. 6. Logic diagram for fusion test facilities, critical issues, and development pathways.

evaluations, siting evaluations, conventional facilities needs, and preparations of comprehensive cost estimates.

Completion of preconceptual design studies for major fusion test facilities is a significant systems design and analysis activity. Such studies require an integrated project team with physics and technological expertise and project-oriented tasks and milestones. The output of such studies provides the program with the basis for decisions to launch major construction projects.

Critical-Issues Analysis

This task consists of reviews of all conceptual-design reports and other systems studies to identify critical technical issues that involve the interaction of several aspects of plasma physics and fusion technology and the analyses of these issues. The activity investigates innovative solutions and identifies required R&D. Some technical issues, such as impurity control and transient electromagnetics, can be properly addressed only in a systems context. Basic information is developed in the physics and technology R&D programs, but the synthesis of this information into workable solutions requires systems analysis.

The study of critical issues may be broken down into two categories: (1) feasibility analysis and optimization and (2) innovative-solutions studies. Feasibility analysis and optimization consists of in-depth analyses of leading candidate systems (e.g., the poloidal divertor for impurity control). This activity consists of model development and verification, analyses to determine performance limits, and detailed analyses to optimize design parameters. Such studies should produce an understanding of how the system works, verification of calculational tools, and guidelines for design optimization. These results are important for the preconceptual design activities of both test facilities and commercial facilities.

Innovative-solutions studies are intended to find better or simpler solutions to critical systems issues. For example, a scheme for cooling the plasma edge could allow a simpler limiter to replace the divertor for impurity control. The results of such studies provide input to the feasibility analysis and optimization studies and also provide guidance for innovative conceptual-design studies. These results will also be integrated into the science and technology R&D programs.

Engineering-Data-Base Assessment

This activity involves the compilation and evaluation of engineering information that will aid the design, construction, and operation of future fusion facilities. As fusion research moves toward the development of more engineering-oriented fusion devices and ultimate commercialization, an ongoing program will be needed to develop and maintain a data base of engineering practices, experiences, and needs. This compilation should be based on knowledge and understanding obtained from the design, construction, and operation of previous and existing fusion devices; on a compilation of perceived engineering-related needs for future fusion devices; and on engineering advances made in advanced technologies related to fusion. Development and maintenance of such an engineering data base will enhance the ability of the fusion program to incorporate the best components, systems, and engineering practices into future fusion devices.

Development-Pathways Analysis

This activity consists of developing and applying methodologies for assessing the cost, risk, and schedule impacts of differing approaches to fusion development. The methodologies incorporate such factors as technical uncertainties and the size, cost, and number of needed test facilities. The technique will incorporate standardized methods for comparing different concepts and different potential applications. An important objective is to identify pathways that lead to useful commercial products while minimizing development times and costs.

SAFETY, ENVIRONMENT, AND LICENSING

The safety, environment, and licensing program element consists of the following three subelements: (1) safety, (2) environment, (3) licensing.

This program element is aimed at performing the experiments and analyses required to develop a quantitative understanding of fusion safety and environmental issues and to provide the needed safety, environment, and licensing input. This input will affect (1) the selection and design of the short-pulse ignition experiment, (2) the long-burn demonstration, (3) fusion-technology separate effects and integrated testing, (4) fusion technology and materials testing in a fusion environment, and (5) the overall evaluation of the potential for commercial fusion and the decision on an integrated fusion facility.

Issues, Objectives, and Attributes

The primary issues in the safety, environment, and licensing program element are associated with the radioactive inventories that will result from the operation of fusion reactors. These inventories can vary widely, depending on the fusion fuel cycle (e.g., DT, DD, or D^3He) and reactor materials chosen. For example, a DT-burning fusion reactor with a stainless steel structure will contain approximately 10^9 Ci of activation products per gigawatt thermal (10^9 Ci/GW) and approximately 10^8 Ci of tritium. Regardless of the choices of fuel cycle and materials, protection of the health and safety of the general public and plant operating personnel must be ensured during normal operation and during accident conditions. Fusion plants must also have acceptable environmental features, and the licensing of fusion plants must be accomplished in an efficient manner. The primary issues are as follows:

1. Protection of the general public and plant operating personnel must be provided during all normal and accident conditions that could occur at a fusion plant. Whenever possible, this protection should be provided by having plants that are inherently safe (having passive safety features rather than extensive engineered safeguards). Research to resolve this issue should focus on the presence and potential release of radioactivity in the fusion plant.

2. Safety-analysis methodologies must be developed for analyzing the potential safety and environmental impacts of fusion plants. These methodologies must be adequately verified by comparison with data from separate-effects and integral systems tests. Results obtained by use of these methodologies must be realistic and have quantifiable uncertainties.

3. Fusion plants must be environmentally benign and comply with environmental criteria acceptable to regulatory agencies and the general public. For example, the U.S. Environmental Protection Agency's standards for air and water quality must be followed.

In terms of waste management, the fusion community should adopt the goal that fusion radioactive wastes be amenable to disposal by shallow land burial, as specified in 10CFR61. Also, materials-utilization strategies must be developed, including recycling, so that implementation of a fusion economy does not strain the natural resources available for fusion-plant deployment.

4. A rational, efficient licensing system must be developed for commercial plants. Ideally, licensing should not constitute a significant cost of installing a fusion plant, and the licensing activity should be easily accomplished within the time required to physically construct the plant. At the present time, a licensing approach based on risk-based safety goals and the risk-assessment methodology appears to be the most rational approach. With such an approach, the risks from fusion can be placed in context with other societal risks.

The objectives and their associated attributes needed for the resolution of these issues are listed in Table VIII.

Table VIII. Objectives and Attributes for Safety, Environment, and Licensing Program Element

Objective	Attribute	Planning target
Maximize safety of general public during normal operation and during accidents	Risk to general public, expressed as an incremental increase in existing risk from all routine and accidental sources	Less than 0.1% per individual
Maximize plant personnel safety	Risk to plant personnel, expressed as a percent of risk from nonoccupational hazards	Less than 10%
Maximize quantitative understanding of safety aspects of fusion systems	Methodologies developed for assessing safety consequences of fusion power	Develop and verify models, with quantifiable uncertainties in calculated results
Maximize inherent safety of fusion	Number of prompt fatalities in general public, calculated as a result of severe but credible accidents, with passive safety features	Zero
Maximize understanding of fusion radioactive wastes produced	Methodologies developed for calculating quantity of radioactive waste to be handled for each radioisotope	Develop and verify models, with quantifiable uncertainties in calculated results
Minimize high-level radioactive wastes from fusion systems	Percentage of radioactive wastes from fusion plants that can qualify for near-surface burial, as defined in 10CFR61	> 99%
Maximize use of abundant or easily recyclable materials	For materials with near-term supply limitations, percentage of wastage per recycle	Less than 5%
Minimize impact of licensing activities on cost of fusion power	Percentage of cost of fusion power that can be attributed to licensing activities and delays	Less than 5%
Minimize licensing time for fusion plants	Time frame for completion of licensing process	Within time required to physically construct plant
Maximize use of probabilistic risk-assessment techniques in fusion licensing.	Capability developed to implement probabilistic risk assessment for fusion systems	Develop methodologies, gather appropriate data base, and obtain approval of safety goals

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Program Logic

The logic diagram for this subelement is shown in Fig. 7. Figures 8 and 9 show the three logic diagrams for the safety subelement and combined environment and licensing subelements, respectively. The implications of these figures are discussed below.

The primary activities involved in the safety subelement are: (1) to develop and apply methodologies for assessing accident consequences and (2) to develop and collect the data base necessary for the verification of these methodologies. Research is focused on the safety concerns of tritium and activation products and on potential mechanisms for their release; these concerns include lithium fires, magnet accidents, plasma disruptions, and coolant-system failures. Safety-related data to be used in the activities will be generated by safety and fusion-technology experiments, by the materials-research program, and by such fusion facilities as TSTA, TFTR, the short-pulse ignition experiment, and the long-burn demonstration.

The primary activities in the environment subelement are: (1) to develop methodologies for analyzing and resolving waste-management issues, (2) to prepare (or assist in preparation of) environmental reports for major fusion-research facilities, and (3) to analyze and develop strategies for utilization and recycling of fusion materials, especially those with near-term supply limitations. The primary generators of radioactive-waste data for this activity include TSTA, TFTR, the short-pulse ignition experiment, and the long-burn demonstration. The output of this activity will be used to prepare environmental reports for future facilities. Ongoing commercial-reactor design studies will be used to assess resource-utilization issues and the need for developing resource-utilization/recycling strategies.

The actual need for a fusion licensing system will not arise until after the beginning of the next century; however, the data requirements for such a system must be anticipated so that relevant data can be generated and collected by ongoing programs. Also, because of the impact that a licensing system can have on fusion economics and on the acceptability of the technology to utilities and the general public, a technically well-founded and streamlined system must be established. The activities in this subelement provide for safety-approval strategies for the major fusion experimental facilities and develop-

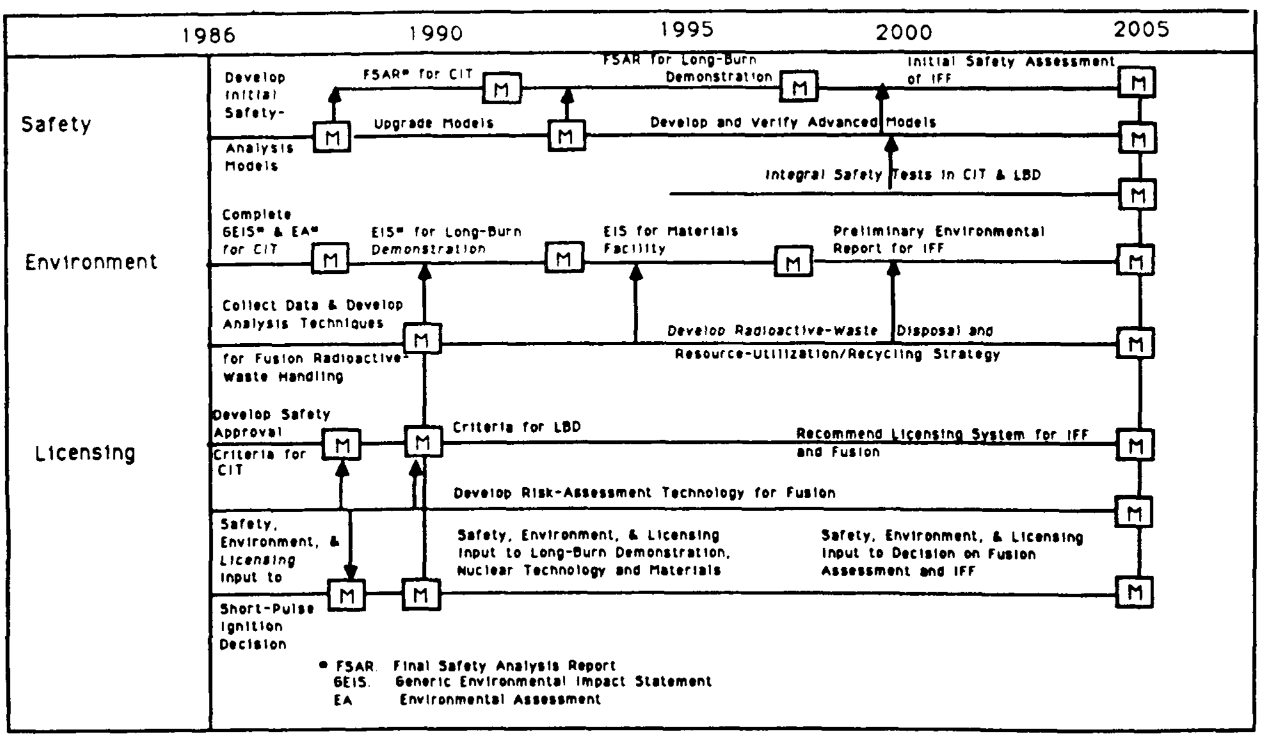

Fig. 7. Logic diagram for safety, environment, and licensing.

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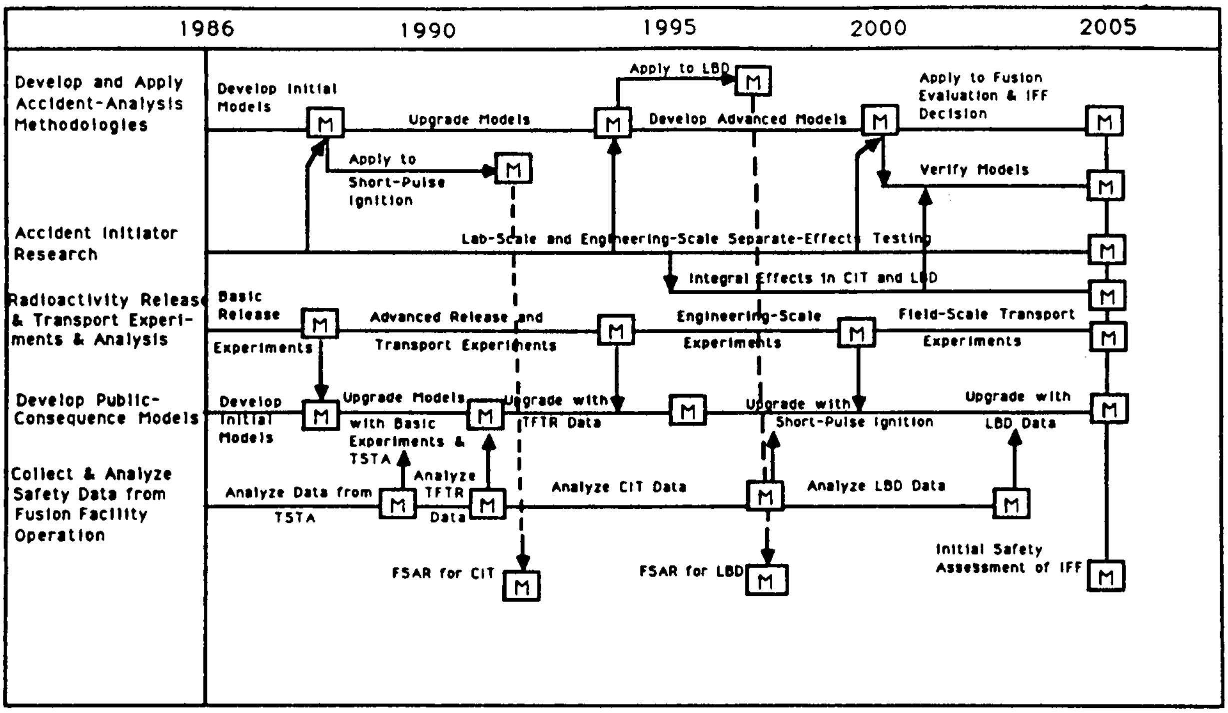

Fig. 8. Logic diagram for safety.

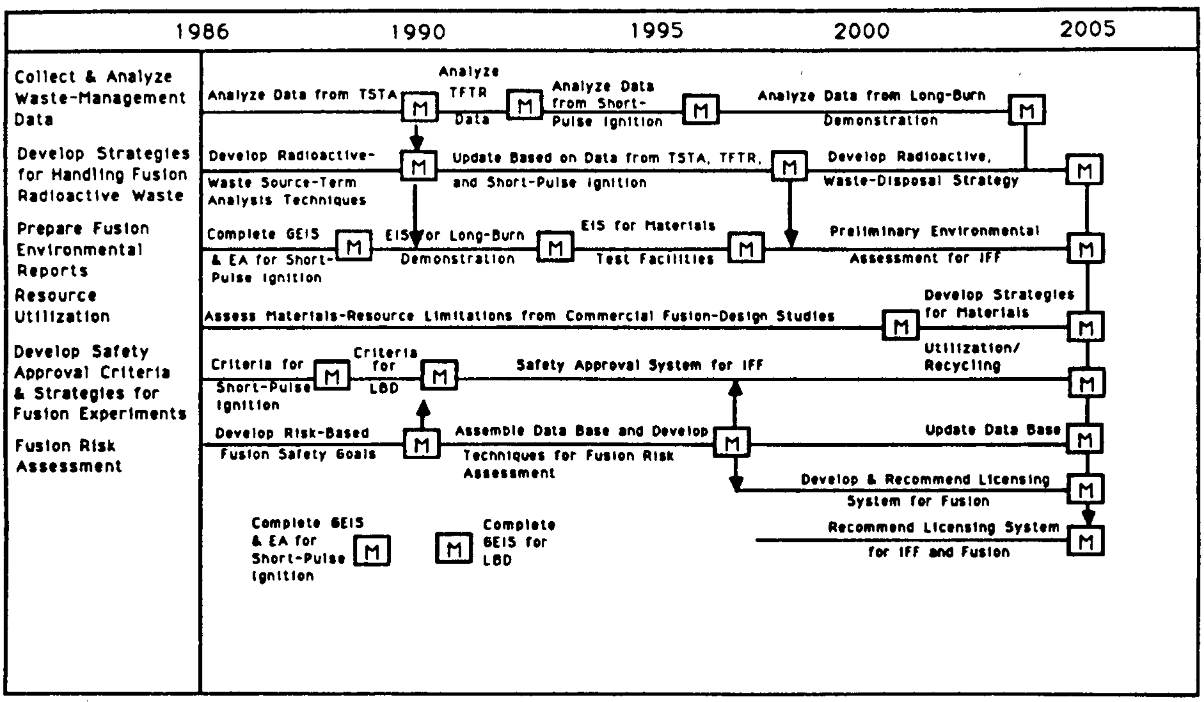

Fig. 9. Logic diagram for environment and licensing.

ment of the risk-assessment methodology that will form the basis for a fusion licensing system. This latter activity requires establishment of risk-based safety goals and collection of a fusion-relevant, failure-rate data base to allow the probabilities of various radioactivity-release scenarios to be calculated.

REMOTE TECHNOLOGY

The primary purpose of the remote-technology program element is to develop the necessary equipment and procedures for design, operation, and maintenance of all future fusion devices, ultimately including commercial fusion plants. All fusion devices to date have been designed, operated, and maintained with the capability of full access by personnel and equipment when adjustments for operation, maintenance, or replacement of components have been necessary. Operation and maintenance in a highly activated environment have, until now, not been required. All future fusion devices will operate and require service in a highly activated environment. Providing for the operation and maintenance of such fusion devices will require substantial integration of remote-technology equipment and practices into the basic design of the device.

Substantial advances in remote technology can be anticipated in fields outside the fusion program. However, many aspects of the fusion program will be unique in the application of this technology. From the requirements unique to fusion will come the guidelines for the design of fusion-system components and the remote-technology equipment necessary to handle and maintain these components. At present, the fusion program relies on each major project to incorporate the remote technology needed in that project. To date, remote-technology needs have been modest, and it has not been necessary to develop a separate remote-technology program within the overall fusion program. Future, major fusion devices will require sufficient attention to remote-technology needs to warrant a base program, in addition to major efforts within large projects.

Planning the elements of the remote-technology base program, as well as defining the large project development needs, should be the first task performed in this program activity. Such planning should involve experts in the field of remote technology; few such experts a found within the fusion program. The two dominant areas for which detailed planning is required are development of components and subsystems compatible with remote-technology applications and development of remote-technology equipment and procedures for future fusion needs.

The hardware associated with this program is embodied in a series of mock-up systems—one for the ignition experiment, one for the long-burn experiment, and one leading to the integrated fusion facility. An alternative approach would involve combining these systems into a dedicated Remote-Technology Development Facility that would support each future reactor project. The fundamental objectives of the remote-technology program are envisioned to be:

1. Establish the reliability of remote-technology equipment for use in the projected operating environment.
2. Modify existing equipment and develop new remote-technology equipment for anticipated operations and maintenance requirements; implement these on prototype reactor components. Existing equipment consists of teleoperated manipulator systems and transport systems, along with the support equipment to accomplish remote operations (i.e., viewing systems, cutting and welding equipment, and other end-effector tools). New developments will focus on robotic equipment that uses a greater degree of artificial intelligence.
3. Investigate the use of standardized interfaces on vacuum joints, coolant connections, electrical connections, and structural joints. Investigate interfaces with mechanical attachments and those that require cutting and welding.
4. Establish requirements for standard hardware and procedures.
5. Develop a remote-technology design and user manual that covers hardware, design practices, and applications principles.
6. Establish a data base for the mean time to repair (MTTR) based on prototype operations and experience from existing operating devices and equipment.
7. Establish a data base for mean time between failures (MTBF) of reactor equipment based on existing and ongoing experience with device operations.

Issues, Objectives, and Attributes

The issues associated with the remote-technology program element are: (1) Fusion facilities will require design approaches and practices compatible with the need to operate and maintain them remotely. Both the design and subsequent operation and maintenance must be performed in a cost-effective manner. (2) Fusion facilities will require complex remote-technology equipment, much of which is beyond the current state of the art.

The objectives and associated attributes for the issues are listed in Table IX.

Program Logic

The logic diagram for this program element, shown as Fig. 10, is discussed.

Develop, Issue, and Update Plan

This task includes the formulation of a comprehensive base program for remote technology within the fusion program. This program will define the context, tasks, coordination, schedule, and resources required to achieve remote-technology objectives in support of the overall program.

Develop, Issue, and Update Guideline Document

This task includes the preparation and maintenance of a remote-technology handbook of design

Table IX. Objectives and Attributes for Remote-Technology Program Element

Objective	Attribute	Planning target
Maximize reactor availability	Minimization of MTBF and MTTR	Availability greater than 75%
Develop and use cost-effective remote maintenance equipment	Simple, modular subsystems and components; compatible remote-maintenance equipment	Equipment costs less than 20% of total capital costs
Minimize exposure of personnel to radiation	Application of remote-handling technology	Less than 25% of exposure permitted by federal regulations

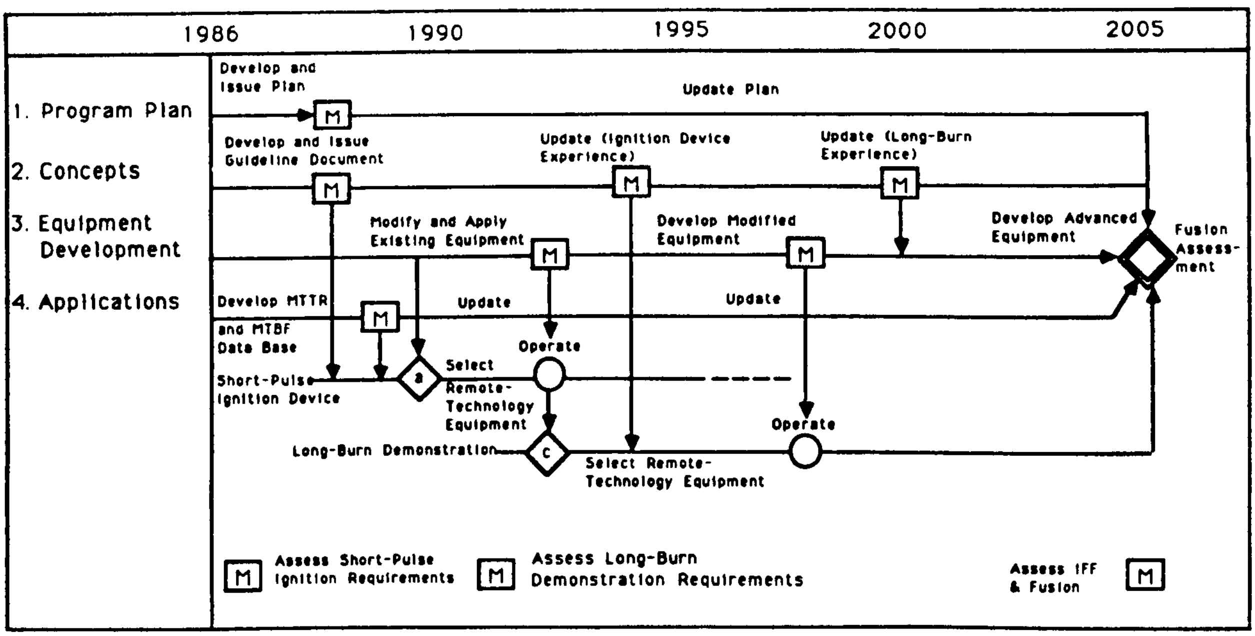

Fig. 10. Logic diagram for remote technology.

practices, principles, typical examples, equipment, and related information necessary for the cognizant design engineers to assure that all components and systems are designed to be compatible with the need for operations and maintenance by remote means.

Achieving high availability with remote technology will require the development and maintenance of a data base of relevant information essential to determination and minimization of the MTTR and the MTBF of equipment in fusion devices. This data base will be essential to the development of reliable equipment for fusion applications. Determination of the remote-technology equipment needed to maintain and operate future fusion devices is required. It includes specification of remote-technology practices essential to the effective use of such equipment. The equipment and practices for the design, installation, maintenance, and replacement of components and systems in fusion devices are included, as are all mock-up developments and associated test equipment. Incorporated into this effort are the necessary training and education of personnel essential to these efforts.

ALTERNATIVE FUEL CYCLES

This program element covers the complete range of science and technology programs required for a non-DT fuel cycle and specifies the required programs that would not otherwise be carried out in support of DT fuel-cycle applications. Consequently, the following program subelements (see Fig. 2) have been chosen: (1) confinement systems and burning plasmas, (2) plasma technology, (3) nuclear technology and materials, (4) systems design and analysis.

Issues, Objectives, and Attributes

The development of an alternative (nontritium) fuel cycle represents a potentially attractive long-range goal for fusion. A base research program and continued assessment of nontritium fuel cycles will allow directions in DT fusion development to be identified that are consistent with potential evolution into an attractive alternative fusion fuel. Operation of fusion systems with a fuel cycle other than DT could significantly reduce certain constraints on reactor design by eliminating the requirement for a tritium-breeding blanket. Eliminating this requirement could allow a much wider range of structural and thermal hydraulic designs, resulting in blankets with higher thermal efficiency. Improved overall designs for reactor assembly and repair may be possible, and greater reliability may also be attainable. However, use of a nontritium fuel cycle means that substantially improved values of beta and density–confinement-time product are necessary relative to those required for DT operation. In addition, devices of larger size and/or stronger magnetic fields may be required in order to use such alternative fuels.

The issues associated with the alternative-fuels program element are: (1) The plasma-confinement conditions required for the alternative fuel cycles must be achievable. (2) The technologies unique to alternative-fuel-cycle applications must be developed. (3) The concepts for alternative fuel cycles must meet the systems requirements for commercial applications.

The objectives and associated attributes for the resolution of these issues are listed in Table X.

Program Logic

The logic diagram for this program element is shown in Fig. 11; the program logic is discussed below.

Confinement Systems and Burning Plasmas

This task involves theoretical and experimental physics activities to establish the feasibility of concepts based on fuel cycles other than deuterium and tritium. There are two basic alternative cycles: deuterium-based (D-based) and proton-based (p-based) cycles. The present plan is directed mainly at D-based cycles, because these cycles indicate high-energy gain can be achieved with ambitious, but possible, plasma parameters. The possibility of igniting p-based cycles, however, remains questionable. Two aspects of D-based cycles should be stressed: DHe^3 is an attractive cycle, offering a significant reduction in neutron flux with only a modest increase in ignition requirements. Other D-based cycles could lead to attractive hybrid (fusion-fission) and synfuel systems.

A key limitation of the DHe^3 cycle is the issue of where to obtain the He^3. An important recent development is the recognition that mining the lunar surface could provide a plentiful, economic supply of He^3. This might make alternative fuels a competitive route to fusion power.

Another possibility is DD/DT operation, where the required tritium-breeding ratio is less than one.

Table X. Objectives and Attributes for Alternative Fuels Program Element

Objectives	Attributes
Minimize production and handling of tritium	Cost of tritium-handling subsystem, expressed as percent of total plant cost
Minimize production of neutrons	Fraction of total fusion energy carried by neutrons, expressed as percent
Maximize potential for nonthermal energy conversion	Overall plant efficiency, in percent
Maximize capability to achieve the higher beta and confinement times necessary for alternative-fuel systems	Predictive capability of plasma theory to verify experiment

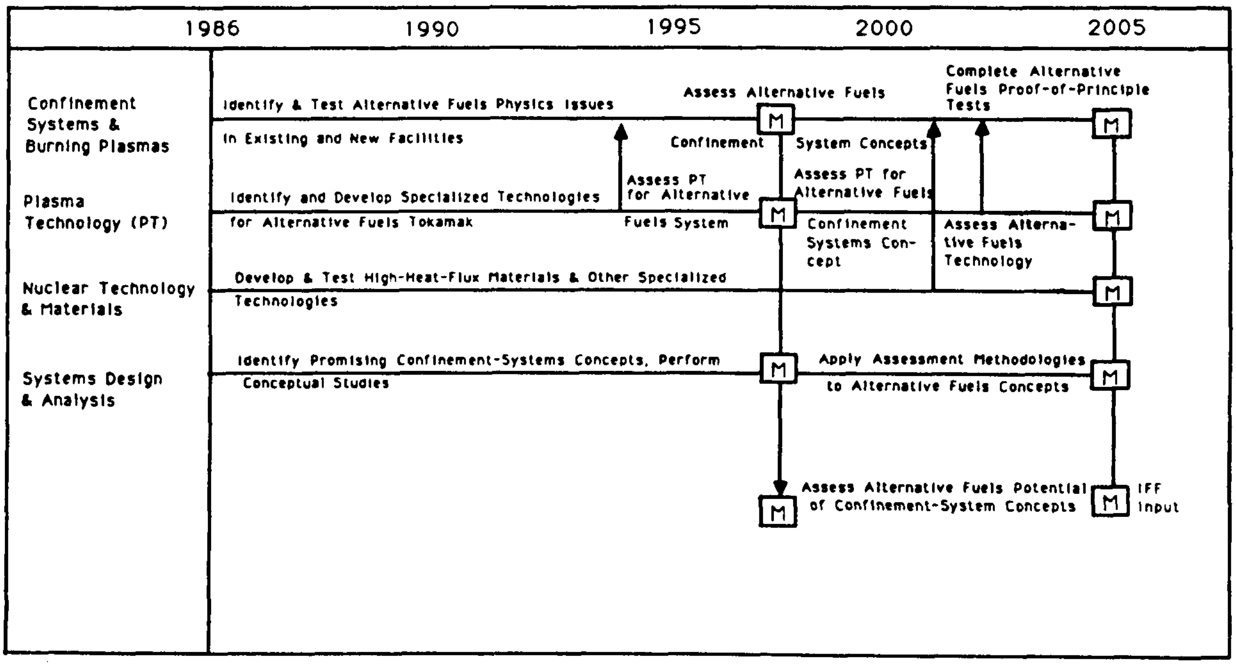

Fig. 11. Logic diagram for alternative fuels.

Breeding requirements are reduced, relative to those for DT operation, but the plasma-physics requirements are not as severe as those for DD operation. The physics requirements for operation of hybrid fusion-fission reactors with DD and DD/DT fuel cycles could be substantially less demanding than for the operation of pure fusion DD reactors.

Issues associated with confinement systems and burning plasmas are:

1. Requirement for very high beta places emphasis on alternative confinement concepts with high beta.

2. Requirement for high-temperature plasmas would emphasize possible extension of DT ignition experiment(s) to stress heating and burn dynamics at higher temperature.

3. Confinement concepts using alternative, non-tritium fuels require high-beta and high-temperature plasma; such concepts must be developed.

4. The potential for direct energy conversion is a desired feature that must be developed.

5. High-temperature, high-density operation leads to increased importance of and sensitivity to plasma-wall interactions, with emphasis needed on

understanding impurity-generation mechanisms, transport, and control.

6. Fusion cross-section data for alternative fuels must be obtained.

Plasma Technology

This area involves the development of technologies unique to handling the plasmas associated with nontritium fuels. Alternative-fuel fusion involves two key characteristics: (1) a high beta or high field to compensate for the relatively low-plasma power density and (2) a high-plasma temperature to achieve ignition. Corresponding engineering constraints require the ability to handle a relatively high first-wall heat load and development of methods to capitalize on the large charged-particle fusion yield (e.g., direct energy conversion). Issues include:

1. Efficient methods are needed to achieve higher ignition temperatures (e.g., bootstrap heating in combination with normal methods).
2. Heating methods are needed that operate at higher temperatures (e.g., negative ion beams and wave heating).
3. Fueling technology is needed for He^3.
4. Methods of impurity control must be developed.
5. A reliable fuel source must be established, especially for He^3 (evaluate lunar mining, satellite approaches, etc.)
6. Advanced and direct energy-conversion methods are needed.
7. High-field magnet technology is needed.
8. Plasma-control systems are needed to prevent rapid plasma quenches.

Nuclear Technology and Materials

This element consists of development activities associated with the nuclear technologies and materials required for alternative-fuel fusion systems. One objective of alternative fuel cycles is to minimize the production of neutrons, so the nuclear technology requirement for alternative fuel-cycle systems is expected to be adequately covered by R&D for DT systems, and no special requirements are projected. Materials needs are expected to be mostly in the area of handling high heat flux.

Systems Design and Analysis

This area consists of studies of alternative fuel systems. Studies are required to:

1. Evaluate the potential of alternative fuels on a basis consistent with DT-based studies.
2. Establish attractive systems-integrated approaches to high-beta value, improved confinement concepts, direct energy conversion, and unique blanket designs.
3. Identify needs and build on the emerging DT data base.
4. Develop test-facility designs and commercial-design concepts.
5. Identify attractive alternative applications that offer unique advantages (e.g., hybrid and synfuels plants).

The key activities are:

1. Select the most promising high-beta confinement concepts for buring alternative fuels. This selection will require studies of available theoretical and experimental data for such concepts as high-field tokamaks, compact tori, reversed-field configurations, tandem mirrors, etc.
2. Identify possible reactivity-enhancement approaches. Enhancement is not essential for D-based fuels, but if p-based cycles are to be considered, this is mandatory.
3. Identify cross-section needs. Again, this is essential for p-based cycles.
4. Identify experiments to study ways to handle the high heat flux on the first wall and identify technology developments (e.g., direct energy conversion) that would provide a high leverage in the utilization of alternative fuels.

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