R-08-126

On fusion driven systems (FDS) for transmutation

O Ågren
Uppsala University, Ångström laboratory, division of electricity

V E Moiseenko
Institute of Plasma Physics, National Science Center
Kharkov Institute of Physics and Technology

K Noack
Forschungszentrum Dresden-Rossendorf

October 2008

Svensk Kärnbränslehantering AB
Swedish Nuclear Fuel
and Waste Management Co
Box 250, SE-101 24 Stockholm
Tel +46 8 459 84 00

ISSN 1402-3091
SKB Rapport R-08-126

On fusion driven systems (FDS) for transmutation

O Ågren
Uppsala University, Ångström laboratory, division of electricity

V E Moiseenko
Institute of Plasma Physics, National Science Center
Kharkov Institute of Physics and Technology

K Noack
Forschungszentrum Dresden-Rossendorf

October 2008

Summary

This SKB report gives a brief description of ongoing activities on fusion driven systems (FDS) for transmutation of the long-lived radioactive isotopes in the spent nuclear waste from fission reactors. Driven subcritical systems appears to be the only option for efficient minor actinide burning. Driven systems offer a possibility to increase reactor safety margins. A comparatively simple fusion device could be sufficient for a fusion-fission machine, and transmutation may become the first industrial application of fusion. Some alternative schemes to create strong fusion neutron fluxes are presented.

Sammanfattning

Denna rapport för SKB ger en övergripande beskrivning av pågående aktiviteter kring fusionsdrivna system (FDS) för transmutation av långlivade radioaktiva isotoper i kärnavfallet från fissionskraftverk. Drivna underkritiska system tycks vara det enda möjliga alternativet att åstadkomma effektiv förbränning av lättare aktinider. Drivna system erbjuder möjligheter att öka reaktorsäkerhetsmarginaler. En förhållandevis enkel fusionsapparat kan vara tillräcklig för en fusion-fissionsmaskin, och transmutation kan komma att bli den första industriella tillämpningen av fusion. Några alternativa metoder för att generera kraftiga flöden av fusionsneutroner presenteras.

Preface

SKB has the responsibility for the spent nuclear fuel produced in the Swedish fission reactors. This SKB report gives a brief description of ongoing activities on fusion driven systems (FDS) for transmutation of the long-lived radioactive isotopes in the spent nuclear waste from fission reactors. The ambition in this first short investigation is mainly to make people involved in nuclear waste handling aware of fusion driven systems and the potentials of FDS to solve important problems connected with nuclear safety and nuclear nonproliferation. A more thorough investigation with feasibility analysis of different concepts is needed for the future. A rapid increase of the world wide research efforts on FDS is anticipated the coming years.

The topic covers many areas of physics and engineering. Researchers with expertise in fusion and plasma physics, nuclear physics, fission energy and electro techniques have contributed with valuable suggestions for the report. Prof. Nathan Fisch (Princeton, USA) has provided information on FDS studies and programs in USA. We are grateful to Professor A. A. Ivanov, leader of the mirror machine and neutron source programs at the Budker Institute at Novosibirsk, for discussions and useful comments. We also acknowledge discussions with colleagues at Uppsala University, in particular Professor Mats Leijon, Professor Jan Källne, Dr Kjell Pernestål and my PhD student A. Hagnestål.

Contents

1 Introduction

The present scenario for the Swedish spent nuclear fuel involves a geological storage under ground for more than 100,000 years. Heat generation and radioactivity are problems for long term storage. Fission products deliver the greatest contribution to heat and radioactivity during the first few hundred years, while the long term radioactivity is dominated by the presence of minor actinides, in particular americium. Future industrial transmutation of long-lived radioactive isotopes could in principle reduce the required storage time to about only 300 years.

Nuclear energy will mainly be produced by conventional light or heavy water reactors for at least the coming 50 years. U^{235} fuel resources are sufficient for a much longer time of operation with conventional fission reactors, even if a majority of the fossil fuel production is replaced by nuclear energy. Fission is perhaps the only alternative in a foreseeable future that can replace the fossil fuel energy production, and in this way solve the CO_2 emission problem.

Although fission energy can be produced over a long time, a concern is the accumulation of the radioactive spent nuclear fuel. A system for industrial transmutation of the spent fuel is desirable for a sustainable fission energy production. Transmutation can also help the even more important nuclear nonproliferation issues. This report will briefly describe fusion driven systems (FDS), which is a realistic option for industrial transmutation in a not too distant future.

Conventional fission reactions produce long-lived radioactive isotopes (in particular various isotopes of plutonium and minor actinides as well as some fission products with long half-lives). Plutonium and minor actinides burning is more efficient in reactors with a fast neutron energy spectrum, but reactor safety margins are reduced by adding minor actinides with a low fraction of delayed neutrons to the fuel. Hazardous events can appear if the efficient neutron multiplicity k_{eff} for some uncontrolled reason would increase above unity. A critical reactor operates with $k_{\mathrm{eff}} = 1$ and relies on the action of delayed neutrons for reactor control.

Another option with improved reactor safety for minor actinide burning is to drive the neutron reactions by an external neutron source. Reactor safety can be arranged in driven subcritical system which operates with $k_{\mathrm{eff}} < 1$, and fission power production can be stopped by turning off the neutron source.

Intense external neutron fluxes can be produced from the deuterium-tritium (D-T) fusion reaction

$$\mathrm{D} + \mathrm{T} \rightarrow He^4\ (3.5\ Mev) + n\ (14.1\ MeV)$$

which produces neutrons with the energy 14.1 MeV. In magnetically confined fusion plasmas, the Coulomb barrier threshold for the D-T reaction is overcome by heating the plasma ions to energies of several keV or higher.

It is feasible to produce neutron fluxes of sufficient intensity in fusion machines. The ITER tokamak device, which is under construction at Cadarache in France, will produce more than 10^{20} neutron per second in pulses lasting for 20 minutes or more. Such a high flux is a bit of overkill for a neutron source, since a substantially smaller continuous flux could be enough to transmute the waste from 5 ordinary sized fission reactors. Tokamaks suffer from the pulsed operation, but other type fusion devices (mirror machines and stellarators) can operate in continuous mode.

The ITER device will be a large toroidal plasma confinement device, with a 36 m long plasma column with a 2 m minor radius, and it has until recently been thought of as a pure fusion device intended to produce 700 MW thermal power. Neutron sources sufficient to drive a subcritical reactor can be substantially smaller.

In subcritical systems driven by fusion neutrons, the fission power exceeds by a large factor the power output from the fusion neutrons. As high value of the effective neutron multiplication factor k_{eff} as possible is desirable to optimize power production, while reactor safety is improved by lower values. Sufficient reactor safety can be expected with $k_{\mathrm{eff}} = 0.96$, and the produced fission power then exceeds the fusion power by a factor

$$\frac{P_{fis}}{P_{fus}} \approx 150$$

The fusion power is of minor importance in FDS, but the fusion neutrons control the level of fission reactions in the subcritical reactor core.

Key technologies for fusion neutron sources have been developed during 50 years of fusion research. Energy production with conventional thermal fission reactors, combined with industrial transmutation of spent nuclear fuel by fusion driven systems, has the prospect to provide a sustainable energy production with sufficient reactor safety, capable of producing energy for the world for at least hundred years. Nuclear nonproliferation can be carefully addressed when accumulation of fissile material is minimized, and this question is of highest importance for a peaceful future of the world.

The first studies on fusion driven transmutation seems to have been initiated this millennium. Transmutation research with spallation neutron sources in accelerator driven systems (ADS) has been going on for a longer time. Input from the ADS research has been valuable for studies on fusion driven systems (FDS). There are several common physics and engineering tasks for ADS and FDS, although there are also important differences concerning the size, power, maintenance, reliability and potential economic use of the systems.

1.1 Fast reactors and reactor safety margins

The basic nuclear fuel in conventional fission reactors contains a mixture of the fissile U-235 and the stable U-238 isotopes. The content of U-235 gradually decreases as the uranium fuel is burnt out, but additional fuel (in particular plutonium and americium isotopes) are slowly built up by neutrons reacting with the uranium. In ordinary fission reactors, the efficiency of burning is prevented by the buildup of the Pu-240 isotope, which absorbs epithermal neutrons.

The Pu-240 isotope is however fissile by fast neutrons. An aim of fast reactors is to obtain a sufficiently large population of fast neutrons to split this isotope. A faster neutron spectrum can be achieved by replacing the water coolant in conventional nuclear reactors by some other coolant. Liquid sodium, a liquid mixture of lead and bismuth (which increases corrosion) or pressurized gaseous helium are coolant that provides a faster neutron energy spectrum. Gas cooling systems would be optimal to reduce slowing down of the neutrons, but a concern is the low heat capacity of the core under emergency conditions (e.g. stop of coolant flow).

Reactor safety is reduced by the presence of plutonium and minor actinides in the fuel. Compared with uranium, these transuranic elements produce a smaller fraction of delayed neutrons which are required to stabilize the efficient neutron multiplicity k_{eff} around unity in a critical reactor. In liquid-metal cooled fast reactors, a hazardous event could be initiated for instance by a sudden loss of coolant (tube rupture) or of coolant flow (flow blockade). In such cases the core could be voided of coolant and as a consequence the neutron multiplicity would increase. The increase in k_{eff} in an hazardous event has to be evaluated by detailed computations, but a representative value for a worst case scenario is an increase by 3%, which would lead to a reactor accident in a critical fast reactor. Liquid-metal cooled fast reactors (operating with $k_{\mathrm{eff}} = 1$) are more susceptible to coolant loss than light and heavy water reactors, and the reduced population of delayed neutrons is an additional effect which reduce the reactor safety margins.

1.2 Driven subcritical systems

A higher reactor safety can be achieved with a driven subcritical fast reactor, where the k_{eff} value of the reactor core is below the margins set by a worst case scenario. A typical value in a subcritical system driven by a neutron source is $k_{\mathrm{eff}} = 0.96$ or lower. The fuel mixture in a driven fast reactor changes slowly resulting in a slow decrease in k_{eff}, which is beneficial for reactor safety.

A subcritical reactor requires an external neutron source to drive the fission reactions, and the neutron source is a tool to control the burning and power output in the reactor core. In steady state the fission power level in the core is proportional to the neutron source strength. The slow decrease in k_{eff} can be compensated by a corresponding increase of the source intensity. Fission production in the reactor can be stopped by turning off the neutron source. This increases reactor safety.

A sufficiently intense neutron source, capable of delivering an average of about $5 \cdot 10^{18}$ neutrons per second, is required for industrial transmutation. For pulsed neutron sources, the repetition frequency needs to be high enough for efficient transmutation.

Critical fast reactors suffer from the weak spot of reactivity-driven power excursions. To mitigate this safety problem the loading of fast reactors with minor actinides in the fuel is restricted to less than 5 per cent (according to the present knowledge), a fact which essentially restricts their usefulness for the incineration of minor actinides. Therefore, from today's point of view this application of driven subcritical systems seems to be without real alternatives.

1.3 Early ideas of fusion breeding

In a pure fusion reactor design, the fusion neutron energy is converted into thermal energy in a lithium blanket, where tritium is produced by neutron reactions with the liquid lithium, which also serves as a coolant.

There has since the early days of fusion research been circulating ideas to use the high energy fusion neutrons for additional purposes other than tritium recovery and a thermal conversion of the energy in a fusion reactor. A hybrid breeder reactor could use the fusion neutrons for breeding of plutonium from uranium-238, with the intention to burn the plutonium and produce energy in a *separate* fission reactor. The origin of the hybrid breeder reactor idea is hard to trace, since the fusion research was classified in the 1950ies. Andrei Sakharov may have been the first researcher to discuss the possibility of a hybrid breeder reactor to amplify the output of the fusion neutrons /1/. Hans Bethe proposed in 1978 a mirror based hybrid-reactor for production of fissile fuel /2, 3/, requiring a fission mantle design that slows down the neutrons to avoid plutonium burning in the mantle surrounding the fusion machine. Transmutation is not intended in hybrid breeder reactors. Following the proposals of H. A. Bethe, the hybrid breeder reactor studies have also aimed at breeding new fissile material U-233 from Th-232, which can be used as fuel in a separate fission reactor. After the Three Mile Island reactor accident in 1979 and the Chernobyl catastrophe in 1986, studies on hybrid breeder reactors are abandoned. The intended application for fusion-fission machines has switched to transmutation combined with a direct energy production in the fission mantle surrounding the fusion neutron source.

1.4 A second wave of fusion-fission R&D

A renewed interest for fusion-fission R&D activities was inspired by proposals in the middle of the nineties for accelerator driven systems. C D Bowman et al. /4/ proposed to use ADS for incineration of nuclear waste from fission reactors and Nobel laureate C Rubbia /5, 6/ proposed these systems as energy amplifiers with great potential for reducing the nuclear waste.

As distinguished from FDS the ADS use an intense spallation neutron source as driver of the surrounding fission blanket. In today's ADS-projects this neutron source is realized by means of a high-current accelerator delivering a beam of protons with energy of about 1 GeV and an average current of several tens of milliamperes which should be continuous or at least quasi-continuous. The proton beam impinges on a heavy metal target, e.g. lead or lead-bismuth, where the spallation reactions take place. The produced high-energetic neutrons should fly out of the target and hit the fission blanket.

At present, several groups consisting of fusion and fission scientists develop project proposals for fusion-fission machines aimed to incinerate nuclear waste produced by fission reactors. Fission reactor technology would then gain a chance of an efficient solution of its vitally important waste disposal problem.

As a response to the Three Mile Island accident and particularly after the Chernobyl catastrophe, the safety of operating, as well as of the safety of new Light Water Reactor (LWR) concepts, was substantially improved with great effort. In the same time, the problem of the nuclear waste disposal more and more attracted notice in the discussion on the acceptance of nuclear energy by the society. On this background the motivations for the new ADS initiative and for the second phase of the FDS development were born.

2 Accelerator driven systems (ADS) and fusion driven systems (FDS)

Accelerators can produce GeV proton beams, which is an adequate beam energy for efficient generation of neutrons at a spallation target. The peak of the neutron energy spectrum is around 1.3 MeV, which is an order lower than the D-T fusion neutron energy. Although the beam energy can be achieved in existing pulsed accelerator systems, there is a need to increase the average beam current by two orders to about 100 mA. This increases the cost of the accelerator part. Although it may in principle be possible to design reliable systems to increase the ADS repetition rate, the heat load on the spallation target is an even more crucial problem. If the spallation target is vaporized, the beam energy would be converted to beam plasma instabilities, preventing efficient neutron generation at the spallation target. Differential pumping, the target heat load of several tens of MW and increase of the repetition rate and the beam current are some of the challenges encountered in ADS projects /7–9/.

A fusion device is an alternative for the neutron source. High intensity neutron fluxes are possible to generate in various kinds of plasma devices which have a sufficient density and energy of the fuel ions and quality of plasma confinement. Major candidates for a fusion neutron source are tokamaks (which has pulsed operation) and certain devices aimed for producing a continuous neutron flux, such as stellarators and mirror machines. Superconducting magnetic coil technology exists for operating a fusion machine in steady state.

The fusion research is not yet fully developed to an applied level, and the majority of plasma experiments are carried out without a tritium fuel component to avoid the need for radioactive protections around the experiments. The plasma performance parameters of the experiments still give insight on the potential use for a fusion driven system. Several experiments are run with deuterium plasmas, and 2.5 MeV neutrons arising from the deuterium-deuterium fusion reaction are detected.

Tokamaks, stellarators and mirror machines are variations of magnetic confinement schemes for the fuel plasma. Fusion neutrons could also be generated in pulsed inertial fusion devices and z pinches, which could be viewed as an intermediate of magnetic and inertial confinement. Although transmutation reactions are possible to generate, a scaling for industrial transmutation is lacking for z pinches and inertial fusion devices. This report will therefore have a focus on magnetically confined systems.

2.1 Noninductive plasma heating

The pulsed mode of tokamaks is connected with the inductive ohmic heating. The ohmic heating in a tokamak drives the toroidal current which is required for plasma confinement. A tokamak with ohmically driven toroidal current cannot operate in steady state, since a quasi-stationary loop voltage is achieved by the continous increase of the current in the tokamak inductor. Noninductive current drive schemes have been tested for tokamaks, but there is no feasible method available today for a continuous tokamak reactor operation.

Steady state machines operate with noninductive plasma heating, such as neutral beam injection and various radio frequency heating schemes. Neutral beam injection, where a neutral beam of deuterium or tritium ions are injected across the magnetic field and charge exchange reactions provide a trapping of the beam in the magnetic field, was originally developed for mirror machines and is now widely used in tokamak experiments to deliver energy to the plasma. Different kinds of radio frequency heating schemes, such as ion or electron cyclotron resonance heating and other resonant heating frequency ranges, are installed on various experiments for plasma heating.

3 Some international studies since 2000 on FDS

Most fusion devices constructed up to now have been made with the intention to contribute to the development of a pure fusion reactor. The research efforts on FDS have so far been comparatively small. A reason for this may be the late awareness in the fusion research community of the potential with fusion driven systems. However, several studies for fusion driven systems have been initiated in recent years, and a growing R&D activity is expected. Some of the more important challenges where FDS offers opportunities are:

1. Nuclear waste storage.
2. Reduction of proliferation risk of weapons-grade nuclear material.
3. Large scale long-term energy production.
4. Increased reactor safety by operating a fleet of LWR's together with FDS's for nuclear energy production.

The FDS has an impact on the following problems of controlled fusion:

1. Reduced demands on the fusion device.
2. Reduction of the first wall load of the fusion device.
3. Reduced cost of the device.
4. A shorter time scenario for application of fusion.

The reduced demands on the fusion device include size, plasma confinement quality and other aspects. Fusion devices with inadequate plasma confinement properties for a fusion reactor could still be sufficient as a neutron source for FDS. The simplified demands for a fusion neutron source has implications on the economic cost for the development and the final cost of the device, as well as the time scale for its development. Compared to critical fast reactors, reactor safety margins can be increased. A long-term energy production with a tolerable environmental impact seems possible with light water reactors in combination with fusion driven systems. For a peaceful future of the world, it is urgent to address nuclear nonproliferation issues.

3.1 Tokamaks

The best plasma confinement properties have been demonstrated in the large tokamak devices. The ITER device is planned to operate in a regime approaching the requirement of a pure fusion reactor, and its plasma confinement properties is predicted from the scaling of large tokamak experiments such as JET, JT 60, TFTR and Tore Supra.

The ITER device, see Figure 3-1, will produce a burning plasma and an intense D-T neutron flux. There are possibilities to increase the power output (about 700 MW thermal fusion power) by using fissile material in the region in between the vacuum wall and the magnetic coils. The initial plans for ITER was to study requirements of a pure fusion reactor, but the scope has recently been widened to also include fusion-fission issues, where one important issue is to increase the power output of tokamaks. More definite fission research plans for ITER will be decided the coming years.

3.1.1 FDS tokamak project in USA

A tokamak FDS project /10–12/ has been run over several years. The project is worked on both from the side of fusion and from fission technology. The latter was done in close collaboration

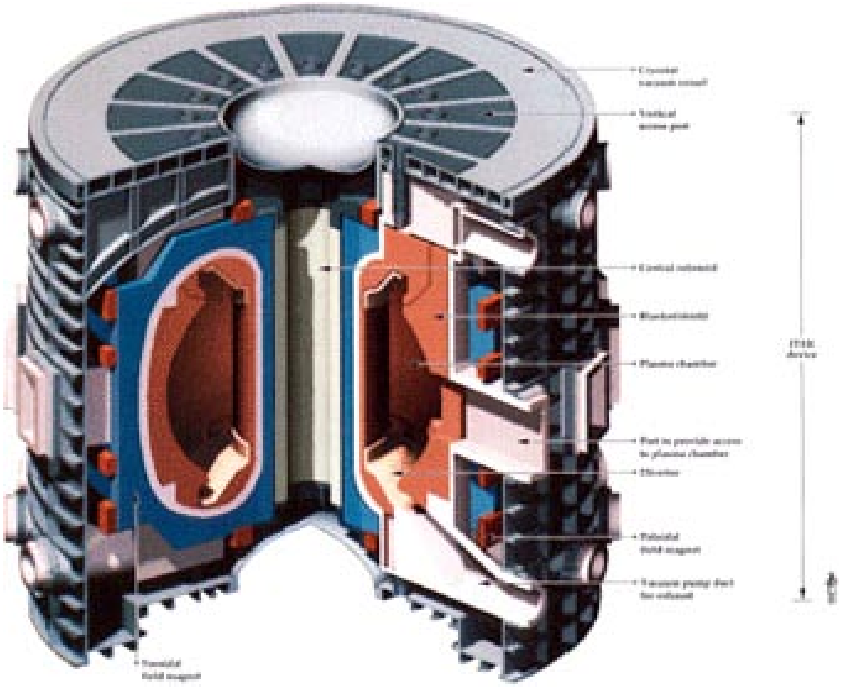

Figure 3-1. *Outline of the ITER device*

with Argonne National Laboratory. Most of the components of the tokamak as well as of the fission blanket are already developed in great technical detail.

An aim of the project is to base a fusion neutron source on downscaled ITER parameters to get smaller sizes and investment costs. The principal layout and some sizes are shown in Figure 3-2. The task of this FDS is to incinerate the transuranic isotopes in that composition as they appear in the spent nuclear fuel from LWR's. Therefore, the application of this transmuter needs that the partitioning technology is available which separates the uranium and the fission products from the spent nuclear fuel.

Regarding fuel and fission blanket materials, improvements are expected to be developed in course of R&D within the GENERATION-IV initiative.

The FTWR-SC version has superconducting magnets, cooled by supercritical helium, adapted from the ITER-FEAT design. The parameters presented in Table 3-1 predict a power producing device with a fusion device smaller than ITER. The study indicates the possibility to transmute the transuranic isotopes of 5 standard fission reactors (i.e. LWR's with a 3GW nominal thermal power each) by this concept for an FDS.

3.1.2 Projects in China

The FDS series consists of four conceptual designs in China for fusion power plants /13/. The FDS-I concept is a subcritical reactor driven by a neutron source, intended for transmutation of nuclear waste and fission fuel breeding. FDS-II has the goal of electric power production. FDS-III is a fusion based hydrogen producing reactor and FST-ST is a compact spherical tokamak reactor. Blanket designs for the concepts are emphasized.

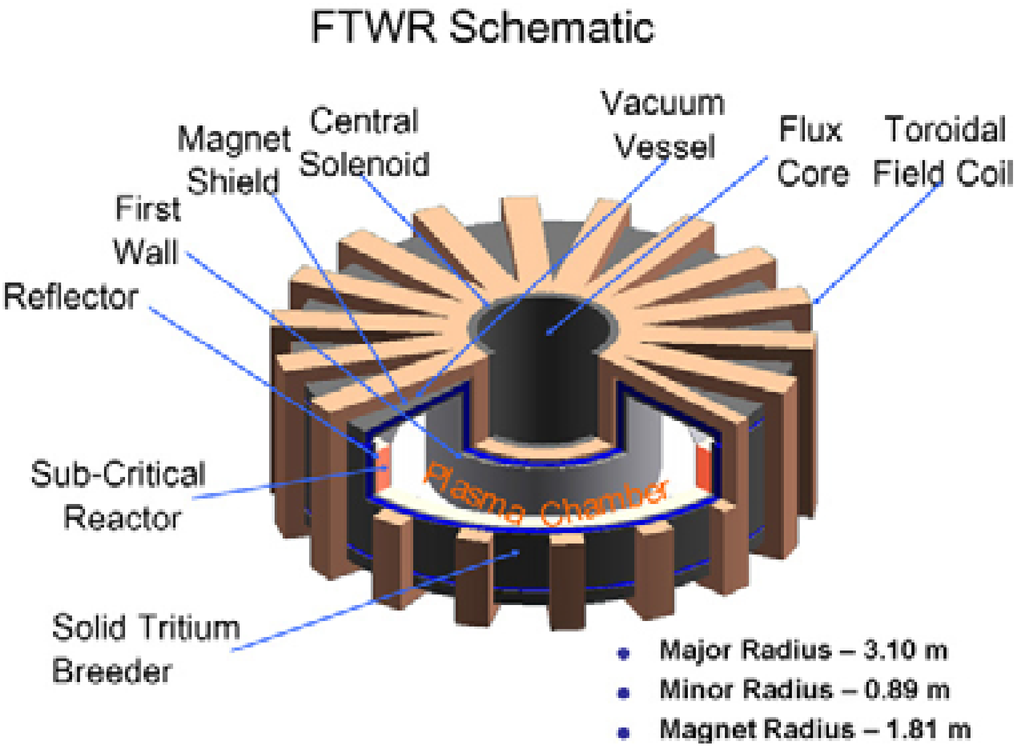

Figure 3-2. *Schematic layout of the FTWR-transmuter.*

Table 3-1. Some parameters of FTWR-SC compared to ITER.

Parameters	FTWR-SC	ITER
Fission power (MW)	4.500	
Fusion power (MW)	≤ 225	410
Major radius, R (m)	4.5	6.2
Minor radius, a (m)	0.9	2.0
Magnetic field, B (T)	7.5	5.3
Plasma power amplification, Q_p	≤ 2.0	10
Eff multiplication factor, k_{eff}	0.95	
Electric power amplification, Q_e	5	

3.2 Mirror machines

Mirror machines rely on the magnetic mirror effect for plasma confinement. The magnetic mirror effect is responsible for the trapping of plasma around the earth's magnetic field, and mirror machines are linear (not toroidal) devices with stronger magnetic fields near the longitudinal ends of the plasma confinement region. The linear geometry provides greater engineering flexibility for plasma access, fuel injection, divertor action etc, and a mirror machine can be run continuously. The open mirror geometry makes possible to utilize thicker fission mantles and thereby to fully employ higher values of k_{eff} and fission power amplifications within reactor safety margins. Compared to toroidal machines, it is harder to achieve sufficient plasma confinement along the magnetic field lines, and it is questionable if a pure fusion reactor can be based on a mirror machine. However, there are greater margins for a mirror based fusion-fission machine /16/.

3.2.1 Tandem mirror

Tandem mirrors have a central cell with a nearly constant magnetic field, with magnetic mirror fields of a special design near the ends of the linear device. Several tandem mirror experiments have been built and tested. An intention with tandem mirrors is to separate the fusion producing part (the central cell) from "end plugging regions" and "anchoring cells" which provide average minimum B stability of the whole device. The end plugging cells are aimed to increase the confinement of ions and electrons. An increase of the electron temperature, combined with the establishment of a high-confinement mode with radial transport barrier formation, has been reported for the Gamma 10 device in Japan /14, 15/.

The central cell region of a tandem mirror is suitable for a fission blanket for minor actinide burning and fission power generation /16/. Figure 3-3 shows a cross section of the TASKA-M neutron source design in the 1980ies, where the intention was to use a fusion neutron source for testing fusion reactor wall materials.

3.2.2 The Gas Dynamic Trap in Russia

The gas dynamic trap (GDT) is an axisymmetric mirror trap with an expander to suppress plasma instabilities. The Budker Institute at Novosibirsk is developing a D-T fusion neutron source based on the GDT, see Figure 3-4. The potential of this neutron source as driver of a minor actinides burner was studied by means of neutron transport calculations /17, 18/. A nearly critical reactor core (with $k_{eff} \approx 0.96$) is obtained with a 1.1 m thick fission blanket around the neutron source.

Table 3-2 shows results from a simulation. The computed power gain is not sufficient for electricity generation, but the performance of the concept is expected to improve with elongation of the neutron production region and increase of the electron temperature. Even with a comparatively low electron temperature, a net power gain is obtained with a large fission power amplification. The axisymmetric GDT device is stabilized by a magnetic flux tube expander and a finite plasma density behind the magnetic mirrors.

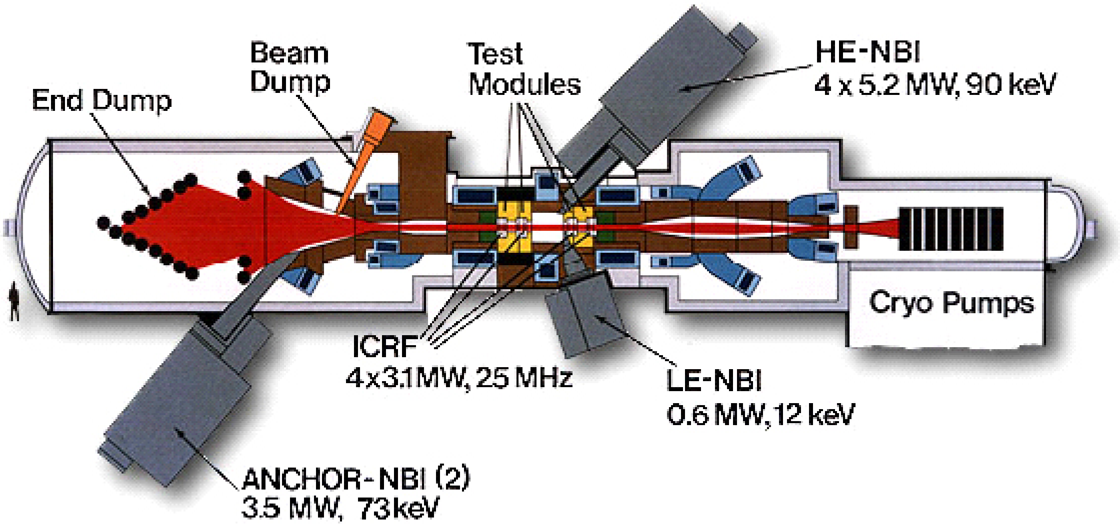

Figure 3-3. Cross section of TASKA-M (figure from http://fti.neep.wisc.edu/studies?rm=TASKA-M&s=1).

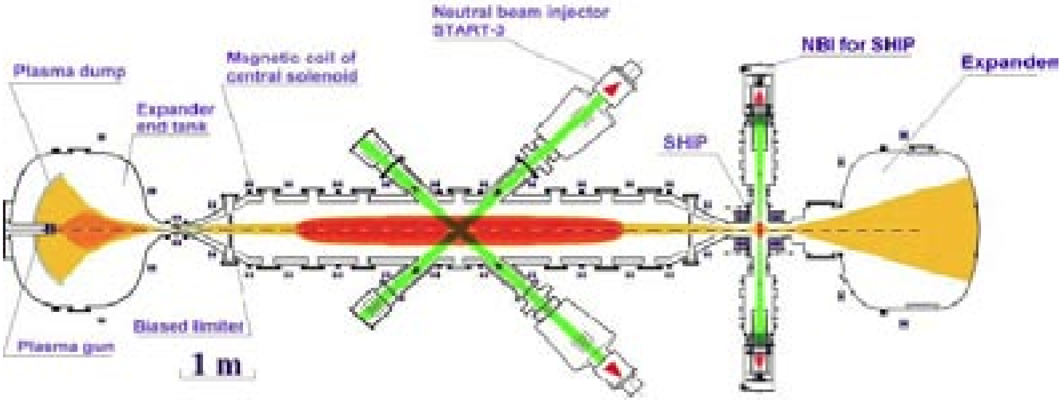

Figure 3-4. *Outline of the GDT experiment (figure from Ref. 14).*

Table 3-2. Parameters of a GDT simulation.

Parameters	GDT, elongated
Thermal power gain	1.82
n b power (MW), (electric input)	83 MW
Electron temperature (eV)	750
Eff. multiplication factor, k_{eff}	0.95817

3.2.3 Single cell mirror FDS studies

Plasma instabilities are suppressed by a minimum B field. A marginally stable minimum field has straight non-parallel magnetic field lines /19/, as shown in Figure 3-5. Plasma heating can be achieved by ion cyclotron resonance heating with antennas outside the plasma confinement region /20/. As fusion-fission reactors have reduced demands on plasma confinement and electron temperature, simplified mirror devices are of interest for neutron sources. The RF antennas, see Figure 3-6 for ion cyclotron heating can be located in the high field region outside the fusion region, and an increased electron temperature is envisioned by a strong ambipolar electric potential, which can be achieved by decreasing the plasma density sufficiently much in the region outside the magnetic mirrors /20/.

3.3 Stellarator-mirror concepts

Stellarators are toroidal devices which can be run continuously. Mirror machines can also operate continuously, but plasma losses along magnetic field lines are a concern. Stellarator-mirror concepts are studied with the goal of using the beneficial features of mirror machines and stellerators. The magnetic field of toroidally linked twisted magnetic mirrors is feasible to construct, as demonstrated with the Wendelstein line of stellarators and other stellarator experiments.

Figure 3-5. *Magnetic field lines of the Straight Field Line Mirror.*

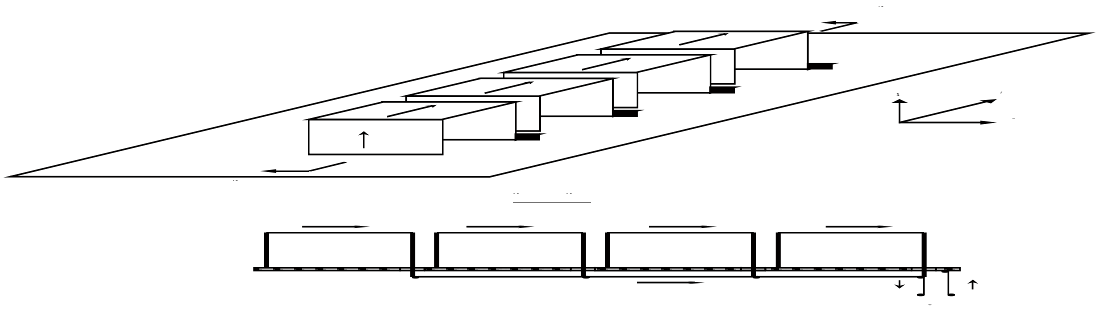

Figure 3-6. Strap antenna layout with scheme of electric connection.

3.3.1 Stellarator-mirror FDS

In a proposed stellarator-mirror concept /21/, the idea is to produce fusion in a mirror module and the mirror module is linked to a stellarator module to increase the electron temperature, see Figure 3-7. The tritium fuel is heated to a high temperature by ion cyclotron resonance heating. Table 3-3 shows results for simulation of a neutron source.

Table 3-3. Parameters for mirror-stellarator.

Parameter	
Perpendicular tritium temperature $T_{\perp}$	250 keV
RF power P_{RF}	63 MW
Neutron generation at mirror part	2.7×10^{18} neutron/s
Fission power	1.7 GW
Plasma minor radius a	36 cm
Mirror length ηL	310 cm
Electric efficiency $Q = P^{out}_{el} P^{RF}_{el}$	6.7

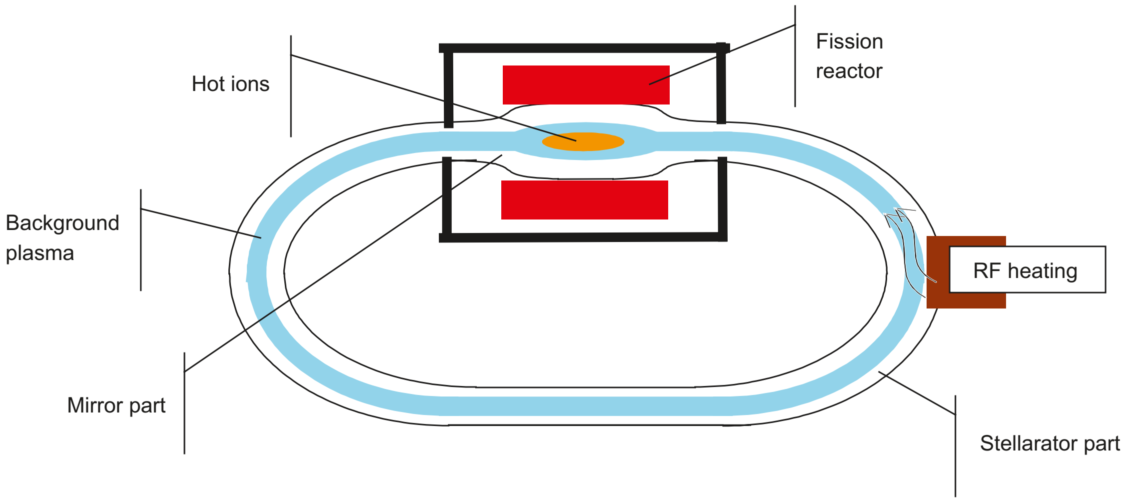

Figure 3-7. Sketch of stellarator-mirror FDS.

3.4 Z pinch

The "In-Zinerator" concept /22/ is investigated at the Sandia National Laboratories. The idea is to use a pulsed Z pinch fusion neutron source inside a subcritical fluid blanket containing minor actinides. Continuous refuelling and removal of fission products are possible with the fluid fuel elements. The predicted capacity of the concept is to yearly burn 1,280 kg actinides with a thermal power production of 3,000 MWh. The considered effective neutron multiplication is high, and special design for reactor safety is considered.

3.5 Inertial fusion

Inertial fusion relies on rapid pulses compressions of deuterium and tritium to create fusion reactions, which is a striking difference compared to the "gentle" fusion burning in magnetically confined plasma. The PROMETHEUS inertial fusion energy power plant designs were completed in 1992. The potential for fissile breeding and transmutation of long-lived fission product of the PROMETHEUS reactor has been analyzed /23/.

3.6 Other ideas

There are several additional proposals to utilise fission with fusion neutrons. The former head of the JET tokamak experiment, H. Rebut, has considered adding U-238 to the mantle surrounding the ITER tokamak to enhance power output /24/. Another proposal is to enhance proliferation resistance properties of plutonium by means of its isotopic denaturing /25/. The approach is exemplified by denaturing of pure Pu-239 and plutonium of typical LWR spent fuel through transmutation of neptunium. There is also a conceptual design for a 200 MW hybrid fusion-fission reactor to be used as a heat source for district heating /26/, where the fission heat-generating blanket is based on the CANDU reactor technology, while the fusion fast neutrons are provided by a high-density pinch plasma, assumed capable of delivering 10 MW fusion power.

3.7 Performances

Performance potentials of the various concepts of fusion driven systems vary greatly. Some issues of critical importance is whether or not the device can operate in steady state, the efficiency of minor actinide burning as well as size and cost of the devices. Plasma confinement is important, as well as geometry of the device and access to the plasma. Since time constraints have not admitted a more thorough analysis of these parameters within this report, that work is left for the future. This report has in any case pointed out that some plasma fusion devices would be capable of providing the basis for industrial transmutation of nuclear waste.

4 Swedish R&D on FDS

The present research in Sweden on fusion driven systems is carried out by our group at the division for electricity at the Ångström laboratory at Uppsala University. The research areas include RF heating of plasmas, Monte Carlo simulations of fission blanket and conceptual design studies of the single cell mirror FDS and the stellarator-mirror FDS. The fusion plasma FDS research also includes studies of magnetic coils designs, plasma stability and overall physical and power performance of the proposed concepts. The group has also derived a general proof from the reactor equation that the fission power amplification for a driven fusion neutron source can be very strong /27/, with the explicit result $P_{fis}/P_{fus} \approx 150$ if $k_{eff} = 0.96$ and $\overline{\nu} \approx 3$ (the averaged number of neutrons emitted in a fission reaction), compare also Ref. /16/. The research is done in collaboration with researchers at Ukraine, Germany and Russia. The research institute in Kharkov in Ukraine has about 2,000 employees working with nuclear physics, fission, fusion and plasma physics, and has a wide experimental program on nuclear energy.

5 International R&D on FDS

The worldwide research on FDS is rapidly increasing. The Russian federation has established two separate fusion oriented research areas, i.e. ITER-related fusion research and another research area aimed for neutron sources studies with application to fission and material testing, where mirror machines and tokamaks are the main devices studied in the transmutation research. Ukraine has initiated research on stellarator-mirror concepts for transmutation. In USA, the interest for fusion based transmutation research is growing. China is increasing its efforts in fusion-fission research, and China may become the leading country on FDS research. EU and Japan are the largest contributors to the ITER project, where several proposals for fission related research are evaluated. Within EU, there are also proposals to use simpler fusion devices, such as a compact spherical tokamak, as a neutron source for transmutation or breeding.

Fusion research is now developed to a level where the construction of a neutron source aimed as a driver for a subcritical fast reactor for transmutation has become feasible. Several possibilities exist for the fusion neutron source, but there are important different properties of the various plasma confinement devices (pulsed or continuous mode of operation, size, plasma confinement quality, complexity, prize, accessibility and so on). The construction of a neutron source for industrial transmutation is a much simpler task than the hard issue of obtaining a thermonuclear fusion reactor.

6 Areas for further investigations

The technical and economic feasibility of different proposals for fusion-fission systems needs to be investigated. A system could be selected out with prospect of delivering a solution with high efficiency, continuous (or "semicontinuous") operation, sufficient reactor safety margins and accessibility of heating and detecting systems. The goal would be to investigate a system capable of reducing the 100,000 years of required geological storage of the spent nuclear fuel, reduce the proliferation risk of weapons-grade nuclear material and which can provide a large scale long-term energy production. Such a system would attract public acceptance of operating a fleet of LWR's together with FDS's for nuclear energy production.

IAEA pays attention for fusion driven transmutation. In Ref. /28/ it is written: "IAEA's Department for Nuclear Energy is enhancing its activities in the field of DT-fusion-plasma/fission systems for energy production and transmutation, and to closely coordinate and cooperate with the Division of Physical and Chemical Sciences within the Department of Nuclear Sciences and Applications. These activities are implemented within the framework of the TWG-TR."

The FDS research activities the coming year will be substantially larger than the research activities on ADS. A continued investigation on the FDS research could be important to show the progress of the field.

Acknowledgement

This work has in part been financed by the Swedish Institute.

References

/1/ **W A Sakharov, 1978.** Memoirs, (Hutchinson, London, 1990), ISBN 0-09-174636-1.

/2/ **H A Bethe, 1978.** Nuclear News, 21.

/3/ **H A Bethe, 1979.** Physics Today 44.

/4/ **C D Bowman et al, 1992.** Nucl. Instr. and Meth. in Physics Research 320, 33 6.

/5/ **C Rubbia, 1994.** AIP Conference Proceedings 346, International Conference on Accelerator-Driven Transmutation Technologies and Applications, Las Vegas, July 1994.

/6/ **C Rubbia, 1997.** Status of the energy amplifier concept, Proceedings of the 2nd International conference on accelerator-driven transmutation technologies and applications. V. 1. Uppsala (Sweden). Uppsala Univ. 1997, p. 35–51.

/7/ **M Cappiello, J Ireland, W Rider, 1991.** Target/blanket design for LANL's accelerator transmutation of waste, Trans. Am. Nucl. Soc. 63, p. 85–86.

/8/ **K Van Tichelen, P Kupschus, H Aït Abderrahim, A Klujkin, E Platacis, 2001.** MYRRHA: Design and verification experiments for the windowless spallation target of the ADS prototype MYRRHA, Accelerator Applications 2001, ISBN:0-89448-666-7, Reno, Nevada, November 11-15, 2001, CD-ROM.

/9/ **A N Dovbnya, ed, 2005.** Proceedings of the Ukraine-USA meeting. Accelerator Driven Sub-critical Assembly Facility, Ukraine, Kharkov, February 24-25, 2005, NSC KIPT, Kharkov, p. 246.

/10/ **W M Stacey, J Mandrekas, E Hoffman, G Kessler, C Kirby, A Mauer, J Noble, D Stopp, D Ulevich, 2002.** Fusion Science and Technology 41, 116.

/11/ **W M Stacey et al, 2002.** Fusion Science and Technology 45, 55.

/12/ **W M Stacey et al, 2007.** Fusion Engineering and Design 82, 11.

/13/ **Y Wu, FDS Team, 2006.** Fusion Engineering and Design 81, 2713.

/14/ **T Cho, J Kohagura, T Numakura, M Hirata, H Higaki, H Hojo, M Ichimura, K Ishii, K Md Islam, A Itakura, I Katanuma, R Minami, Y Nakashima, T Saito, Y Tatematsu, O Watanabe, M Yoshikawa, A Kojima, Y Miyake, Y Miyata, K Shimizu, Y Tomii, M Yoshida, K Sakamoto, T Imai, V P Pastukhov, S Miyoshi, GAMMA 10 Group, 2006.** Phys. Rev. Lett. 97, 055001.

/15/ **T Cho, V P Pastukhov, W Horton, T Numakura, M Hirata, J Kohagura, N V Chudin, J Pratt, 2008.** Phys. Plasmas 14, 056120.

/16/ **S Taczanowski, 2007.** Premises for development of fusion-fission hybrid systems in IAEA-RC-870.3, TWG-FR/132, Third Research Coordination Meeting (RCM) of the Coordinated Research Project (CRP) on Studies of Advanced Reactor Technology Options for Effective Incineration of Radioactive Waste, Chennai, India 15–19 January 2007.

/17/ **K Noack, A Rogov, A V Anikeev, A A Ivanov, E P Kruglyakov, Yu A Tsidulko, 2008.** Annals of Nuclear Energy 35, 1216.

/18/ **A A Ivanov et al, 2008.** Presentaion at the Alushta-2008 meeting, Alushta, Ukraine, Sept 21–28 2008.

/19/ **O Ågren, N Savenko, 2004.** Phys. Plasmas, 11, 5041.

/20/ **V E Moiseenko, O Ågren, 2005.** Phys. Plasmas 12, 102504.

/21/ **V E Moiseenko, K Noack, O Ågren, 2008.** 35th EPS Conference on Plasma Phys. Hersonissos, ECA 2008, v.32, P-2.114, pp. 1–4, 9–13 June 2008.

/22/ **B Cipiti, W Martin, T Mehlhorn, G Rochau, J Smith, R Grady, P Phruksarojanakun, P Wilson, A Guild-Bingham, P Tsvetkov, T Drennen, W Kamery, 2007.** Report SAND2007-6487.

/23/ **Hüseyin Yapıcı, Gülşah Ozışık, 2008.** Modification of PROMETHEUS Reactor as a Fusion Breeder and Fission Product Transmuter. Journal of Fusion Energy, 27, 256.

/24/ **P H Rebut, 2006.** From JET to the reactor, EPS meeting, Rome, June.

/25/ **Alan Takibayev, Masaki Saito, Hiroshi Sagara, 2007.** Journal of Nuclear Science and Technology 44, 1126.

/26/ **Vasile Zoita, Sterian Lungu, 2001.** Nukleonika 46 (Supplement 1): S81–S84.

/27/ **V E Moiseenko, O Ågren, K Noack, A Hagnestål, 2008.** Maximum fission power amplification in fusion-fission machines with reactor safety margins, to be submitted to Journal of Fusion Science and Technology.

/28/ http://www.iaea.org/inisnkm/nkm/aws/fnss/auxiliary/DTIntro.html