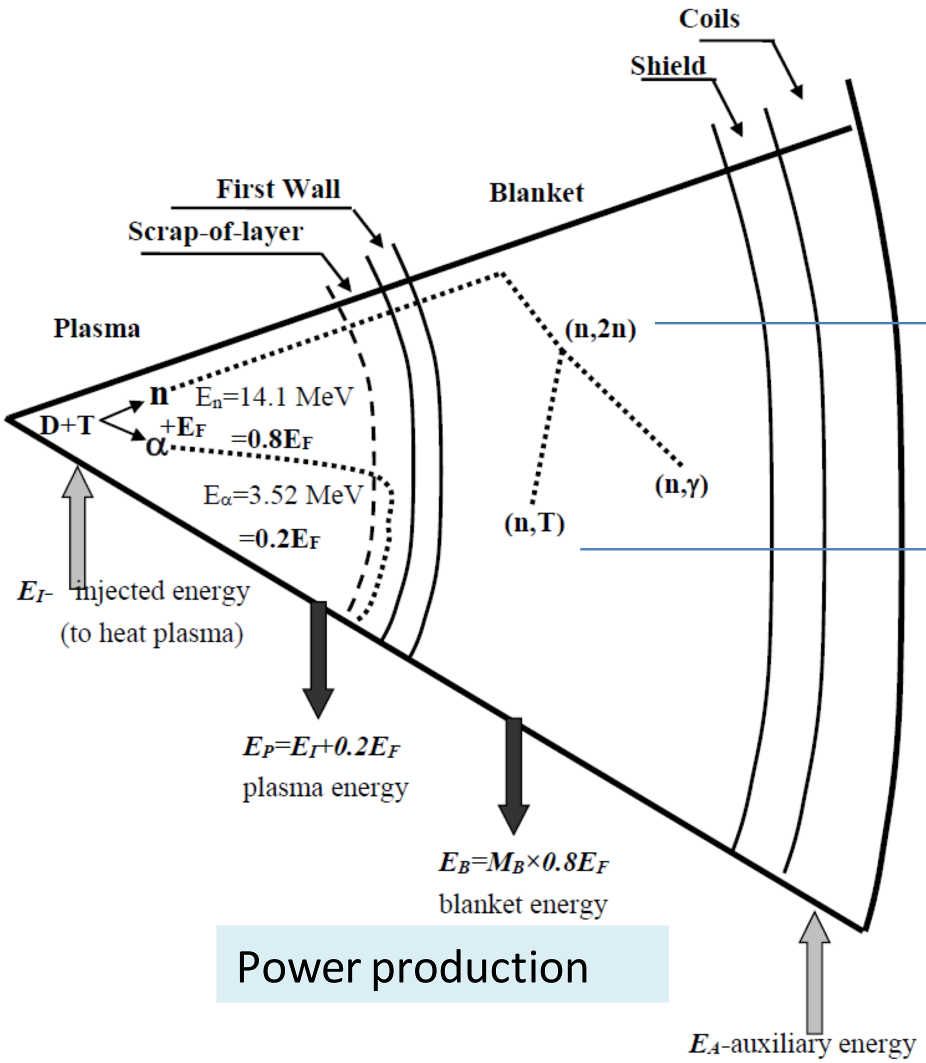
IAEA
International Atomic Energy Agency

6. Fission-fusion hybrid systems

Minghuang Wang, Vladimir Artisyuk, Yican Wu

**Technical Meeting
on Synergies Between Nuclear Fusion Technology Developments
and Advanced Nuclear Fission Technologies
06-10, June 2022**

Essentials of Fusion Power Generation



Neutron multiplication

Tritium breeding

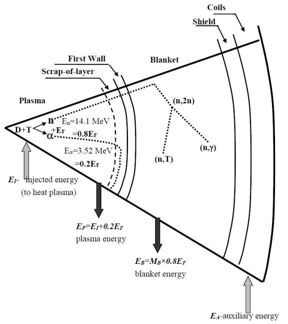
Power production

Characteristics of Power Reactors

	PWR	BWR	HTGR	LMFBR	Fusion[b]
Equivalent core diameter (m)	3.6	4.6	8.4	2.1	30
Core length (m)	3.8	3.8	6.3	0.9	15
Av.core power density (W/cm^3)	96	56	9	240	1.2
Peak-to-av.heat flux at coolant interface	2.8	2.6	12.8	1.43	50

[a] ABDOU, M., Exploring Novel High Power Density Concepts for Attractive Fusion Systems, Fusion Eng.Des. **45** (1999) 145

[b] NWL=3 MW/m^2 ;volume was taken for “in-vessel” component and magnets, so plasma void is excluded



Concepts of Hybrid Reactors

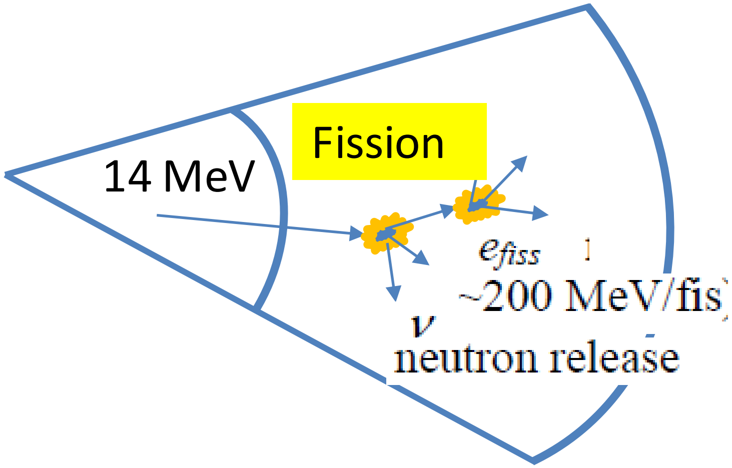
$$P_B^{fiss} = S\frac{k_{eff}}{1-k_{eff}} \times \frac{1}{\nu} \times e_{fiss}$$

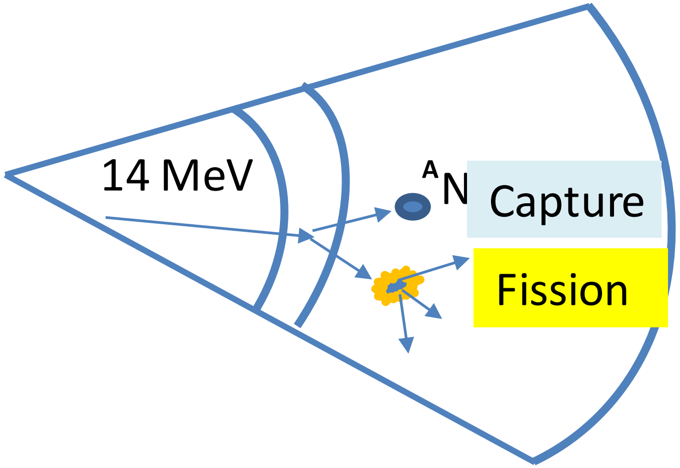
Fissile: U-235, U-233, Pu-239

Fissionable: Th-232, U-238, MA (Np-237…)

^{238}U+n = ^{239}Pu

^{232} Th+n = ^{233}U





Brief History of Fusion-Fission Hybrids

1954: The idea of hybrids was first considered at the Lawrence Livermore Laboratory (Imhoff et al.)

1961: Integral experiments with a natural uranium pile and a DT neutrons (Weale et al.)

1969: The concept of fusion-fission "symbioses" was presented (Lidsky)

1972: Fusion neutron induced fission of U-238 was introduced as a way to improve the power balance of low-Q fusion systems (Lee).

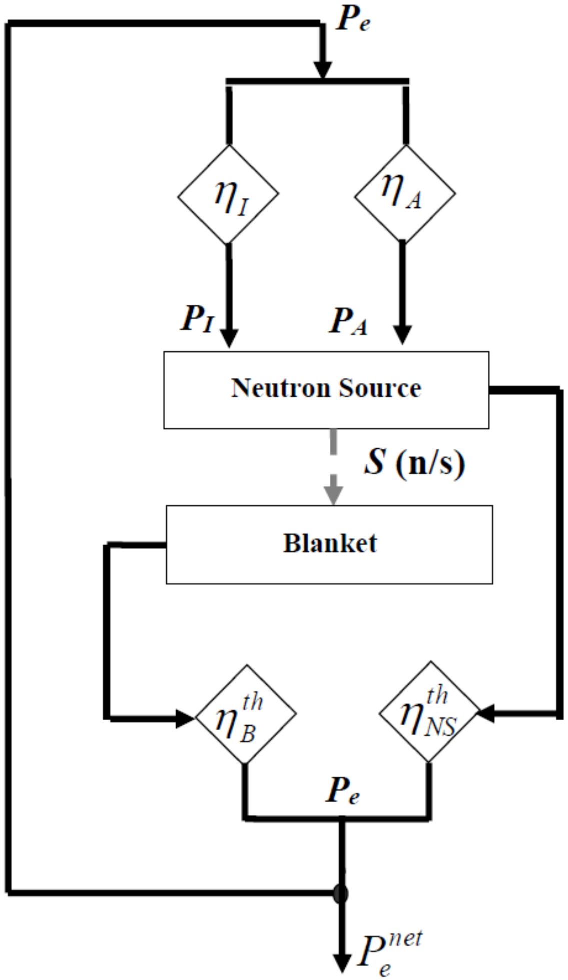
1979: Fission-suppressed class of fissile-breeding blankets (U, Th) (Lee)

1990-s Fusion-Driven transmutation of nuclear wastes (Minor Actinides)

Power Flows in Fusion Facilities

$$P_e^{net} = 0.8P_F \times M_B\eta_B^{th} + (0.2P_F + P_I)\eta_{NS}^{th} - \frac{P_I}{\eta_I} - \frac{P_A}{\eta_A}$$

P_i	is the power of *i*-type (*i*=fusion power, ignited, auxiliary)
η_j^{th}	is the thermal conversion efficiency (j= blanket power, power release in the neutron source) η_k to produce electric power
η_k	is the conversion efficiency of electric power to the power of k-type(k=injection power, auxiliary power).



$$P_e^{net} = P_F[\eta_B^{th}(0.8M_B + 0.2 + 1/Q - 1/(Q\eta_I)] - P_A/\eta_A$$

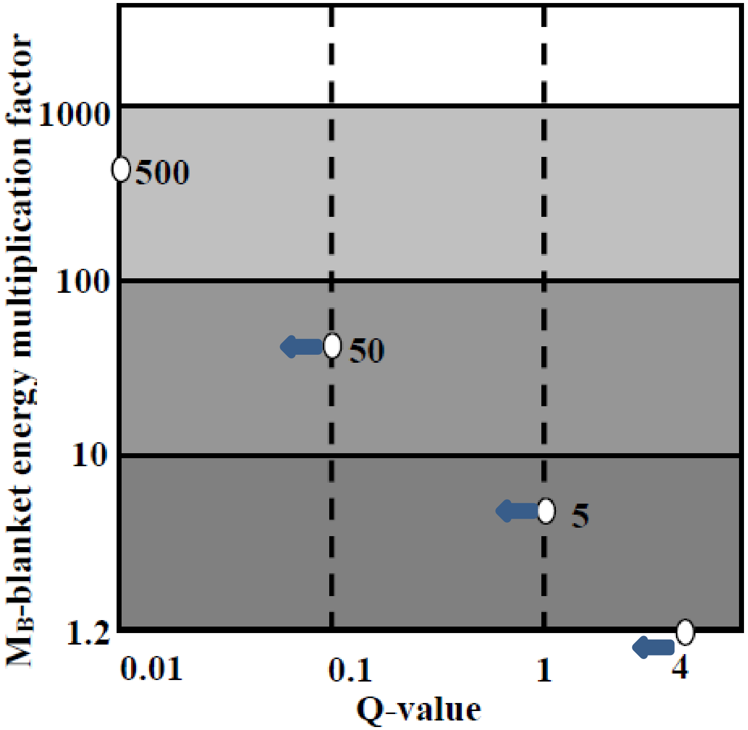
$Q = P_F/P_I$ is the ratio of fusion power to the power injected to plasma

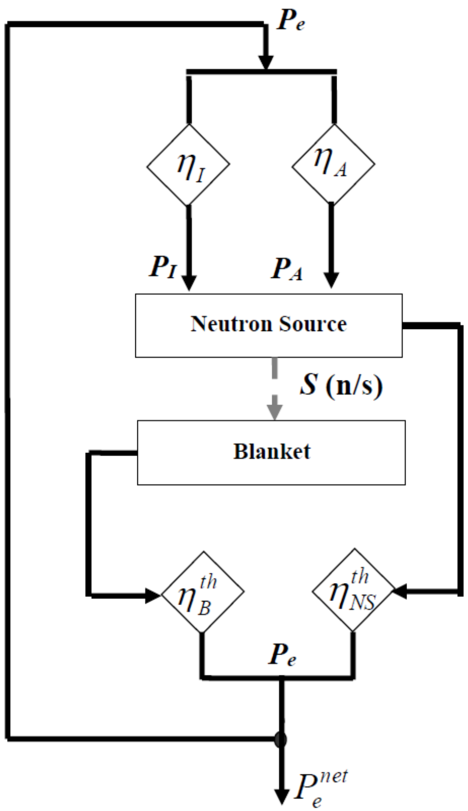
Break-Even Condition

efficiency of net electricity generation:
a ratio of net electric power produced to total heat generation

$$\eta_{net} = \eta_B^{th} - \frac{P_F/(Q\eta_I) + P_A/\eta_A}{P_F(0.8M_B + 0.2 + 1/Q)}.$$

electric power self-sustaining in fusion reactor $(\eta_{net} = 0)$

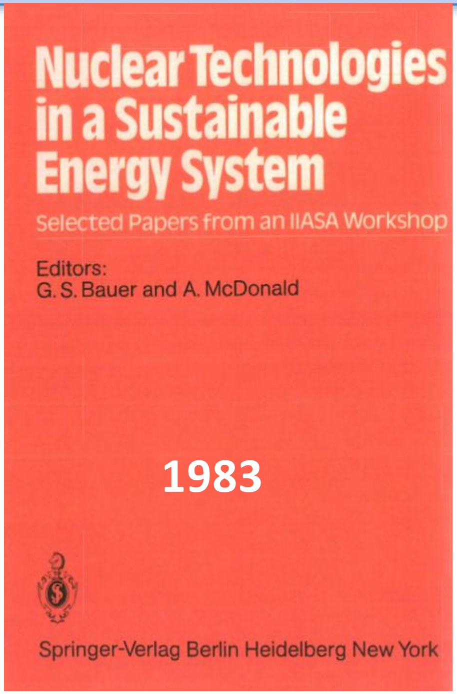




Glance at History

On the Role and Technological Readiness of Fast Breeders and Fusion-Fission Hybrids in the World Nuclear Future

S.I. Abdel-Khalik and G.L. Kulcinski Nuclear Engineering Department, University of Wisconsin, Madison, Wisconsin 53706 (USA)
G. Kessler Nuclear Research Center, D-7500 Karlsruhe (FRG)



Nuclear Technologies in a Sustainable Energy System

Selected Papers from an IIASA Workshop

Editors:
G. S. Bauer and A. McDonald

1983

Springer-Verlag Berlin Heidelberg New York

"…whether or not it is possible for hybrids to be commercially introduced within the time window (2000-2020) identified earlier as necessary for the world demand to be met within the known resource base."

Examination of the current status of fusion physics and technology reveals that there are only three fusion devices which might realistically achieve the necessary performance and be commercially available at such

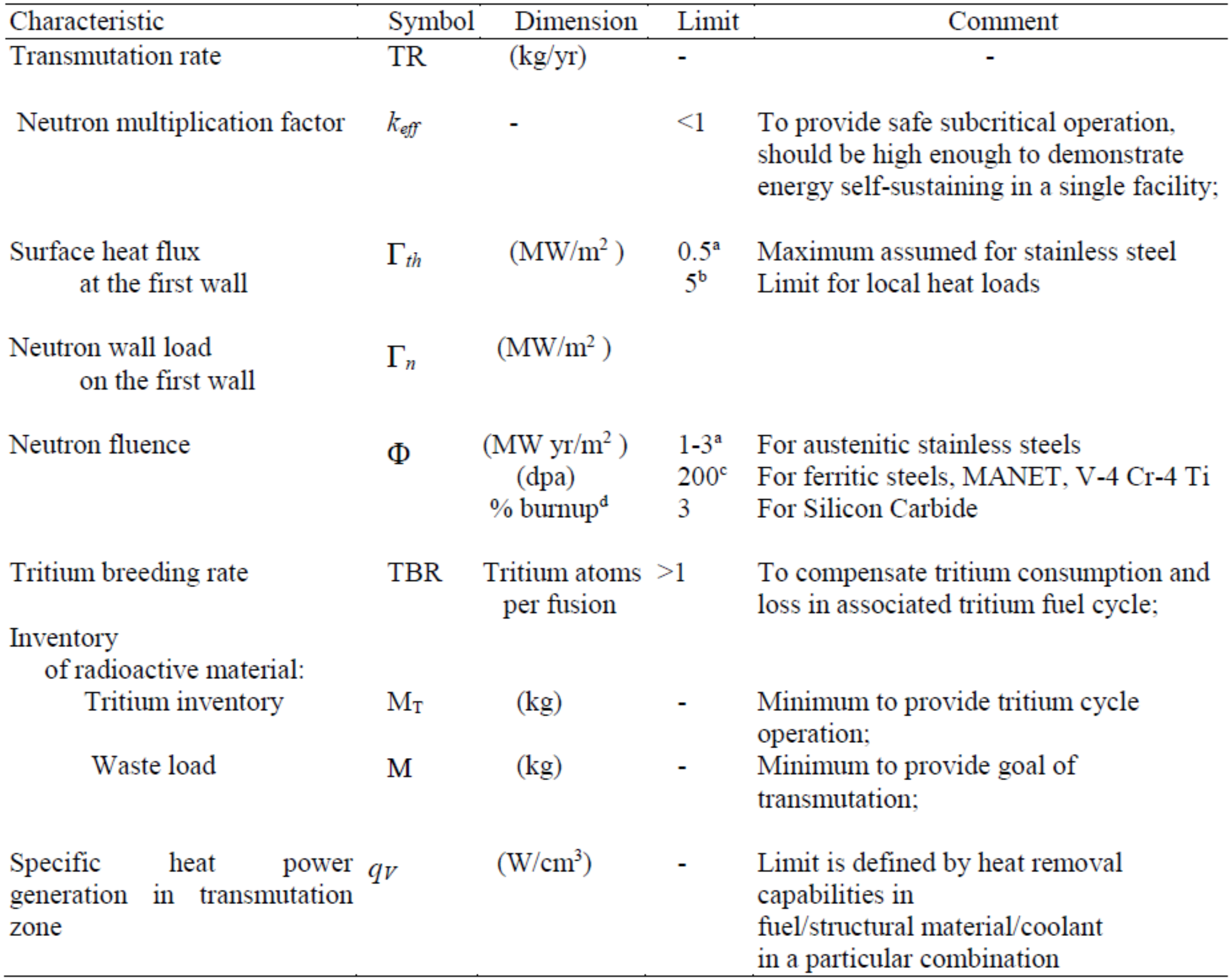
- ✓ tokamaks,
- ✓ tandemmirror devices, and
- ✓ light-ion beam-driven inertial-confinement fusion systems

Fuel Breeding:

1 Fast Breeder – supports	2/3 LWR (the same power)
1 Fus-Fis-Hybrid -	25 LWR
(suppressed fission)	(U-233)

Subcritical Blanket

Parameters&Limitations



Characteristic	Symbol	Dimension	Limit	Comment
Transmutation rate	TR	(kg/yr)	-	-
Neutron multiplication factor	k_{eff}	-	<1	To provide safe subcritical operation, should be high enough to demonstrate energy self-sustaining in a single facility;
Surface heat flux at the first wall	Γ_{th}	(MW/m^2)	0.5[a] 5[b]	Maximum assumed for stainless steel Limit for local heat loads
Neutron wall load on the first wall	Γ_n	(MW/m^2)		
Neutron fluence	Φ	(MW yr/m^2) (dpa) % burnup[d]	1-3[a] 200[c] 3	For austenitic stainless steels For ferritic steels, MANET, V-4 Cr-4 Ti For Silicon Carbide
Tritium breeding rate	TBR	Tritium atoms per fusion	>1	To compensate tritium consumption and loss in associated tritium fuel cycle;
Inventory of radioactive material:				
Tritium inventory	M_T	(kg)	-	Minimum to provide tritium cycle operation;
Waste load	M	(kg)	-	Minimum to provide goal of transmutation;
Specific heat power generation in transmutation zone	q_V	(W/cm^3)	-	Limit is defined by heat removal capabilities in fuel/structural material/coolant in a particular combination

a STACEY W., Capabilities of a DT Tokamak Fusion Reactor for Driving a Spent Nuclear Fuel Transmutation Reactor, Nuclear Fusion , **41** (2001) 135

B REITER, D., et al, Edge Plasma Physics Overview, Transactions of Fusion Technology, Design, **29** (1996) 267

c HOFFMAN, E., et al., Radioactive Waste Disposal Characteristics of Candidate Tokamak Demonstration Reactors, Fusion Technology, **31** (1997) 35

d GIANCARLI, L., et al, Design Requirements for SiC/SiC Composites Structural Material in Fusion Power Reactor Blankets, Fusion Engineering Design, **41** (1998) 165

Content of the Chapter 1/2

1.Principle and brief history of fusion fission hybrid system（~1 page）

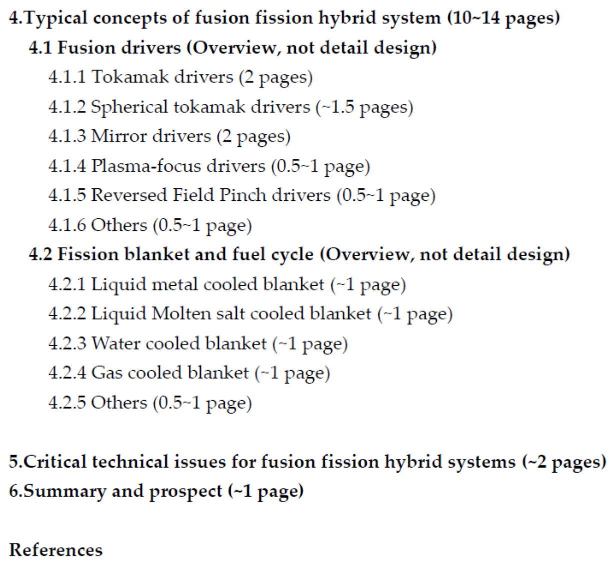
Why to develop hybrid reactor? A brief introduction to the basic structure and physical principle of hybrid reactor and its development history.

2.Features of fusion fission hybrid system (~1 page)

Features and functions of hybrid system.

3. Requirements of fusion driver and fission blanket for practical hybrid system (2~3 pages)

4.Typical concepts of fusion fission hybrid system (10~14 pages)



4.Typical concepts of fusion fission hybrid system (10~14 pages)
  4.1 Fusion drivers (Overview, not detail design)
    4.1.1 Tokamak drivers (2 pages)
    4.1.2 Spherical tokamak drivers (~1.5 pages)
    4.1.3 Mirror drivers (2 pages)
    4.1.4 Plasma-focus drivers (0.5~1 page)
    4.1.5 Reversed Field Pinch drivers (0.5~1 page)
    4.1.6 Others (0.5~1 page)
  4.2 Fission blanket and fuel cycle (Overview, not detail design)
    4.2.1 Liquid metal cooled blanket (~1 page)
    4.2.2 Liquid Molten salt cooled blanket (~1 page)
    4.2.3 Water cooled blanket (~1 page)
    4.2.4 Gas cooled blanket (~1 page)
    4.2.5 Others (0.5~1 page)

5.Critical technical issues for fusion fission hybrid systems (~2 pages)
6.Summary and prospect (~1 page)

References

Content of the Chapter 2/2

4.Typical concepts of fusion fission hybrid system (10~14 pages)

4.1 Fusion drivers (Overview, not detail design)

- 4.1.1 Tokamak drivers (2 pages)
- 4.1.2 Spherical tokamak drivers (~1.5 pages)
- 4.1.3 Mirror drivers (2 pages)
- 4.1.4 Plasma-focus drivers (0.5~1 page)
- 4.1.5 Reversed Field Pinch drivers (0.5~1 page)
- 4.1.6 Others (0.5~1 page)

4.2 Fission blanket and fuel cycle (Overview, not detail design)

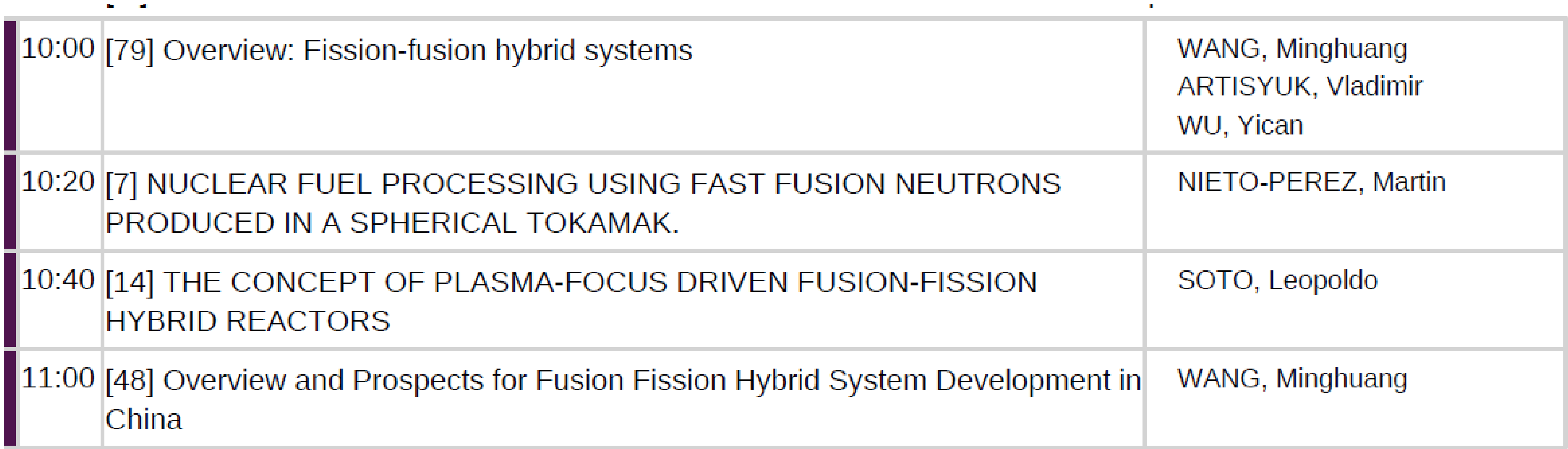
- 4.2.1 Liquid metal cooled blanket (~1 page)
- 4.2.2 Liquid Molten salt cooled blanket (~1 page)
- 4.2.3 Water cooled blanket (~1 page)
- 4.2.4 Gas cooled blanket (~1 page)
- 4.2.5 Others (0.5~1 page)

5.Critical technical issues for fusion fission hybrid systems (~2 pages)

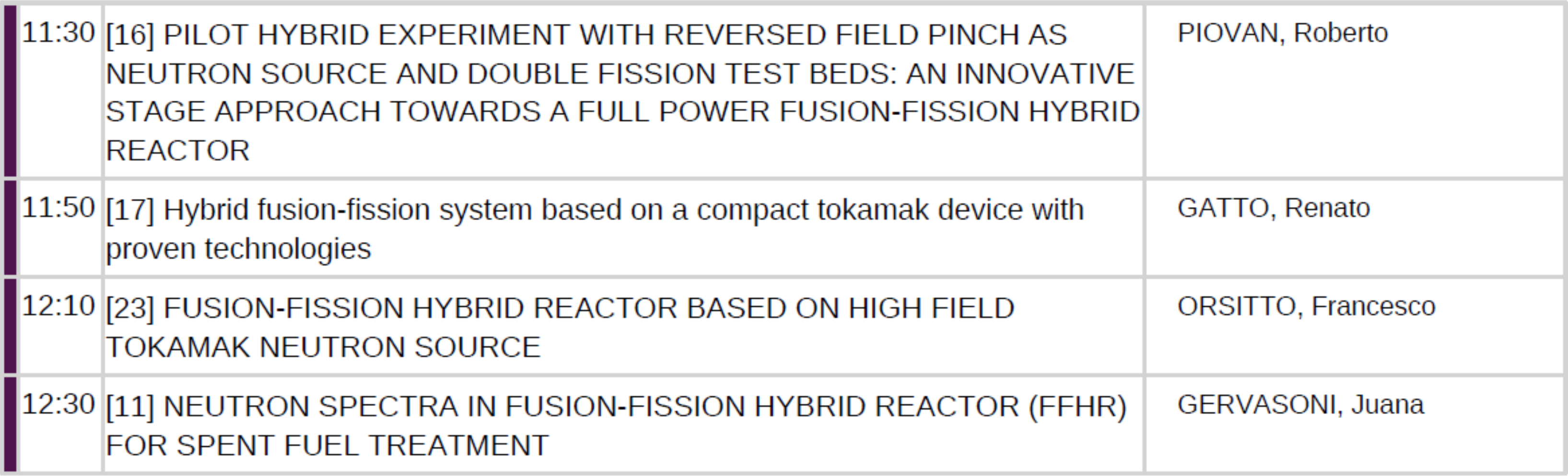
6.Summary and prospect (~1 page)

References

Session on Hybrid Reactors 10.06.2022



10:00	[79] Overview: Fission-fusion hybrid systems	WANG, Minghuang ARTISYUK, Vladimir WU, Yican
10:20	[7] NUCLEAR FUEL PROCESSING USING FAST FUSION NEUTRONS PRODUCED IN A SPHERICAL TOKAMAK.	NIETO-PEREZ, Martin
10:40	[14] THE CONCEPT OF PLASMA-FOCUS DRIVEN FUSION-FISSION HYBRID REACTORS	SOTO, Leopoldo
11:00	[48] Overview and Prospects for Fusion Fission Hybrid System Development in China	WANG, Minghuang



11:30	[16] PILOT HYBRID EXPERIMENT WITH REVERSED FIELD PINCH AS NEUTRON SOURCE AND DOUBLE FISSION TEST BEDS: AN INNOVATIVE STAGE APPROACH TOWARDS A FULL POWER FUSION-FISSION HYBRID REACTOR	PIOVAN, Roberto
11:50	[17] Hybrid fusion-fission system based on a compact tokamak device with proven technologies	GATTO, Renato
12:10	[23] FUSION-FISSION HYBRID REACTOR BASED ON HIGH FIELD TOKAMAK NEUTRON SOURCE	ORSITTO, Francesco
12:30	[11] NEUTRON SPECTRA IN FUSION-FISSION HYBRID REACTOR (FFHR) FOR SPENT FUEL TREATMENT	GERVASONI, Juana