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Pilot Plant: An Affordable Step Toward Fusion Power

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Progress is reported on a study to define a "pilot plant" to demonstrate the production of high grade heat in a fusion power plant configuration at the lowest possible capital cost. We are considering several driven reactor tokamak designs with fusion power production levels in the 15–50 MWth range, using demountable copper coils. We conclude that it is acceptable for such facilities to be net consumers of electricity as a trade-off to achieve low capital cost, which we estimate to be in the $1 billion range. These designs are based on currently accepted physics models. Even lower cost designs may be possible, if we depart somewhat from the current physics database.

KEY WORDS: fusion; energy.

1. INTRODUCTION

The investment in new baseload power plants on the North American continent during the first 50 years of the next century will total about $5 trillion, or an average of about $100 billion per year. It is important that fusion be an option for this market, since the other major alternatives (coal, fission, and solar) could well be restricted because of environmental, safety, or supply considerations.

Previous fusion reactor systems studies (e.g., STARFIRE, ARIES) have focused on the desired characteristics of fusion reactors in a mature, commercial fusion market or on full scale "demonstration reactors" as commercial prototypes. In many technologies (e.g., chemical and nuclear industries) "pilot plants" have been constructed in advance of full-scale facilities. Such pilot plants have had the characteristics of small size, low capital cost, and a limited set of objectives, while still having the integrated performance deemed necessary to gain experience with the operating characteristics of the new technology. In combination with other development activities, they have provided essential confidence and experience leading to successful commercialization.

It is the purpose of this Pilot Plant Study to explore the possibilities for proposing a pilot plant as part of the strategy for fusion development. In particular, the study seeks to define the mission requirements and technical objectives of such a facility and then searches for credible designs for the lowest cost fusion reactor that could fulfill a pilot plant mission.

The present study is a follow-on activity to an earlier study[(1)] sponsored by the Agency for the Advancement of Fusion Power. The present study group, consisting of scientists and engineers from Fusion Power Associates, EBASCO, MIT, ORNL, and Ontario Hydro/CFFTP,

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met for the first time in April 1991. This report represents the first written progress report of the work between April–November 1991.

The study group is an informal, but unique, university-national laboratory-electric utility–industry partnership. It is also a U.S.–Canada collaboration, building on a growing trend for nations interested in fusion to work together. The study provides the first opportunity for utilities and industry to play a lead role in defining and designing a fusion reactor to satisfy utility/industry requirements.

2. MISSION STATEMENT AND OBJECTIVES

The mission of the pilot plant is to demonstrate energy production from fusion in a power plant configuration at the lowest practicable cost and earliest possible time. The primary objectives of the pilot plant are: to demonstrate the production of high grade heat with high availability for extended run periods, to provide operational experience demonstrating safe and reliable operation of the plant, and to provide, in combination with other fusion test facilities, engineering data and confidence in the design and construction of demonstration and commercial fusion plants.

3. DESIRED CHARACTERISTICS OF FUSION PILOT PLANTS

A variety of fusion research and development facilities are currently planned in the international fusion effort (cf. e.g., National Energy Strategy, U.S. DOE, February 1991, p. 130).[2] The pilot plant should complement these R&D facilities, and be aimed at issues of primary interest to the electric utilities as operators of future fusion power plants. The pilot plant should therefore provide experience in the following areas:

- Production and extraction of high grade heat
- Operation and maintenance
- Instrumentation, control, and protection
- Safety, environment, and licensing
- Fuel cycle and tritium handling
- Waste management and decommissioning
- Utility input in design for ease of construction, operation, and maintenance

These issues are discussed in more detail in Section 8.

4. TECHNICAL ISSUES AND DESIGN GUIDELINES

Low capital cost and small thermal power are primary design guidelines for the pilot plant study. The pilot plant must produce high grade heat with high availability for extended run periods but may be a net consumer of electricity. The design should allow for a short construction schedule, leading to a facility in which there is high confidence in safe operation, but need have a design life of only a few full-power years.

Tritium will be supplied to the pilot plant from external sources so that full tritium breeding capability is not required. However, the incorporation of a tritium breeding test module is desirable. The use of superconducting magnets is not required, although they would be desirable if consistent with the requirement for low capital cost. For example, it may be cost-effective to employ one or more poloidal field superconducting magnets but not superconducting toroidal field magnets. Similarly, steady state current drive is not required, but may be incorporated if consistent with the state-of-the-art and other cost trade-offs. Reduced-activation materials are also desirable but compromises in this area may be required depending on the state-of-the-art at the time of construction.

During the ongoing initial scoping studies, a range of physics and technology assumptions are being investigated. These include departures from the currently accepted "ITER-P" transport scaling law, as well as departures from current experience at higher magnetic field, higher beta, and higher and lower aspect ratio. In the technology area, the study assumes the availability of technologies required for ITER in the areas of high heat flux and impurity control components, robotics, magnetics, structural materials, plasma technologies, control systems, and tritium handling. We also assume the need for developments beyond ITER in the area of high temperature blankets and possibly in the area of higher field magnets.

5. ILLUSTRATIVE DESIGN CONCEPTS

Illustrative scoping level tokamak designs, performed at MIT and ORNL, indicate that an acceptable design point can be found to fulfill the pilot plant objective. The design concepts that appear most promising to us at this time are based on demountable copper coils and employ driven plasmas with Q of about one. The magnets are similar to those used on Alcator C-MOD. Using today's ITER-P physics scaling (but with substantially less extrapolation from the current physics data

Table I.

Major radius (m)	1.05–2.0
Minor radius (m)	0.46–0.5
Aspect ratio	2.28–4.0
Elongation	2.0
Max toroidal field (T)	3.6–6.0
Plasma current (MA)	3.0–3.2
Safety factor	3.0–4.0
Average electron density ($10^{20}m^{-3}$)	0.6–1.2
Average temperature (keV)	6–8
Average neutron wall load (MW/m^2)	0.3–0.5
Average thermal wall load (MW/m^2)	0.5
Fusion power (MW)	15–50

base than ITER), we have arrived at designs we believe can be built for about $1 billion and possibly less. The basic concepts that have evolved at MIT and ORNL are similar, although they differ in detail. The range of parameters for these design concepts is shown in Table I.

Calculations have also been performed for small aspect ratio tokamaks (1.8–1.9). These design concepts might further reduce the cost of the pilot plant. Stimulated, in part, by the Pilot Plant study, researchers at MIT and ORNL have also suggested physics and technology test facilities which are similar in scale and design philosophy to the Pilot Plant.

6. MATERIALS CHOICES AND TRITIUM SUPPLY

The following are desired characteristics of materials to be used in power reactors:

- Radiation damage resistance
- Chemical compatibility (e.g., with coolant)
- Operational at elevated temperatures
- Good mechanical stress characteristics
- Tritium compatibility
- Ease of fabrication
- Low activation

The choice of materials for the Pilot Plant must seek the above characteristics, recognizing the state-of-the-art at the time of its construction. The materials that have been discussed as primary candidates for the structural material for the primary in-vessel components for fusion power reactors are:

- Austenitic stainless (300 series) steels
- Martensitic/bainitic stainless steels
- Vanadium alloys
- SiC/SiC composites

The latter two are desirable for future fusion power reactors but will not be available for several decades. Thus, for a near-term Pilot Plant, we are limiting are consideration to the first two.

Tritium inventory from Ontario Hydro CANDU reactors is projected to increase to about 20 kg around the year 2000 at rate of about 2.4 kg per year. Commercial tritium demand is low, about 0.1 kg per year. Calculations of tritium demand for ITER and Pilot Plant, for a range of assumed power levels and availabilities, project sufficient tritium for both for a reasonable number of years.

7. RELATION TO WORLD FUSION PROGRAM

Beyond the current generation of large fusion devices, it is generally agreed that additional research and development is required in the following areas:

- Tokamak physics scaling to reactor conditions at long pulse or steady state
- Physics of burning plasmas
- Development of the technologies and materials required for power reactors
- Demonstration of fusion in a power plant configuration

A combination of facilities has been proposed to accomplish the above needs (see, for example, the U.S. National Energy Strategy).[(2)] The mix of facilities is currently under review. The Pilot Plant is aimed at providing an early demonstration of fusion in a power plant configuration. The Pilot Plant will provide operational experience, including issues of safety, environment and licensing, to utility engineers. The Pilot Plant thus would play a key role in bridging the gap from physics and technology research and development facilities to full scale demonstration reactors and early commercial plants.

8. CHARACTERISTICS OF FUSION PILOT PLANTS OF INTEREST TO UTILITIES

Electric utilities are under considerable pressure to provide a sustainable electricity supply with reduced environmental impact and minimum public risk. Fusion energy has potentially favorable characteristics in this regard, and should be of real interest now to utilities as a future alternative energy supply.

However, it does not appear possible to build a low cost, small-scale model of a complete fusion power plant like has been done previously in the development of hydraulic power, fossil-fuelled power stations or even in the development of fission power stations, to demonstrate concepts and provide fully integrated operating experience to utilities. To test out fusion concepts, designs, and materials and to provide needed operating experience with fusion, it is necessary to build specific facilities called Fusion Pilot Plants, (FPPs), which will develop and demonstrate particular aspects of future fusion power plants.

To be of interest to utilities, FPPs should build on existing knowledge and experience in the power industry and on scientific knowledge from existing fusion R&D (JET, TFTR, JT-60, etc.) and should complement other planned fusion experimental projects (ITER, etc.), to answer one or more outstanding questions or concerns involved in building and operating future full-scale fusion power stations.

While utilities would eventually have interest in knowing all about new and innovative scientific features of a fusion energy system, their initial interest would be in the areas which they have direct responsibility for in building, operating and maintaining a reliable, economic electric power supply system. This would include:

1. Production and extraction of high grade heat
2. Operation and maintenance
3. Instrumentation, control, and protection
4. Safety, environment, and licensing
5. Fuel cycle and tritium self-sufficiency
6. Waste management and decommissioning
7. Utility input in design for ease of: construction, operation, and maintenance

8.1.0. Utility Interests and Requirements

8.1.1. Production and Extraction of High Grade Heat

Pilot must be at least capable of generating high grade heat suitable for conversion to electricity through a proven steam cycle, if it is to attract the interest of electric utilities. Conversion of this heat to electricity through a conventional steam cycle, would increase the public interest in fusion, but may not add significantly to the knowledge of fusion plant behavior relative to the cost involved, unless existing facilities are utilized to produce electricity.

Ultimately, fusion plants may be capable of direct conversion of heat to electricity. However this is too large a technological step to contemplate in Pilot.

Desired Steam Conditions. The various steam cycles currently used in large power stations are listed in Section 8.3.1. It is to be noted that higher temperature steam conditions yield higher thermal efficiencies—a goal with obvious advantages to utilities. The minimum practical steam conditions which should be considered for Pilot should not be less than those used in the CANDU system (600 psi saturated steam at 485°F). The maximum steam conditions which should be considered are 2400 psi, 1000°F.

From the steam cycle viewpoint, it is quite practical to have about two-thirds of the heat provided at a lower grade to warm up condensed water and convert it into saturated steam at modest temperatures. Superheating the steam could then be achieved using the balance of the heat from a higher grade primary heat source. Extraction of heat at two temperatures may match the different thermal/material limitations in parts of Pilot, such as the components adjacent to the plasma or which provide shielding around the plasma and the magnets and structures.

Primary Coolants. The major fusion reactor systems which require cooling and are sources of heat available for steam generation are: First Wall, Breeder Blanket/Shield Blanket, Divertor, and Magnets and Structures. The candidate primary coolants are water, helium, organic, and liquid metal. A review of the primary system cooling studies at NET/ITER and ARIES would allow a selection of the optimum one or two coolants which should be selected as the Pilot reference primary coolant or coolants. Utility preferences would be for coolants with which they are familiar and which are not significantly activated or changed by the neutron fluxes and which minimize safety and maintenance provisions.

8.1.2. Operation and Maintenance

Pilot could provide utilities with hands-on experience in operating and maintaining this new energy source under conditions similar to a utility setting. Perhaps the greatest utility concern about fusion is maintainability. Pilot, which operated for periods of weeks followed by periods of adjustment or maintenance, should provide direct experience on accessibility, maintenance techniques, and repair and replaceability of components. For example Pilot should:

- Establish the extent of the need for robotic maintenance as well as indicate the degree of direct manual maintenance permissible
- Demonstrate robotic maintenance of systems and subsystems
- Demonstrate both selective replacement and total change out of diverters and first wall components

- Provide experience on robotic welding and remote inspection of weldments
- Demonstrate feasibility of replacement of both toroidal and poloidal coils
- Demonstrate integration of in-vessel and ex-vessel maintenance systems for material and component handling
- Provide feedback on accessibility and maintainability for design of subsequent facilities

8.1.3. Instrumentation, Control, and Protection

A key objective of Pilot will be to demonstrate that a fusion reactor can be controlled safety, using a combination of automatic and human actions, to produce the high grade heat required for power production. An electrical utility will be especially interested in those aspects of the process that differ significantly from their current range of experience. These areas include:

- The special instrumentation devices for measuring and controlling the fusion reaction and its auxiliary systems
- The use of computers in the control and protection of the fusion reactor
- The control room, operator interfaces, and required staff complement
- The special electrical requirements for the fusion process and their effect on the power grid and plant station service
- The design and operation of a shutdown system capable of responding to reactor upsets without resultant machine damage
- The demonstration that post-shutdown cooling can be adequately and reliably met without the need for a dedicated protective cooling system
- The integration of atmospheric management, ventilation, and containment to prevent radioactive releases from the facility under all normal and off-normal conditions.

8.1.4. Safety, Licensing, and Environment

Designing, licensing, and operating Pilot which produces high grade heat will bring out many of the safety and environmental issues the utility would have to deal with in licensing and operating a full-scale fusion power station, and allow the utility to compare these issues with the more familiar issues in building and licensing a fission power plant. The lessons learned from Pilot will also be valuable for the Demo plant as well as for the development and/or refinement of fusion safety and licensing requirements. The safety, licensing, and environmental issues on Pilot which would be of interest to utilities include:

- The inherent/passive safety characteristics of fusion
- The degree of application of existing nuclear power regulations, qualifications, and licensing procedures
- The degree of application of existing radiation protection principles and requirements
- The development of practical regulatory and radiation protection requirements for fusion power development
- The public reaction to the transport and handling of significant quantities of tritium
- Demonstration that radioactive wastes are manageable within existing regulations

8.1.5. Fuel Cycle

Fueling fusion power plants will be a new experience for most utilities. Fuel and fuel handling for Pilot could provide utilities with knowledge and experience about fuel materials, availability of fusion fuels, fueling techniques, restrictions, precautions, and limitations. Specifically utilities would be interested in learning from Pilot about:

Tritium supply

- The external sources of tritium
- The form and purity of the tritium needed
- The method of shipping and the quantity of tritium per shipment
- The method and capacity of the on-site storage
- Required tritium accounting procedures

Production

- The facilities and processes required for tritium breeding
- Extraction of heat and tritium from a blanket module
- The potential capability for tritium self-suffiency
- The reliability and replaceability of the breeding components
- How tritium breeding in Pilot compares to that expected in future full-scale fusion plants

Purification/separation

- The facilities and processes required for fuel clean-

up (FCU) and hydrogen isotope separation systems (ISS)
- The relative size of the FCU and ISS in Pilot compared to that in a full-scale fusion plant
- The plant processes/effluents requiring purification and isotope separation, and the product specifications
- The required reliability of the purification/separation systems for efficient operation

8.1.6. Waste Management and Decommissioning

Utilities are moving or are being directed to move toward lower environmental impact for future power production. Pilot could provide utilities with a demonstration that future electrical power may be produced without significant environmental degradation. With respect to waste, this requires the following demonstration that:

- Liquid and gaseous radioactive emissions can be limited to acceptable values for chronic releases, and for upset conditions
- Solid radioactive wastes will not have very long half-lives and that the quantities are at least no greater than for fission
- All radioactive wastes from future fusion power plants will decay to or below deminimus levels in 300 years
- All waste hazard levels (radiological, toxicological, and environmental) are less or no greater than those produced by other energy sources
- If waste treatment is required to achieve the above objective, such treatment is practical and effective on a commercial scale.

Pilot will eventually have to be decommissioned and will provide utilities with some early knowledge/experience in decommissioning future fusion facilities. It is expected that decommissioning of Pilot will have similar requirements to decommissioning of fission plants. For this reason, lessons learned from planning, design, and decommissioning of fission plants should be incorporated into fusion plant design, to ensure that the decommissioning process can be accomplished in the most efficient manner.

8.1.7. Utility Input in Design for ease of: Construction, Operation, Maintenance, and Decommissioning

Utilities have first-hand experience on the strengths and weaknesses in the design of existing power plants (fossil fired and fission) which affect: licensing and approval, construction schedule and cost, maintainability and operational capability, waste and environmental management, and economic performance. It is recommended that utility input and interest in Pilot be secured by:

- Utility participation in design from the concept design stage onward
- Use of proven utility materials control and management systems
- Application of practical quality assurance programs
- Adoption of sound utility operating practices, principles, policies, and procedures
- Having the utilities produce the commissioning and operating manuals for Pilots
- Having the utilities provide and train the operating and maintenance staff for Pilot
- If possible, locate Pilot on a utility power plant site which has in place: security, operating and maintenance infrastructure, site management, cooling and heat conversion facilities, waste management, and training facilities, etc.

8.2. Site-Related Opportunities and Benefits of Utility Participation

8.2.1. Utilization of Existing Facilities

Considerable cost savings could be realized by building Pilot on an existing licensed nuclear site. Further savings may be realized if a decommissioned nuclear plant of suitable capacity were available. Such a plant could provide:

- A primary containment building
- A service building
- An administration building with offices
- Heat transport and cooling capability
- Transportation and equipment handling capability
- Competent and reliable on-site electrical transmission, transformation and distribution facilities, and possible conversion facilities
- Warehousing and material storage and handling
- Meeting and training facilities
- Security and access control

The balance of plant equipment may include a turbine generator which could be brought into service to generate electricity using the fusion-generated heat. If this is not practical, the boiler and/or main condenser may be used as a heat sink to dispose of heat generated by the Pilot primary systems.

There are several decommissioned plants in North America which might be available. In Canada, Douglas Point, a 220 Mwe CANDU station at the Bruce NGS site, could possibly be made available. The 250 Mwe Gentilly-1 site in Quebec is also a possibility. In the United States, Fort St. Vrain may be a possibility with the capacity to utilize helium primary coolant in its steam generators. There may be other locations which should be investigated early in the Pilot design phase. An early site selection will simplify Pilot design and influence specific features of the design.

For waste management, it would be advantageous to locate PILOT at a fully-integrated nuclear site, as this would allow waste treatment, storage, and, if appropriate, disposal, without the need for off-site handling and shipment. This would allow the efficient management of wastes without the need to characterize, license, or develop extensive packaging before actual waste composition is known, a feature which will be most valuable for a PILOT type of operation.

Similarly, decommissioning would be easier if PILOT were located on such a site, since fission decommissioning infrastructure and technical expertise would be in place.

8.2.2. Utilization of Existing Expertise

Locating Pilot at the site of an existing nuclear power station with its managerial and skills infrastructure could provide economic and technical benefits. These benefits would include:

- Utilization of established site management and administrative services and systems at minimum additional effort and cost
- Use of existing skilled trades and technical services at the cost of an incremental increase to the workforce
- Use of existing health and safety monitoring capability and services at no or very small incremental cost
- Use of established training experts and materials

8.2.3. Licensing and Environmental Approvals

The selection of an appropriate site for PILOT can have significant beneficial effects on the licensing process. An already licensed site is preferable over a green-field site for several reasons:

- The site characteristics are already well known and already demonstrated to be acceptable for a nuclear facility
- The environmental impact of an additional facility on a licensed site will be easier to quantify on the basis of actual data from the construction and operation of existing facilities. Hence, the impact can be estimated on an incremental basis. The net result should be a simpler and shorter environmental assessment process.
- Public acceptance of PILOT on an already licensed facility may be easier to obtain, as the local communities are generally more enlightened on the effects of radiation and the local economy has become dependent on the operation of the nuclear facility.
- Site regulatory authorities already familiar with nuclear reactor safety, particularly if they have working experience with tritium, will have a better awareness and appreciation of the radiation safety aspects of a fusion PILOT.
- Existing infrastructure such as: site physical security, access control systems, radiation monitoring systems, waste management systems and emergency preparedness plans and procedures, would facilitate the licensing of Pilot.

8.3. Supporting Information on Utility Interests and Requirements in a Fusion Pilot Plant

8.3.1. Production and Extraction of High Grade Heat

Steam Cycle Requirements. As a first, simple approach, the study team should consider established steam cycle conditions as candidate options as shown in Table II.

Table II.

Option	Steam pressure (psig)	Steam temp. (°F)	Typical turbine cycle efficiency (%)
A. CANDU	600	485	33
B. PWR	900	570	34
C. BWR	1000	540	34
D. Coal/oil fired plant and FBRs, HTGRs	2400	1000	44
E. Super critical coal/oil fired plant	3500	1000	46

The candidate steam cycle conditions will influence the selection of the primary coolant or coolants. The higher quality steam conditions are associated with better cycle efficiencies and should be assessed on a cost-benefit analysis in consideration with the primary coolant selection.

Options A, B, and C would allow water as a primary coolant with organic as an alternate. Organic coolant would allow somewhat higher steam conditions. Options D and E would require helium or liquid metal primary coolant. It is to be noted that Pilot does not necessarily have to build a steam generator; simply utilizing primary coolant with suitable parameters for raising steam at the selected conditions would be an adequate demonstration.

Primary Cooling Requirements. There are five major systems in a tokamak which have different cooling requirements. These are First Wall, Breeder Blanket/Shield Blanket, Magnets, Structures, and Divertors. For simplicity, one cooling medium, e.g., water, should serve the various system requirements. However, because of the diverse cooling requirements, it may be more practical to use two primary cooling mediums or one coolant in separate loops at different conditions. This lends itself to a dual cycle approach where the lower grade primary heat could be used to generate saturated steam (normally about 60–70% of the total heat load) and a higher grade primary coolant used to superheat the saturated steam. This may allow the Option D steam cycle conditions which would be attractive to a utility since it would allow a conventional steam turbine set giving better than 40% turbine cycle efficiency vs. 30% for the saturated steam cycles associated with fission plants. Candidate coolants are water, helium, organic, and liquid metal.

Suggested Approach.

- Identify the cooling requirements of the primary systems
- Review the current technology developed for specific systems, such as divertors and first wall
- List the main advantages and disadvantages of candidate coolants from established fission technology
- Assess the primary coolants against the desirable steam cycle requirements
- Select one or two primary coolants for the preliminary design of Pilot
- Establish the reference primary coolant parameters for the appropriate coolant loops
- Assess the safety aspects, such as the consequences of a Loss of Coolant and Loss of Circulation Accident, and review the choice of primary coolant and the coolant parameters to ensure the best choice has been made.

8.3.2. Operation and Maintenance

A comprehensive set of operating and maintenance procedures must be prepared prior to station operation, and reviewed by design and regulator experts. The staff must operate and maintain the plant systematically and rigorously in accordance with these procedures.

The role of the Operator of a nuclear facility is a management task of information gathering, planning and decision making. The Operator needs to be able to: understand what the normal conditions are in all the systems relevant to the overall status of the plant, recognize when abnormal conditions arise, and know how to respond correctly to restore the plant to normal operation.

The ability of the Operator to do the above depends on how the plant systems are designed and on the Operator's ability and training. The Operator needs the ability to understand, diagnose, and anticipate the development of situations from data provided by instrumentation.

Testing, monitoring, and maintenance programs in a nuclear power plant ensure the plant process and safety systems performs or are capable of performing to match the design intent. The plant systems are maintained and tested according to quality assurance requirements to ensure reliability throughout their service life.

It is important during design to recognize the Operator's and Maintainer's responsibilities and functions, and their human capabilities and limitations.

8.3.3. Instrumentation, Control, and Protection

Control System. The pilot plant should demonstrate that a fusion reactor can be controlled, using a combination of automatic and human actions, to produce the high grade heat required for power production. A successful program will demonstrate:

- A control strategy that will integrate the special controls relating to a tokamak with the conventional requirements for a steam turbine cycle
- The algorithms required to control a power generating plasma over the designed pulse length
- The capability to detect unsafe conditions and initiate the automatic shutdown of the fusion process
- The down-time in the event of a safety initiated shutdown in the case of both disrupted states

Monitoring. A fusion plant will require both the special instrumentation for the management of the plasma and the more conventional devices associated with the process control systems. A utility will be interested in:

- The identification of the diagnostic equipment that will be required in the power production mode of plasma management
- The assurance that the required diagnostic instruments can be made to survive in a power plant environment (as opposed to the current laboratory-style environment)
- The indication that the sophisticated diagnostic instrumentation can achieve a level of reliability that is consistent with normal power plant operation
- The ability of the conventional process control and monitoring devices can perform in close proximity to the conditions surrounding a fusion reactor
- A demonstration that all of the instrumentation can be maintained by plant personnel both *in situ* or in-shop as required
- The testability of control and protection systems and devices

Computer Control and Protection Systems. The control and protection of a fusion reactor will require the use of highly reliable computer control systems. Pilot should demonstrate the following:

- The development of commercial, high speed, I/O systems, in particular for use in the plasma control systems. (The Starfire project specifications indicate that an increase of an order of magnitude will be required over present-day equipment)
- The development of highly reliable control software
- The development of software for protection systems
- The development of computer configurations that will meet all of the data handling and control requirements, for example, the relative merits of distributed vs. centralized configurations should be investigated
- That the software can be developed, tested, and maintained using well-proven methods by the normal population of software programmers, and that the software can be verified and validated to meet any regulatory requirements

Machine Protective Systems. The three Cs of machine, staff, and public safety are the same for fusion as for fission, namely: control, cool, and contain. The definition of "Safety Systems" to cope with these requirements, as distinct from "Process Systems," has proven to be a valuable concept for CANDU safety and may be a useful basis for future fusion regulatory developments.

Shutdown. Pilot will likely use the D-T reaction to produce fusion power. The relatively large amounts of stored energy, substantial tritium inventories and the presence of activation products inherent in this process will require ample demonstration that fusion is "safe."

Plasma stability at high fusion powers, particularly under ignition conditions is still very uncertain. It appears that ignition may have negative stability, i.e., that a small positive power excursion will be amplified rapidly into a larger one, while power control is relatively slow. This will make control difficult and many transients will ultimately result in a disruption at the beta or density limit. This scenario poses two threats: (1) the overpower transient will cause overheating unless adequate design margins exist, and (2) the disruption itself is a major stress for the machine.

Thus, one challenge for Pilot will be to develop a control system capable of preventing such runaways, and to develop a protective shut down system fast enough to be effective without causing the very disruption which may result in machine damage if such a condition were to occur. Fusion, unlike fission, does not have any "criticality concerns," and once the reaction is terminated, it will not "re-ignite" spontaneously. Hence once the shutdown system has acted, its mission will have been accomplished, and there is no need to monitor and control the reaction in the long term.

Cooling. Since D-T fusion will not result in radioactive "ash," the only radioactive materials are tritium (unused fuel) and activation products, the decay heat drops much quicker after shutdown and is substantially less than that of fission reactors. In fact, preliminary calculations have shown that in the absence of *any* cooling capability after shutdown, limiting tokamak temperatures of about 1000°C could result after approximately 10 days. Even this extreme example, would not result in volatilizing activation products, and hence would not pose a major threat to staff and public safety.

Given the number of separate systems to remove heat from blankets, first wall and divertors, a complete loss of heat removal from the machine is extremely unlikely to happen. It must thus be possible to avoid the need for an emergency cooling system, if assurance can be provided that post-shutdown heating can be controlled under all conceivable conditions.

Containment. The substantial inventories of tritium, the presence of activation products, and the high temperatures found in fusion reactions, coupled with our current lack of experience will place a strong emphasis on containment. In addition to the process envelope, and perhaps a secondary enclosure (glove box or caisson), an outer envelope will likely be provided for large inventories of tritium and to contain high temperature (and pressure?) coolants.

In addition to systems provided to handle tritium and activation products in the process loops, each barrier will have to be provided with a means of detecting contamination and will require some means of removing this contamination. Pilot will be an excellent test bed to show that these multiple systems can be integrated and operated with high reliability in a production environment. Pilot will thus serve to develop the experience database for more efficient designs and operations, providing both qualitative and quantitative inputs to future designs, PRAs, and licensing considerations.

Another vital function of containment will be the containing of hot, and possibly radioactive, coolants released from heat transport systems in the event of pipe failures. ITER has considered using low temperature/low pressure coolants to minimize this problem, but Pilot will have to resort to high temperature coolants if high grade heat is to be produced. This will mean that the containment structure will have to withstand the LOCA pressure transients and remain leaktight in the long term to prevent any releases of tritium and/or activation products which may have occurred during the LOCA. As an end of life exercise, Pilot may perform LOFT type experiments to provide actual data and experience for such transients.

Control Room. The control room for Pilot should demonstrate that a fusion plant can be controlled from a central location with a staff complement similar to that of fission plants. To achieve this an operator interface will be required that merges the fusion reactor controls and the conventional process controls into an integrated system of software and hardware-based control and monitoring methods.

It should be demonstrated that a fusion-based plant can be operated by the normal operator population in both normal and emergency conditions.

It must be possible to format computer-based displays to present the fusion process to the operators in a clearly understood manner, and to prepare procedures for both normal and emergency operating states.

Electrical System and Station Service. The electrical requirements for the fusion reactor are very demanding and can create problems both within the plant and on the power grid.

Pilot should demonstrate:

- That high currents required by the magnet systems can be controlled over the long pulse period
- There will be no deterioration of power quality on the grid or station service equipment because of the high current demand
- The plant control systems and cabling will be immune to the effects of EMI and transient interference that may result from the special nature of the fusion reactor

8.3.4. Safety, Licensing, and Environment

Safety Requirements. It would be desirable from a utility viewpoint to limit safety requirements for a fusion pilot to high level performance requirements such as:

1. Recommendations of the International Commission on Radiation Protection (ICRP-60) shall be followed in the design of Pilot.
2. ALARA (as low as reasonably achievable, social, and economic factors taken into consideration) principle shall be used to determine the extent to which radiation protection measures shall be provided. ALARA is automatically satisfied for doses below the deminimus level (10 micro-Sv/year).
3. The maximum radiation exposure to an atomic radiation worker, from direct radiation or from radionuclides ingested, inhaled, or absorbed through the skin, shall not exceed 100 mSv over any 5-year period, with a maximum of 50 mSv in any 1-year period.
4. The maximum radiation exposure to a member of the public shall not exceed 1 mSv/year averaged over a 5-year period. A value of 0.1 mSv/year can be used as a design target.
5. The maximum radiation exposure to a member of the public, resulting from a design basis accident, shall not exceed 250 mSv.

Safety Cost. Experience with fission facilities has indicated that the "safety cost" is proportional to the number of systems, structures, and components designated as important to safety. Systems, structures, and components that are identified in the safety case as being important for assuring the safety of the facility are burdened with additional requirements, such as:

- Seismic qualification
- Environmental qualification
- tornado protection
- Flooding protection
- Nuclear codes and standards for both design and manufacturing (code classification)
- In-service inspection
- Availability and reliability testing during operation

- Redundancy, diversity, and separation

The above requirements add significantly to the cost of equipment, construction, and operation. Therefore, the number of systems, structures, and components designated as important to safety must be kept as small as practicable.

Assurance of Safety. Regulatory authorities require assurances that the facility is designed, constructed, and operated safely. The safety report, which documents the safety case, provides assurances of the design. Construction completion assurances are provided prior to operation. Operation safety assurances are required on a continual basis during the life of the facility. Such assurances are provided by regular testing, inspection, and maintenance of systems and components credited in the safety analysis. It is important, therefore, from a utility perspective, to reduce the annual effort required to provide the licensing authority assurances of safety.

Training Requirements. The level of training required and the number of qualified and certified staff required to operate the facility safely is directly dependent on (a) the complexity of the design, and (b) the complexity of the safety case. To keep operating costs at desirable levels overall training requirements must be kept as low as practicable.

Licensing Requirements. It would be desirable, from a utility viewpoint, to keep the licensing process as simple as possible. The following considerations are noted:

1. Demonstration of Licensability. The successful licensing of Pilot should provide sufficient demonstration of licensability of a commercial fusion power plant. The lessons learned from Pilot should demonstrate whether or not licensing will be as big an issue for fusion plant as it has been for fission plants.

2. Regulations. The Licensing Regulations to be applied to Pilot will depend on several factors, including location (DOE reservation vs. industrial site) and regulatory authority (DOE vs. NRC). In Canada it would depend whether it was located at a remote nuclear power site (e.g., Bruce Nuclear Power Development Site) or at a remote nuclear laboratory site (Chalk River). In the absence of specific, fusion regulations, regulatory authorities will undoubtedly impose fission reactor regulations to the greatest extent possible. Hence, it is important to develop a rational set of licensing regulations for fusion and to have them adopted by the appropriate regulatory authority.

3. Schedule and Cost. The licensing process to be adopted for Pilot (and subsequently to commercial fusion power plants) must not impact adversely on the cost and schedule of the project. The process must be simple and predictable.

4. Predictable Process. The requirements must be well established and understood at the beginning of the project and must not be allowed to change during the project duration. The licensee must have assurances that the facility will be licensed after the requirements have been satisfied.

5. Safety Case. The safety case must be built on conservative assumptions and employ simple analysis tools. The safety analysis must not depend on a large supporting R&D program to verify assumptions and computer codes and models. The amount of safety analysis required to make the safety case should be as little as possible (e.g., should be based on bounding conditions).

Environmental Protection Requirements. For normal plant operation, requirements applied to the design for safeguarding the health and safety of the public will also assure the protection of the environment. But, whereas the public can be protected by evacuation, if necessary during an accident, the environment cannot be protected by the same means. Therefore, for any possible accident, regardless of its likelihood of occurrence, contamination of the environment, beyond the exclusion zone, should not lead to the need for evacuation of the population, nor to the loss of production or utilization of the land.

8.3.5. Fuel Cycle and Tritium Self-Sufficiency

Tritium Supply. Tritium will be supplied as tritium gas (T_2) at a purity of not less than 99.7% T (TFTR specs).

It will be shipped in metal tritide form using approved shipping containers. The capacity of the shipping container should not be less than 50 gm tritium to ensure that no more than one shipment per day needs to be handled even if Pilot does not breed any tritium.

Tritium supply will be stored on-site in metal tritide beds. The capacity of the storage beds should be 150 gm tritium to minimize the number of getter beds needed.

Acceptable accountability procedures should be in place to account for tritium supplied, consumed, in storage, and in machine components and process systems.

Based only on existing Ontario Hydro CANDU stations (i.e., no new stations or other CANDUs), there will be a cumulative tritium inventory of about 40 kg (decay corrected) at the time Pilot would be expected to go into operation. A 500 MW fusion reactor operating at full power 20% of the time will consume 5.6 kg tritium per year. The Ontario Hydro inventory should be adequate for Pilot. The situation should be evaluated carefully if ITER goes into operation about the same time as Pilot and if ITER either does not have a driver blanket or has one with low tritium breeding ratio.

If more CANDUs are built over the next 20 years, the potential tritium supply will be increased. PILOT itself may also breed some tritium.

Production. A full breeding blanket is not essential for PILOT since external tritium supply will be available. However, we recommended that a blanket segment or module, which does not completely cover the torus, be provided to demonstrate to utilities that tritium self-sufficiency is at least possible, and can be achieved safely and reliably in a "hot" (high temperature) blanket required to produce high grade heat.

The blanket segment should cover approximately 1/10 of the surface area of the torus. It should be replaceable with a replacement time of not more than 1/2 year. The service lifetime of the blanket segment is 5 years.

The blanket segment should demonstrate that, on a pro-rated basis (on the basis of the fraction of torus covered by the blanket segment), the tritium breeding ratio (TBR) should be equal to or greater than unity.

The blanket segment should be tested to 1–3 MW-yr/m^2. The overall availability of the blanket system (blanket and on-line tritium extraction system) should be greater than 80%.

Purification/Separation. Pilot should demonstrate the reliability and safety of a full scale fuel cleanup (FCU) and hydrogen isotope separation system (ISS) in an integrated manner. It will also provide operating experience and training for utilities.

The FCU should be sized to process at least 30 times the fuel burn-up rate since the burn-up is only 3–5%.

The ISS should be sized to process the plasma exhaust flow, hydrogen recirculating flow for effluent water detritiation, pellet fueler injection propellant, and other tritium carrying streams from waste recovery.

The product specifications are:

Hydrogen. This must be releasable quality and therefore the atom fraction of T must be less than 1×10^{-9}.

Deuterium. The atom fraction of H should be less than 1×10^{-5}. Since the deuterium is re-injected into the torum, the T fraction is not important and will be specified during machine optimization.

Tritium. The tritium purity should be greater than 99.7%.

Discharges. Water discharges from waste water purification must be releasable quality and therefore the HTO mole fraction in the product must be less than 5×10^{-12}.

The overall availability of the purification/separation system should be greater than 80%.

8.3.6. Waste Management and Decommissioning

Waste management technology and decommissioning planning and experience from fission is considered generally applicable for fusion.

8.3.7. Utility Input in Design for Ease of Construction and Operation and Maintenances

Utility Acceptance Process. A typical utility will compare the demonstrated pilot with the already proven and applied or with any other new option which could emerge at that time in the following key performance categories:

- Cost
- Safety
- Implementation schedule
- Licensing requirements
- Environmental performance
- Public acceptance
- Indigenous fuel supply
- Constructability
- Operability
- Reliability, capability factors
- Maintainability
- System control
- Flexibility
- Availability of strategic materials, fuels
- Waste management

On balance, Pilot should show that fusion has a chance of better performance in at least one specialized application. The new concept must be a winner in the categories of safety and impact on the environment and should have potential for competitive energy cost.

Utilities Involvement in the Pilot—Design Phase. In order to secure utilities understanding of the pilot project it is recommended that proper utility representation is secured from the very beginning by way of:

- Utility participation from the conceptual design stage
- A well-managed acquisition phase program
- Clarifying and keeping clear the differences between fusion and fission and thoroughly addressing where the concepts are different and what these differences mean for the target user
- Applying design and quality assurance concepts analogous to the ones applied by the industry
- Applying procedural approach to operation and adopting operating practices and policies consistent with those prevailing in the industry

Utilities Involvement in Pilot Commissioning and

Operating. The following Utility—Pilot interfacing activities for the commissioning and operating stage is suggested:

1. Consideration should be given to placing contracts with utilities for using their own personnel for preparing operating manuals with advising Pilot on nuclear operations.

2. Operational staffing of Pilot from utilities would also be beneficial, both to Pilot and the utilities. Pilot would gain experienced operating resources and the utilities would be able to determine the required personnel qualifications and numbers compared to existing fission plants. The challenge for Pilot is to demonstrate that no excessively large staffing is required in a fusion power facility and that the level of skills are compatible with fission plants.

3. Operator/maintainer training by established utility training centres would make use of the training scope and methods already applied by the industry, such as the use of training simulators, procedures for certification of nuclear workers etc. Training records would show utilities what effort is required to train staff for operating a fusion plant.

The use of fission plant training facilities and instructors for training operation/maintenance personnel would also probably minimize training costs for Pilot.

4. Operating and maintaining Pilot with its unique fusion components and infrastructure, would allow utilities to become familiar at an early date with the specific aspects of fusion which are different from the fission industry. The challenge for Pilot is to secure the support and confidence of the utility industry for this and subsequent demonstration facilities.

5. It will be desirable demonstrate to utilities through Pilot, that a fusion plant can be constructed with similar resources, quality, and skills customary to the nuclear industry. Unique on site and off-site fabrication processes must be well documented and preserved for reproducibility and accessibility to subsequent users.

Pilot Definition and Location Strategy. One of the reasons for building the pilot is to gain industrial acceptance. The most effective method of achieving this would be by building the pilot at the site of an already established fission plant and having it operated by the same operating personnel and under the same management as is already established at the fission facility. The pilot undertaking, particularly with the severely limited funding, will involve significant business risk. It is rationalized that if the pilot operation is not successful, the project could do more harm to the fusion progress than if it were not attempted at this time. In order to secure success, the project should consider adopting the following cost saving and risk mitigating steps: demonstrating production of high grade energy from fusion by the lowest level of technology possible, and utilization of conventional and nuclear support structure where possible.

Utilization of Licensing and Environmental Approvals. The licensing of a fusion pilot plant at a green field site may encounter significant public opposition, depending on the geographic location and local political environment. The key issues likely to be raised will include: environmental impact of a large project on the local community, tritium releases and assurance that large releases (i.e., those requiring evacuation) are not possible, tritium transportation safety, and waste management and disposal.

The process required to license a new site for a nuclear facility is quite lengthy, and because fusion is new and largely an unknown to anti-nuclear groups, the process could be considerably longer for Pilot. An existing licensed site will have previously addressed all of the above issues, if not specifically for tritium, for other radioactive substances. Therefore, there will be significant advantages by utilizing an already licensed site. For example: a potentially simpler and shorter environmental assessment and review process, a potentially simpler and shorter licensing process, as many of the administrative system for radiation monitoring, security, access control, communication, and emergency preparedness are already in place, and the utilization of existing waste disposal capabilities, which would eliminate the need to license new facilities on site or off site.

There may also be some benefits to be gained from a local public (community) that is already enlightened on the effects of radiation, and a local regulatory structure that is familiar with the site and local issues.

REFERENCES

1. S. O. Dean *et al.* (1991). *J. Fusion Energy* **10**, 197.
2. National Energy Strategy, U.S. Government Printing Office, February 1991.