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Analysis of Technical Issues for Development of Fusion-Fission Hybrid Reactor (FFHR)

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1. Introduction

The nuclear fission reactors remain public concerns about the safety, waste and decommissioning (afterwards) that they produce. The most optimistic assessment predicts that fusion technology will not be able to produce electricity on a commercial scale for at least another four decades. There is a third nuclear option led to a resurgence of interest, which combines the aspects of fission and fusion technologies in the form of the fusion-fission hybrid reactor (FFHR) [1]. An FFHR is a fusion reactor surrounded by a fission blanket, containing the thorium, uranium, and transuranic (TRU) elements, to increase output power, to breed fissile fuels, and to incinerate (transmute) radioactive materials [2]. Thus, the FFHR is a sub-critical fission reactor with a variable strength fusion neutron source, including a mission of supporting the sustainable expansion of nuclear power in the world by helping to close the nuclear fuel cycle [3]. In this presentation, major technical issues and basic requirements are summarized and analyzed for the development of FFHRs in Korea.

2. Background Study and Review of FFHR

In this section, the background studies and characteristic reviews of FFHRs are summarized [3].

2.1 Needed R&D for Fusion Power Production

(a) To achieve the required level of individual physics and technology performance parameters (physics and technology experiments)
(b) To achieve the required levels of all the different individual physics and technology performance parameters simultaneously (component test facilities and experimental reactors, e.g. ITER)
(c) To achieve the required level of all the individual physics and technology performance parameters simultaneously and reliably over long periods of continuous operation (advanced physics experiments, component test facilities and demonstration reactors)
(d) To demonstrate the economic competitiveness of the power that will be produced (prototype reactors)

2.2 R&D Status of Magnetic Fusion Reactor

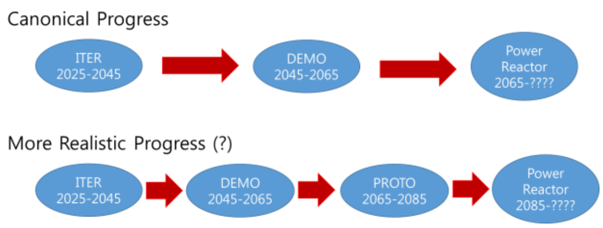
(a) Tokamak is the leading plasma physics confinement concept (until this time)

- ~100 tokamaks in the worldwide since 1957
- Physics performance parameters achieved at or near lower limit of reactor relevance
- Large, world-wide physics and technology programs supporting ITER (initial operation in 2025, but possible delay again)
- ITER will achieve reactor-relevant physics and technology parameters simultaneously, produce 500 MW_{th} and investigate very long-pulse operation

(b) Many other confinement concepts (e.g. mirror, bumpy torus) have fallen by the wayside or remain on the backburner
(c) A few other confinement concepts (e.g. stellarator, spherical torus) have some attractive features, which justifies their continued development. However, the performance parameters are at least 1-2 orders of magnitude below what is required for a power reactor, and at least 25 years would be required to advance any other concept to the present tokamak level
(d) Plasma support technology (SC magnets, heating, fueling, vacuum, etc.) for the tokamak is at the reactor-relevant level, due to the large ITER R&D effort
(e) Fusion nuclear technology (tritium production, recovery and processing) has had a low priority within fusion R&D. ITER will test fusion tritium breeding blanket modules
(f) The continued lack of a radiation damage resistant structural material would greatly complicate fusion experiments beyond the ITER level (e.g. DEMO) and might make a fusion reactor uneconomical, if not altogether impractical

2.3 Fusion Development Schedule

The following processes are a conventionally well-known schedule for development of the fusion power reactors in the worldwide.



2.4 Sustainable Nuclear Power Expansion

(a) The present “once-through” LWR fuel cycle utilizes < 1% of the potential uranium fuel resource and leaves a substantial amount of long-term radioactive TRU in the spent nuclear fuel. The TRU produced by the present LWR fleet will require a new HLWR every 30 years, and a significant expansion of nuclear power would require new HLWRs even more frequently
(b) A significant expansion of nuclear power in the world would deplete the known uranium supply within 50 years at the present <1% utilization
(c) Fast “burner” reactors can in principle solve the spent fuel accumulation problem by fissioning the TRU in spent nuclear fuel, thus reducing the number of HLWRs needed to store them, while at the same time utilizing more of the uranium energy content
(d) Fast “breeder” reactors can in principle solve the uranium fuel supply issue by transmuting ^{238}U into fissionable (in LWRs and fast reactors) TRU (plutonium and the higher ‘minor actinides’), leading to the utilization of >90% of the potential energy content of uranium
(e) Fast reactors cannot be fueled entirely with TRU because the reactivity safety margin to prompt critical would be too small, and the requirement to remain critical requires periodic removal and reprocessing of the fuel. Operating fast reactors subcritical with a variable-strength fusion neutron source can solve both of these problems, resulting in fewer fast burner reactors and fewer HLWRs

2.5 Rationale of FFH (Fast Burner) Reactors

The fast burner reactors could dramatically reduce the required number of high-level waste repositories by fissioning the TRU in the LWR SNF. The potential advantages of FFH burner reactors over critical burner reactors are:

- Fewer reprocessing steps, hence fewer reprocessing facilities and HLWR repositories (separation of TRU from fission products is not perfect, and a small fraction of the TRU will go with the fission products to the HLWR on each reprocessing) - No criticality constraint, so the TRU fuel can remain in the FFH for deeper burnup to the radiation damage limit
- Larger LWR support ratio - FFH can be fueled with 100% TRU, since sub-criticality provides a large reactivity safety margin to prompt critical, so fewer burner reactors would be needed

2.6 Choice of Fission Technologies for FFH (Fast Burner) Reactor

(a) Sodium-cooled fast reactor is the most developed burner reactor technology, and most of the worldwide fast reactor R&D is being devoted to it (deploy 15-20yr)
- The metal-fuel fast reactor (IFR) and associated pyroprocessing separation and actinide fuel fabrication technologies are the most highly developed in the USA. The IFR is passively safe against LOCA & LOHSA. The IFR fuel cycle is proliferation resistant
- The sodium-cooled, oxide fuel FR with aqueous separation technologies are highly developed in France, Russia, Japan and the USA

(b) Gas-cooled fast reactor is a much less developed backup technology
- With the oxide fuel and aqueous reprocessing
- With the TRISO fuel (burn and bury). Radiation damage would limit TRISO in fast flux, and it is probably not possible to reprocess

(c) Other liquid metal coolants (Pb, PbLi, Li)
(d) Molten salt fuel would simplify refueling, but there are some issues (Molten salt coolant only (?))

2.7 Choice of Fusion Technologies for FFH (Fast Burner) Reactor

(a) The tokamak is the most developed fusion neutron source technology. Most of the worldwide fusion physics and technology R&D is being devoted to it, and ITER will demonstrate much of the physics and technology performance needed for a FFH (deploy 20-25 yr)
(b) Other magnetic confinement concepts promise some advantages relative to the tokamak, but their choice for a FFH would require a massive redirection of the fusion R&D program (not presently justified by their performance)
- Stellarator, spherical torus, etc. are at least 25 years behind the tokamak in physics and technology (deploy 40-50 yr)
- Mirror could probably be deployed in 20-25 years, but would require redirection of the fusion R&D program into a dead-end technology that would not lead to a power reactor

3. Technical Issues of FFHR

In this section, the major technical issues for development of the FFHR are shortly summarized [3, 4].

3.1 Fusion Physics

- Current drive efficiency and bootstrap current
- Plasma heating with lower-hybrid resonance (LHR)
- Disruption avoidance and mitigation

Steady-state maintenance of the magnetic field for plasma confinement of the fusion devices is difficult with the inductive method. Then, the plasma current must be driven without depending on the inductive method for a steady-state operation, and a non-inductive current drive is thereby required. For the non-inductive current drive with external input, there are two principal schemes, as the use of a particle beam (neutral beam injection, NBI) and radio-frequency (RF) waves including the effect of core plasma heating sources. The plasma current is spontaneously generated when the pressure of the plasma increases with respect to the magnetic pressure of poloidal field. This current fraction is known as the bootstrap current. The continuous operation of a tokamak fusion reactor is realized by the combination of the bootstrap current and the non-inductive current drive, supplied externally as a beam or RF waves.

A major disruption is induced by several different causes, which are classified into the following categories, namely, density limits, impurity accumulations, too low or too high internal inductance, stability limits of plasma pressure, external error field, vertical instability, plasma surface safety factor around 2 or 3, and the minimum safety factor around 2 or 3 in reversed shear plasma configuration. It is expected that disruptions caused by the above mechanisms can be avoided through the deliberate engineering design of the device and optimization of the operating scenario. Therefore, possible occurrences of disruption in the fusion reactor could be considered as possible events in the process of the optimization of operation scenarios, fault operation, failures in hardware, or an emergency interrupt triggered by the safety interlock.

3.2 Fusion Technology

• Tritium retention
• Tritium breeding and recovery
• 100~200 dpa structural material

It is the most important to maintain the breeder and multiplier temperature in the appropriate range not only from the view of proper tritium release but also to preserve the mechanical integrity of the pebble bed. Past pebble bed experiments have resulted the data accumulation for effective thermal conductivity of a pebble bed as well as the wall heat transfer coefficient. The mechanical characteristics of a pebble bed are a new area of research so the data accumulated and the theoretical research on the pebble bed Young's modulus, the Poisson ratio, and on the modeling of the mechanical behavior of pebble bed are all significant. The combined behavior of the thermal and mechanical characteristics and irradiation effects are further issues.

Tritium generation and release kinetics research are investigating purge gas conditions and the temperature dependence for tritium release and breeder irradiation experiments. Sound tritium generation and release characteristics have been demonstrated up to 5% Li burn-up (i.e., DEMO: 10~15%). Non-steady-state data is needed by simulated pulse irradiation. Model development is further needed for evaluating tritium release behavior. Higher Li burn-up experiments are needed to demonstrate the feasibility of tritium production (such as in DEMO conditions). The technology of tritium recovery from large amounts of He-urge gas has already been established by technological research and operational experience of the tritium systems test loops. Further development is necessary for scale-up testing, high efficiency process development, and so on.

Service condition of the structural materials in the burning fusion devices will be quite severe. D-T fusion reaction 14 MeV neutrons introduce displacement damage, transmutation produced gas atoms (hydrogen and helium), and solid transmutation elements in considerable amounts. Materials are expected to retain enough strength to maintain the integrity of the component under the radiation damage by both the high-energy neutrons and the effect of high thermal stress at elevated temperatures. Radiation damage for the materials of the first wall of the blanket is expected to attain levels of ~100 dpa and several thousand appm of helium in the demonstration reactor. Because of this expected severe service condition, a rather long time will be needed for the development and this program should be carefully planned and managed.

3.3 Fission Technology

• MHD effects on Na-flow in magnetic field (molten salt coolant backup (?))
• Refueling in tokamak geometry

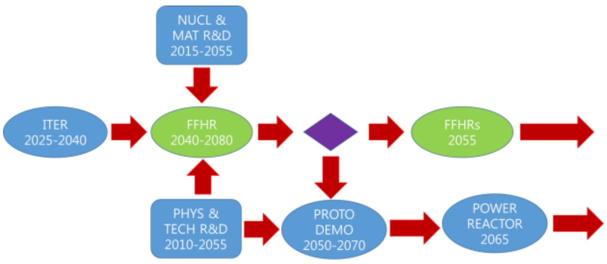
Selection of coolants for the hybrid system affects the transmutation performance of the FFHR. LiPb coolant (as a conventional coolant for a FFHR) has problems such as reduction in neutron economic and magneto-hydro-dynamic (MHD) pressure drop. The transmutation performance has been evaluated and compared for various coolant options such as LiPb, H_2O, D_2O, Na, PbBi, LiF-BeF_2, and NaF-BeF_2 applicable to a hybrid reactor for waste transmutation [5]. Compared to LiPb, H_2O and D_2O are not suitable for waste transmutation because of neutron moderation effect. Waste transmutation performances with Na and PbBi are similar to each other and not different much from LiPb. Even though the molten salt, such as LiF-BeF_2 and NaF-BeF_2, is good for avoiding MHD pressure drop problem, waste transmutation performance is dropped compared with LiPb.

Hybrid blanket systems must perform all the functions required of pure fusion blanket systems, namely, producing and recovering tritium sufficient to continuously refuel the plasma targets; capturing and exhausting the fusion power; and shielding other components (such as magnets, vacuum vessel, and mirrors) as necessary to meet their lifetime, waste disposal, or reweldability requirements. In a hybrid, the pure fusion functions are augmented by the desire to use the fusion neutrons to drive an additional fission blanket system that accomplishes some combination of transmuting fission waste, producing power from fissionable fuel, and/or producing additional fissile material for fission reactor fuels [6].

The combined fusion-fission blanket must typically multiply fusion neutrons via reactions in beryllium, lead, and/or fissionable isotopes; allow neutrons to reach and drive the fission fuel with additional neutron and energy multiplication; and minimize parasitic capture and leakage of neutrons such that tritium self-sufficiency can still be achieved via reactions of unused neutrons with lithium. Depending on the type of hybrid considered (transuranic transmuter, power producer, fuel producer) and the nature of the fusion driver (tokamak, ST, mirror, inertial fusion, and so on) the fusion-fission blankets can take different forms and adopt different strategies for meeting their respective mission, cost, and availability targets. Other aspects of fusion nuclear technology, such as the need for viable divertors, plasma heating and current drive systems, mirrors, and target injection and tracking systems, must still be accomplished together and by sharing space with the fusion-fission blanket systems.

4. Fusion Power Development with a Dual FFH Path

The following process is the suggestion of a dual fusion-fission hybrid path for fusion power development in USA [3].



4.1 Fusion Physics (Advances beyond ITER)

- PROTODEMO must achieve reliable, long pulse plasma operation with plasma parameters (β, τ) significantly more advanced than ITER
- FFHR must achieve highly reliable, very long pulse plasma operation with plasma parameters similar to those achieved in ITER

4.2 Fusion Technology (Advances beyond ITER)

- FFHR must operate with moderately higher surface heat and neutron fluxes and with much higher reliability than ITER.
- PROTODEMO must operate with significantly higher surface heat and neutron fluxes and with higher reliability than ITER
- PROTODEMO and FFHR would have similar magnetic field, plasma heating, tritium breeding and other fusion technologies
- PROTODEMO and FFHR would have a similar requirement for a radiation-resistant structural material to 100~200 dpa

4.3 Fusion R&D for FFHR (on the Path to Fusion Power)

(a) Plasma Physics R&D for FFHR or PROTODEMO
- Control of instabilities.
- Reliable, very long-pulse operation.
- Disruption avoidance and mitigation.
- Control of burning plasmas.

(b) Fusion Technology R&D for FFHR or PROTODEMO
- Plasma Support Technology (magnets, heating, vacuum, etc.)-improved reliability of the same type components operating at same level as in ITER
- Heat Removal Technology (first-wall, divertor)-adapt ITER components to Na-coolant and improve reliability
- Tritium Breeding Technology-develop reliable, full-scale blanket & tritium processing systems based on technology tested on modular scale in ITER
- Advanced Structural (100~200 dpa) and Other Materials
- Configuration for remote assembly & maintenance

(c) Additional Fusion R&D beyond FFHR for Tokamak Electric Power
- Advanced plasma physics operating limits (β, τ)
- Improved components and materials

4.4 Integration of Fusion & Fission Technologies

- For Na, or any other liquid metal coolant, the magnetic field creates heat removal challenges (e.g. MHD pressure drop, flow redistribution). Coating of metal surfaces with electrical insulation is one possible solution. This is also an issue for a PROTODEMO with liquid Li or LiPb
- Refueling is greatly complicated by the tokamak geometry, but then so is remote maintenance of the tokamak itself, which is being dealt with in ITER and must be dealt with in any tokamak reactor. However, redesign of fuel assemblies to facilitate remote fueling in tokamak geometry may be necessary
- The fusion plasma and plasma heating systems constitute additional energy sources that conceivably could lead to reactor accidents. On the other hand, the safety margin to prompt critical is orders of magnitude larger than in a critical reactor, and simply turning off the plasma heating power would shut the reactor down to the decay heat level in seconds

4.5 Supplemental FFHR Path of Fusion Power Development

- Fusion would be used to help meet the world energy needs at an earlier date than is possible with "pure" fusion power reactors. This, in turn, would increase the technology development and operating experience needed to develop economical fusion power reactors
- FFHRs would support (may be necessary for) the full expansion of sustainable nuclear power in the world
- An FFHR will be more complex and more expensive than either a Fast Reactor (critical) or a Fusion Reactor
- However, a nuclear fleet with FFHRs and LWRs should require fewer burner reactors, reprocessing plants and HLWRs than a similar fleet with critical Fast Burner Reactors
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4.6 Main Issues for FFH Burner Reactor System

- A detailed conceptual design study of an FFH Burner Reactor and the fuel reprocessing/refabrication system should be performed to identify: a) the readiness and technical feasibility issues of the separate fusion, nuclear and fuel reprocessing/refabricating technologies; and b) the technical feasibility and safety issues of integrating fusion and nuclear technologies in a FFH burner reactor. This study should involve experts in all physics and engineering aspects of a FFHR system: a) fusion; b) fast reactors; c) materials; d) fuel reprocessing/refabrication; e) high level radioactive waste (HLW) repository; etc. The study should focus first on the most advanced technologies in each area; e.g. the tokamak fusion system, the sodium-cooled fast reactor system
- At first, dynamic safety and fuel cycle analyses should be performed to quantify the advantages in transmutation performance in a FFHR that result from the larger reactivity margin to prompt critical and the relaxation of the criticality constraint. Then, a comparative systems study of several scenarios for permanent disposal of the accumulating SNF inventory should be performed, under different assumptions regarding the future expansion of nuclear power. The scenarios should include: a) burying SNF in geological HLW repositories without further reprocessing; b) burying SNF in geological HLW repositories after separating out the uranium; c) reprocessing SNF to remove the TRU for recycling in a mixture of critical and FFH burner reactors (0-100% FFHR) and burying only the fission products and trace TRUs remaining after reprocessing; d) scenario "c" but with the plutonium set aside to fuel future fast breeder reactors (FFHR or critical) and only the "minor actinides" recycled; e) scenarios (c) and (d) but with pre-recycle in LWRs; etc. Figures of merit would be: a) cost of overall systems; b) long-time radioactive hazard potential; c) long-time proliferation resistance; etc.
- Additional R&Ds needed for a FFH Burner Reactor in addition to the R&D needed to develop the fast reactor and the fusion neutron source technologies should be developed in the conceptual design study identified above

5. Conclusions

The background information was studied and reviewed for the development of FFHR based on the fusion and fission reactors. A development progress of FFHR was suggested by the worldwide path of fusion power reactors. Major technical issues and basic requirements are summarized and analyzed for the development of FFHR in Korea.

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