Italian National Agency for New Technologies, Energy and Sustainable Economic Development

Politecnico di Torino

1859

Synergies between Fusion and Fission Energy Conversion Systems

IAEA Technical Meeting on Synergies in Technology Development between Nuclear Fission and Fusion for Energy Production

Vienna – June 6-10, 2022

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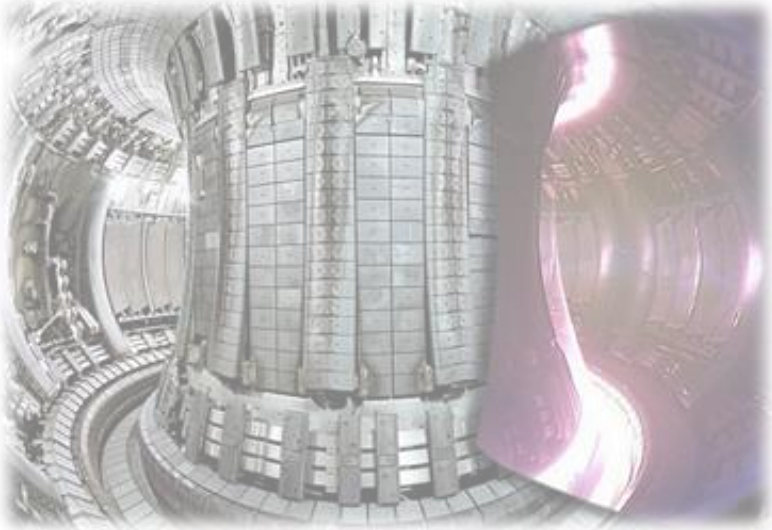
IAEA

Outline

- Overview on worldwide demand evolution
- Energy scenarios
- Gen-IV fission reactors
- Fusion reactors
- Cross cutting activities fission/fusion
- Conclusions



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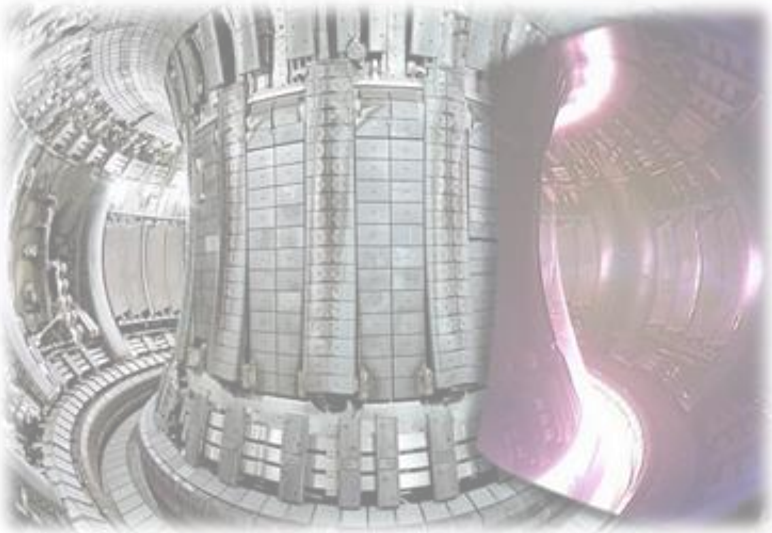
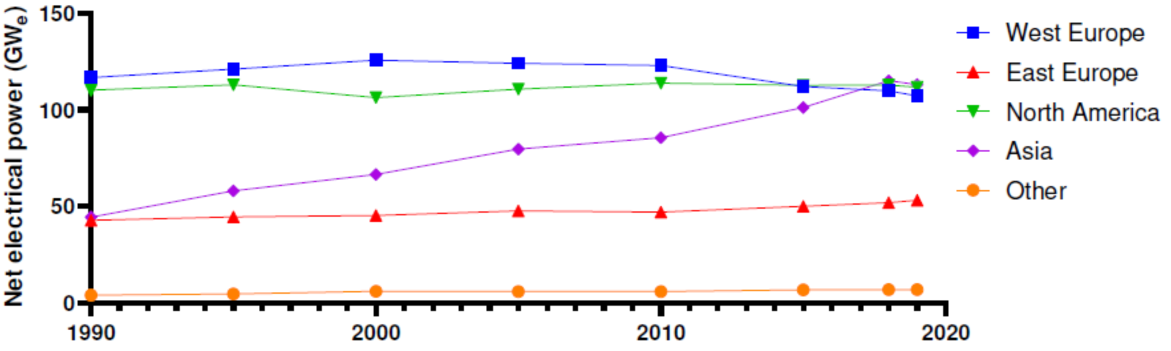


Overview on worldwide demand evolution (1/2)

The main goal of nuclear power plants is to take a fuel like uranium, and transform it into electricity, making power plants an energy conversion technology, and they are the largest energy conversion technologies by far.



443

- Nuclear power plants (NPPs) in operation worldwide in 2020

392 GW_e

- Net electrical output

14%

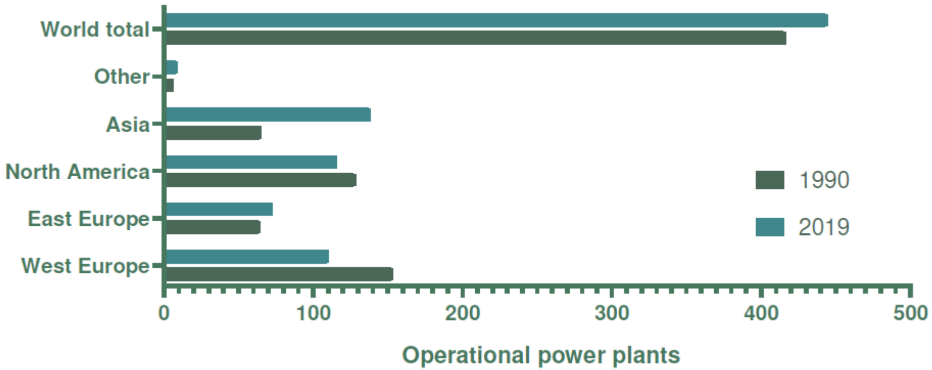
- Of total installed power for electricity generation

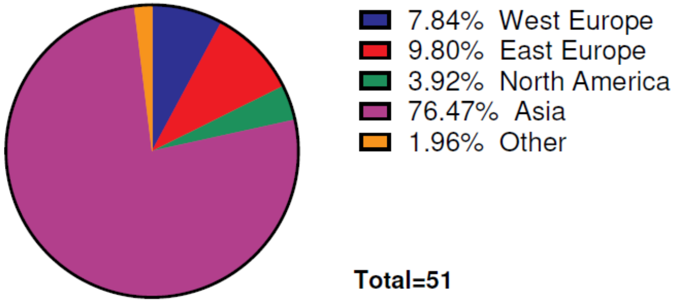
The annual electricity consumption will grow up till the end of this century with the rate of at least 1.5% and by the end of century will reach about 9.1 TW.

IAEA. *Reference Data Series no. 2 - Nuclear Power Reactors in the World*. IAEA, 2020.

Overview on worldwide demand evolution (2/2)

- Globally, the number of nuclear power plants has increased by 6.5% compared to 1990.
- China has greatly expanded the construction of nuclear power plants since 1995, increasing from 3 installed NPPs to 48 in 2019.





- About 30 countries, from advanced economies to developing countries, are planning or starting nuclear power programmes.
- For the period 2021-2027, the construction of 51 NPPs is planned or already underway.
- 76.5% of the planned NPPs will be built in Asia; of these, 46.2% will be in China and 17.9% in India.

IAEA. *Nuclear Energy for a Net Zero World*. IAEA, 2021.

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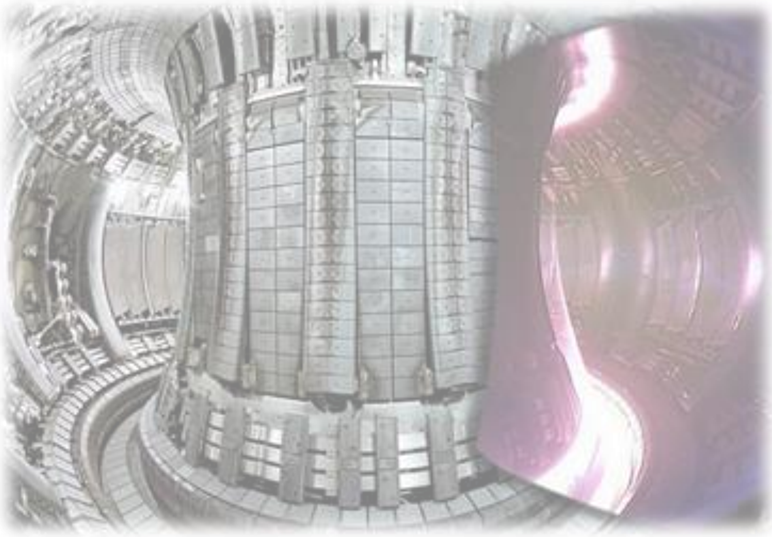

Energy scenarios

- IAEA “high” scenario. Current nuclear power generation capacity is projected to double by 2050. This is based both on extending the life of existing plants and on about 550 GW of new reactors.
- IAEA “low” scenario. Unwillingness to embrace nuclear power could result in almost no change in capacity by 2050.
- IEA “Stated Policies Scenario” forecasts an 18% growth in installed nuclear capacity (with about 480 GW_e of installed capacity) for the period 2019-2040. Most of the growth concentrated in Asia, particularly India and China. The share of nuclear power in global electricity generation is about 8.5% in 2040, but this limited role of nuclear power would lead to an increase in global carbon dioxide emissions in 2040.
- IEA “450 scenario” aims to keep CO_2 concentrations at a level of 450 ppm to have a 50% probability of keeping the temperature rise below 2°C, but considered as transition scenarios, as well as “Sustainable Development Scenario”, which aims to measures needed to simultaneously deliver energy access, clean air and climate goals, foreseeing an increase in installed nuclear power capacity to 599 GW_e by 2040.

IAEA. *Nuclear Energy for a Net Zero World*. IAEA, 2021.
IEA. *World Energy Outlook 2020*. IEA, 2020.

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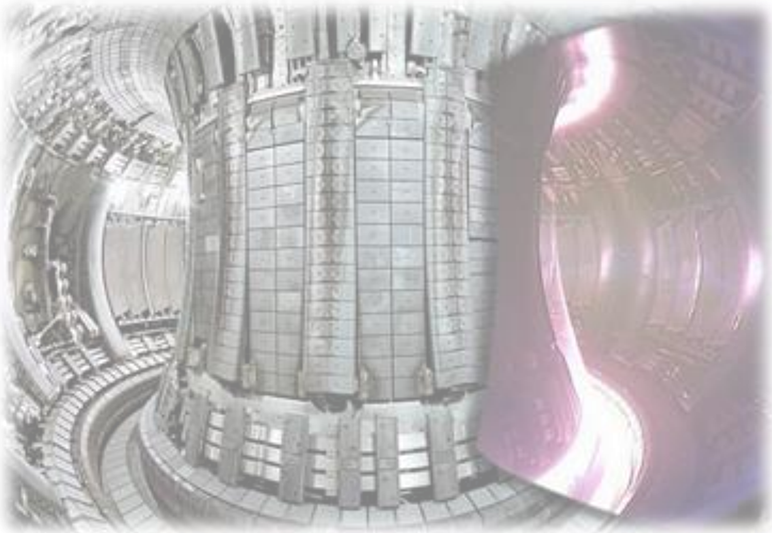


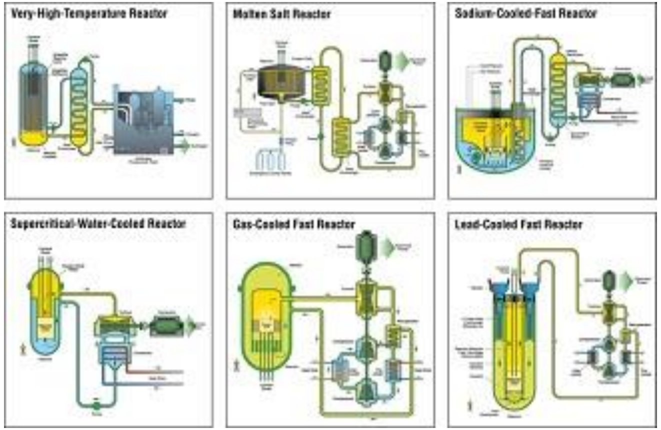
Gen-IV fission reactors (1/2)

Generation IV reactors are being developed under the Generation IV International Forum (GIF) project, founded in 2001:

- Cooperative international endeavor;
- Development of necessary R&D;
- Feasibility and performance test on next-gen fission reactors.

GEN IV International Forum
Expertise | Collaboration | Excellence

Some of these reactor designs could be demonstrated within the next decade, with commercial deployment beginning in 2030.

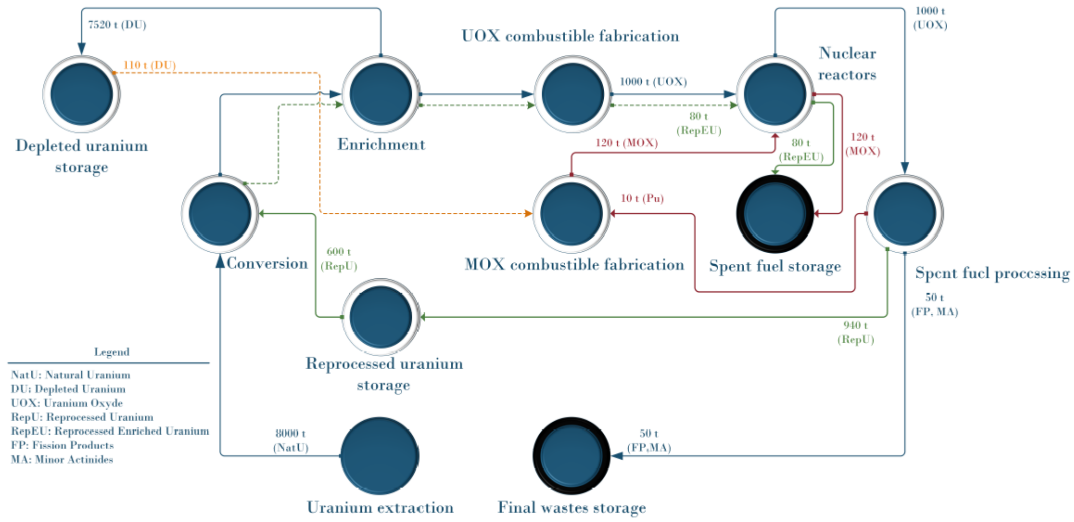


Six reactor technologies:

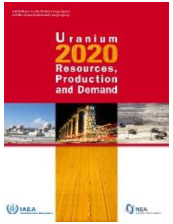
1) gas-cooled fast reactor (GFR)
2) lead-cooled fast reactor (LFR)
3) molten salt reactor (MSR)
4) sodium-cooled fast reactor (SFR)
5) supercritical water-cooled reactor (SCWR)
6) Very high-temperature reactor (VHTR).

Gen-IV fission reactors (2/2)

The fast neutron reactors of the IV generation aims to fully reprocessing the fuel, through the multi-recycling of plutonium (without limitation linked to an evolution of isotopic composition) and to value all uranium resources (including depleted and reprocessing uranium).



Resource category	2017	2019	Change (1000 tU)	% change
		Total		
<USD 260/kgU	7988.6	8070.4	81.8	1.0
<USD 130/kgU	6142.2	6148.3	6.1	0.1
<USD 80/kgU	2079.5	2007.6	-71.9	-3.5
<USD 40/kgU	1057.7	1080.5	22.8	2.2
		RAR		
<USD 260/kgU	4815.0	4723.7	-91.3	-1.9
<USD 130/kgU	3865.0	3791.7	-73.3	-1.9
<USD 80/kgU	1279.9	1243.9	-36.0	-2.8
<USD 40/kgU	713.4	744.5	31.1	4.4
		IR		
<USD 260/kgU	3173.0	3346.4	173.4	5.5
<USD 130/kgU	2277.0	2355.7	78.7	3.5
<USD 80/kgU	799.9	763.6	-36.3	-4.5
<USD 40/kgU	344.4	335.9	-8.5	-2.5



Nuclear Energy Agency and the International Atomic Energy Agency. *Uranium 2020: Resources, Production and Demand*. Nuclear Energy Agency, the Organisation for Economic Co-operation, and Development, 2020.

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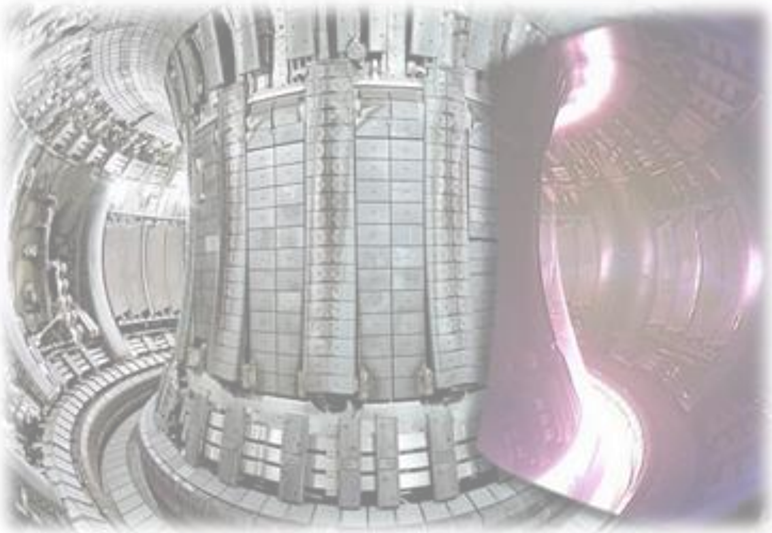
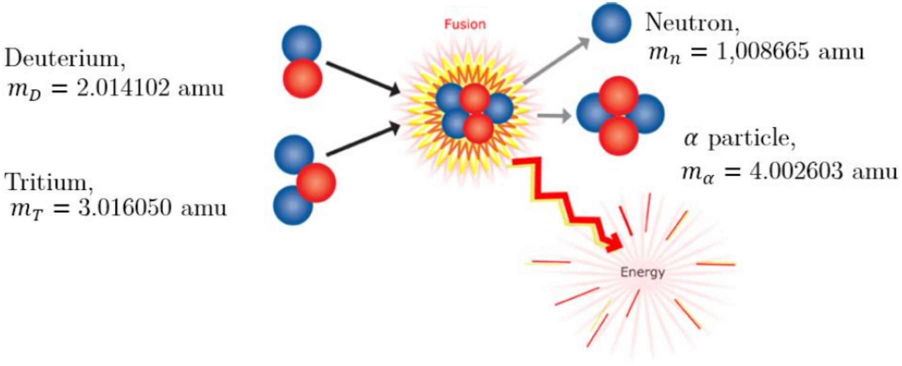


Fusion reactors

G-IV Nuclear Reactor will represent a suitable energy production system in the middle period, however taking into account the huge request of energy in the word a parallel solution able to satisfy the actual trend in long period with the possibility to create less radioactive material than fission and a nearly unlimited fuel supply has to be developed.
In fusion reactors, since fusion fuel is abundant, namely, light atoms such as the isotopes of hydrogen, and essentially limitless are one of the possible solution.

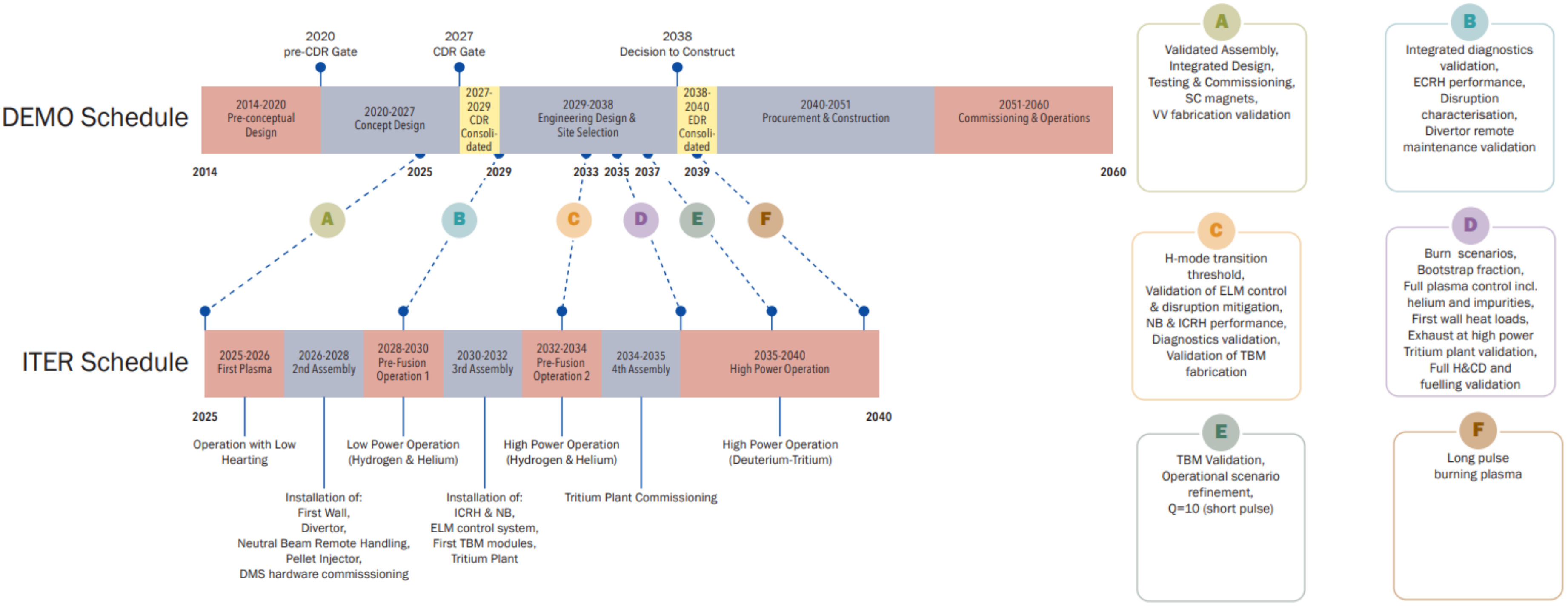
- Deuterium is abundant in nature: for example, it makes up 0.015 atomic percent of the hydrogen in seawater with a volume of about $1.35 \cdot 10^9\ \mathrm{km}^3$.
- Tritium can be produced in the mantel (breeding blanket) surrounding the area of the D-T fusion reactions.

$$^{6}_{3}\mathrm{Li} + {}^{1}_{0}\mathrm{n(slow)} \longrightarrow {}^{4}_{2}\mathrm{He} + {}^{3}_{1}\mathrm{T} + 4.9\,\mathrm{MeV}$$
$$^{7}_{3}\mathrm{Li} + {}^{1}_{0}\mathrm{n(fast)} \longrightarrow {}^{4}_{2}\mathrm{He} + {}^{3}_{1}\mathrm{T} + {}^{1}_{0}\mathrm{n} - 2.5\,\mathrm{MeV}$$



The first equation generates energy, while the second consumes energy. The Li-6 reaction consumes one slow neutron and produces tritium, and it is easier to initiate this reaction with respect to the second.

Fusion reactors - ITER and DEMO time schedule



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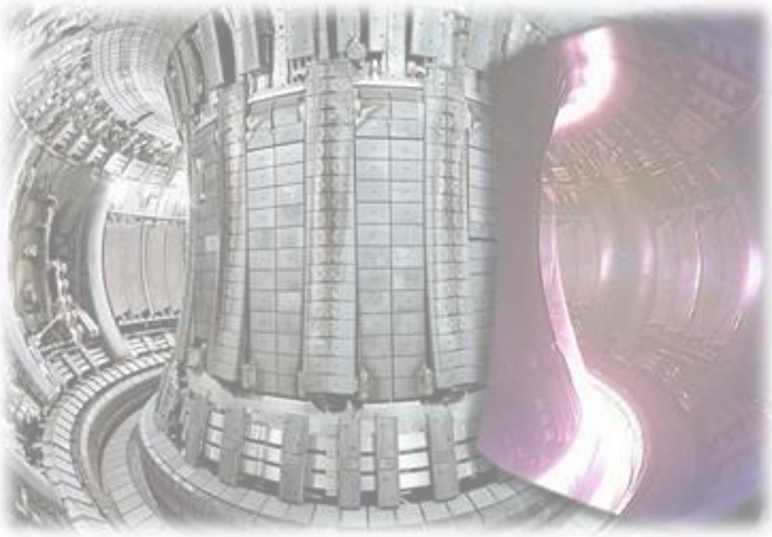


Cross cutting activities fission/fusion

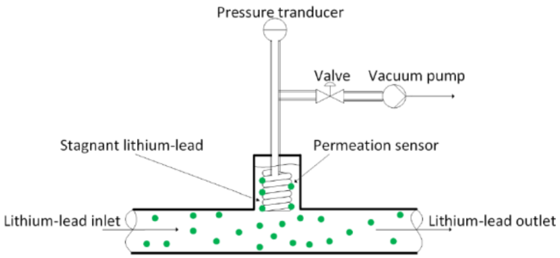
In order to save time and use the competence and knowledge developed in the frame of fission reactors a dedicated R&D program has to be established. The main area identified related cross cutting R&D research are:

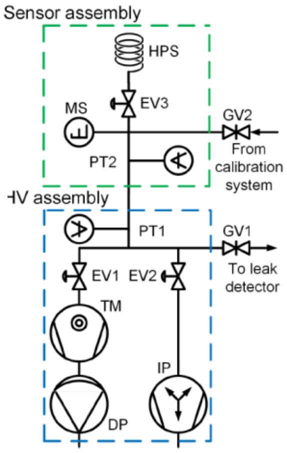
- Development of structural material able to operate under extreme neutron flux and harsh environments (liquid metals or pressurised gas);
- Development of mitigation system able to protect the materials;
- System with high reliability and efficiency able to operate in harsh environment to increase nuclear sustainability and economics;
- Waste management system and Decommissioning;
- Detritiation technologies;
- Diagnostic and instrumentations;
- Modelling and simulations;
- Safety analysis;
- Advanced Manufacturing and supply chain;
- Operational and maintenance.

Cross cutting activities fission/fusion

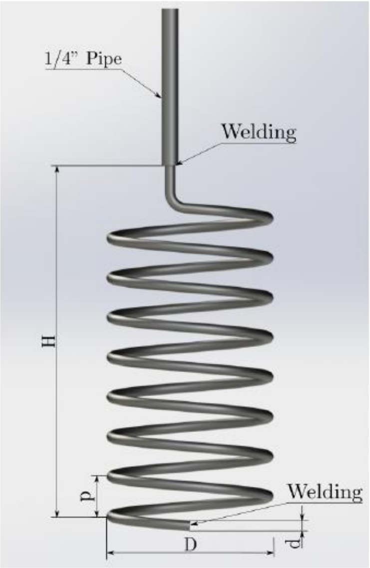
Example: tritium meters for LiPb breeding blankets and for Sodium Fast Reactors.

- In the liquid breeder fusion reactor blankets, such as the Water-Cooled Lithium-Lead (WCLL), the partial pressure of hydrogen isotopes, including tritium, has been measured in the liquid metal in the past using batch or on-line processes. However, a better solution is to use in-process, near real-time technologies that can track tritium production.
- In Sodium Fast Reactors, R&D focused on the development of instruments capable of detecting very small amounts of radioactive tritium produced by ternary fissions. Based on the modelling activities carried out for the fusion applications and the technology developed for the hydrogen isotopes permeation sensors, a hydrogen/tritium meter has been developed for use in liquid sodium to meet SFR requirements.





Parameter	Value
Minor diameter, d	$2 \cdot 10^{-3}$ m
Major diameter, D	$2.6 \cdot 10^{-2}$ m
Pitch between coils, p	$5 \cdot 10^{-3}$ m
Height of the sensor, H	$6 \cdot 10^{-2}$ m
Thickness, t_s	$2 \cdot 10^{-4}$ m
Angle between coils, α	$3.8°$
Number of coils, N	8
Total tube length, l_{tot}	$6.3 \cdot 10^{-1}$ m



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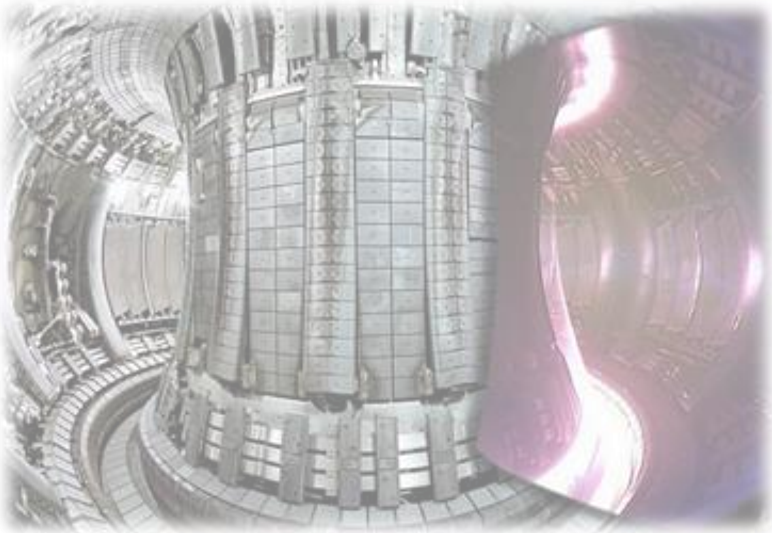

Conclusions

The main conclusions on this work are resumed in the following:

- In 2020, 443 NPPs were operating worldwide generating 14% of total electricity demand, and more than 30 countries are planning or starting nuclear power programmes.
- The annual electricity consumption will grow by end of this century with the rate of at least 1.5% to reach 9.1 TW.
- Nuclear power plant are increasing in number and they have to be included in the energy mix to respond to different energy scenarios. 550 GW_e of new NPPs foreseen by the end of 2050 within IAEA high scenario. Absence of nuclear in future energy plan will lead to either impossibility in increasing actual electrical capacity or increase in carbon dioxide emissions.
- Gen-IV fission reactors design could be demonstrated within the next decade, with commercial deployment beginning in 2030.
- Fast neutron reactors can rely on closed fuel cycle.
- On the other hand, in a long term perspective, fusion reactors will be able to satisfy the actual trend in long period with the possibility to create less radioactive materials than fission and a nearly unlimited fuel supply.
- Established R&D programme to save time and use the competence and knowledge developed in the frame of fission reactors also for fusion reactors, and *vice versa*. As an example, in the field of innovative instrumentation development, tritium meters were presented.

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