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Latest Fusion R&D Activities at INEST

**Presented by Yican Wu
(Zhibin Chen on behalf)**

Contributed by FDS Team

Institute of Nuclear Energy Safety Technology (INEST)

Chinese Academy of Sciences

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Outline

I. Highlights of Fusion R&D Activities

- Fusion Neutron Sources
- Neutronics Methodology and Simulation
- Materials and TBM Technologies
- Fusion Safety

II. International Communication and Collaboration

1. Fusion Neutron Sources

Development of the HINEG Fusion Neutron Sources

(High Intensity D-T Fusion Neutron Generator)

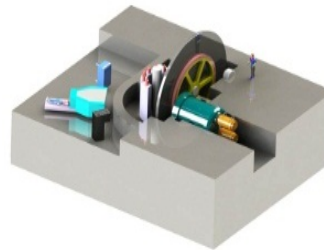


$10^{12}-10^{13}$ n/s

HINEG-I

D-T Fusion Neutron Generator
(Under Operation)

- Verification of neutron cross section data, induced radioactivity...
- Test of tritium production ratio of TBM mock-up
- Test of neutron detectors, electronics, new shielding materials...
- Study of biological effects under neutron radiation
- Nuclear technology applications...

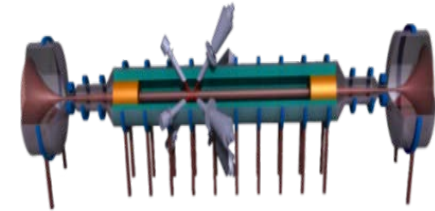


$10^{15}-10^{16}$ n/s

HINEG-II

D-T Multi-beam Fusion Neutron Source
(solid/gas target)

- Test of Materials irradiation damage (2 dpa/FPY)
- Validation and calibration of materials irradiation experimental data
- Study of coolant/materials interaction under neutron irradiation



$10^{17}-10^{18}$ n/s

HINEG-III

GDT-based Fusion Neutron Source

- Full lifetime test of fusion materials (≥ 20 dpa/FPY)
- Component test of blanket and divertor
- Reliability data of nuclear components
- Transmutation of radioactive waste

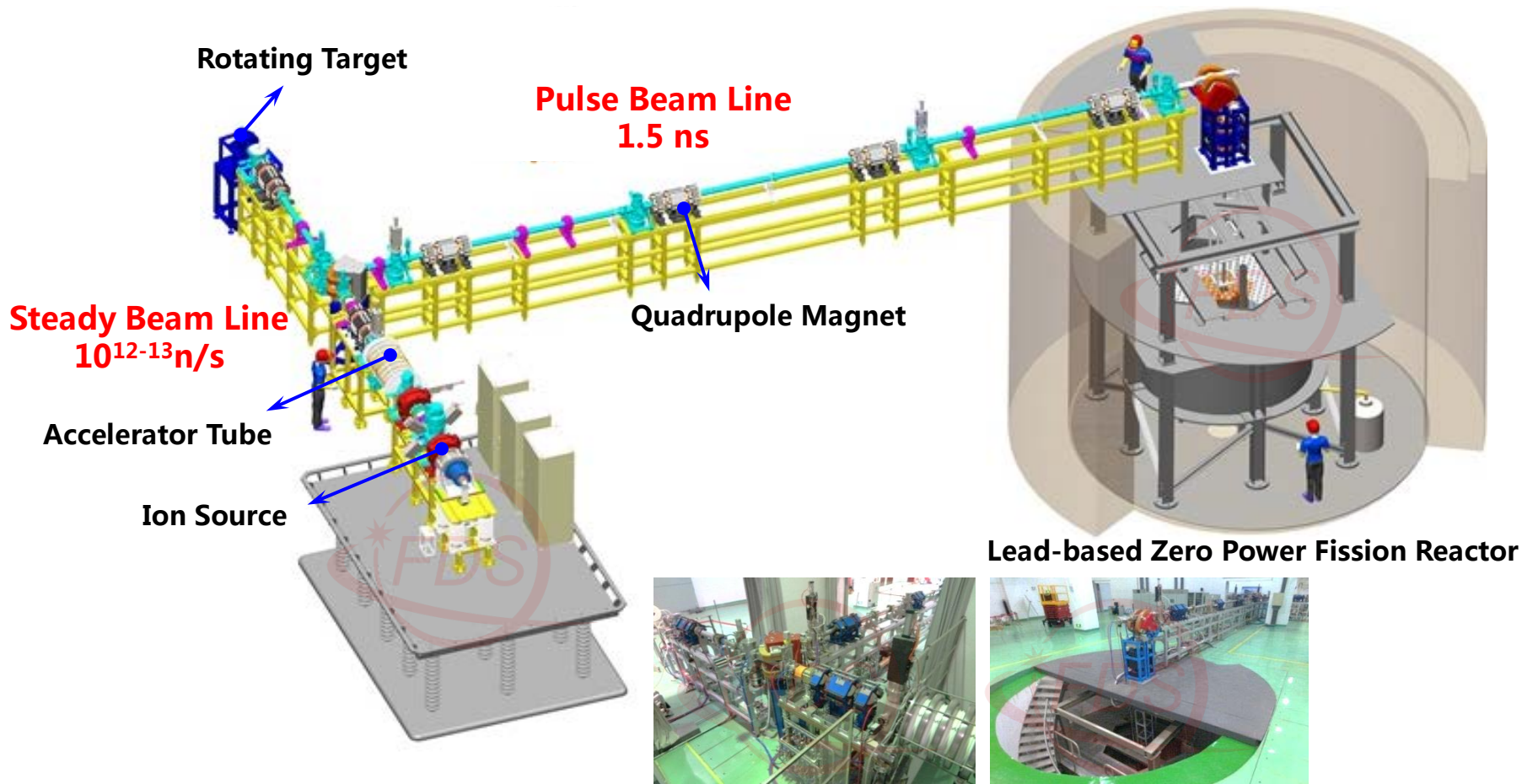
Neutronics Design Validation

Material Irradiation Test

Component Performance Test

HINEG-I: D-T Fusion Neutron Generator

Coupling with Lead-based Zero Power Fission Reactor



Fusion neutrons with yield of $6.4 \times 10^{12} \text{ n/s}$

HINEG-II: D-T Multi-beam Fusion Neutron Source (solid target option)

□ Goals

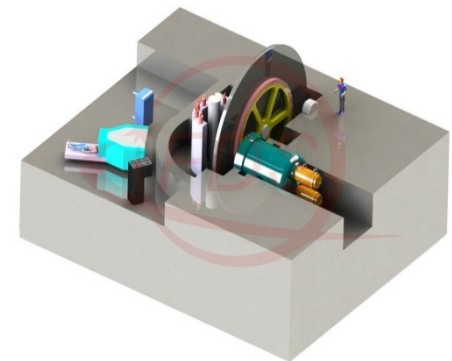
- Materials irradiation damage (2 dpa/FPY)
- Validation and calibration of materials irradiation experimental data in other ion/neutron source (e.g. reactor, spallation)
- Study of coolant/materials interaction under neutron irradiation (e.g. corrosion, sputtering etc.)

□ Challenges

- 20A steady-state ion source
- High thermal loading large-size rotating target (40 kW/cm²)

□ Main Parameters

- Neutron yield: 10¹⁵-10¹⁶ n/s
- Beam current: 20 A (D⁺) +20 A (T⁺)
- Beam energy: 200 keV



Conceptual design of HINEG-II
(refer to “Sorgentina” of ENEA)

The evaluation and preliminary analysis of other options for HINEG-II are under way.

**Design optimization and R&D for key technologies of HINEG-II are on going
in collaboration/discussion with ENEA...**

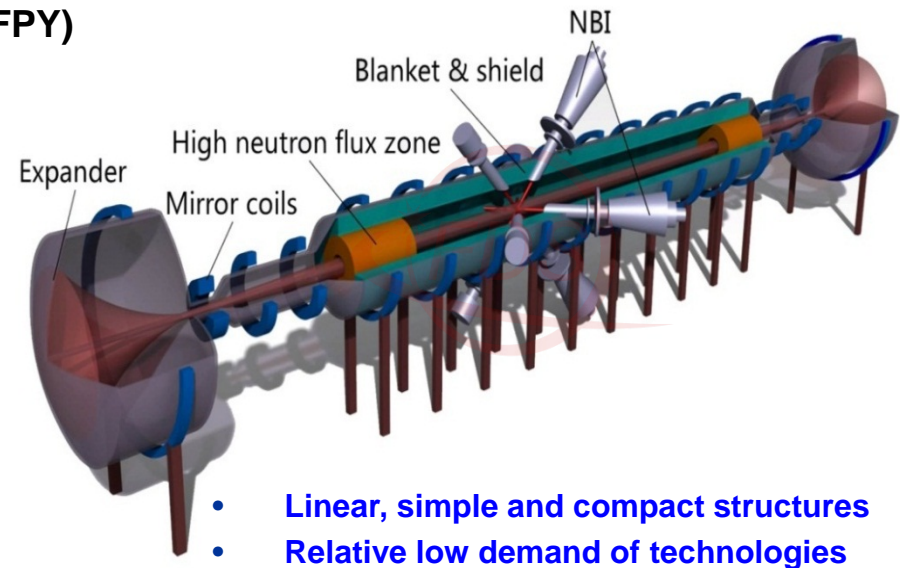
**Based on HINEG-III (GDT based fusion neutron source),
INEST and BINP jointly initiated an international mega-science project proposal
Axisymmetric Linear Advanced Neutron source (ALIANCE)**

❖ **Goals**

- Full lifetime test of fusion materials (≥ 20 dpa/FPY)
- Component test of blanket and divertor
- Reliability data of nuclear components
- Validation of radioactive waste transmutation

❖ **Design target**

- Availability: $> 70\%$
- Operation mode: steady-state
- Tritium consumption rate: < 200 g/FPY
- Neutron flux and test volume:
 - ≥ 2 MW/m² (> 10 L)
 - 1~2 MW/m² (~ 100 L)



An international preparatory committee for the mega-science project was established in 2018, with more invitations on-going.

Development Strategy of ALIANCE project

❖ **ALIANCE-I: Steady State GDT machine**

- Development of continuously operating low power NBI

❖ **ALIANCE-II: D-D GDT neutron source ($>10^{13}$ n/s)**

- Demonstrate the GDT machine as a steady state neutron source with high availability
- Schemes to flatten the gradient of neutron flux

❖ **ALIANCE-III: D-T GDT neutron source ($> 10^{18}$ n/s)**

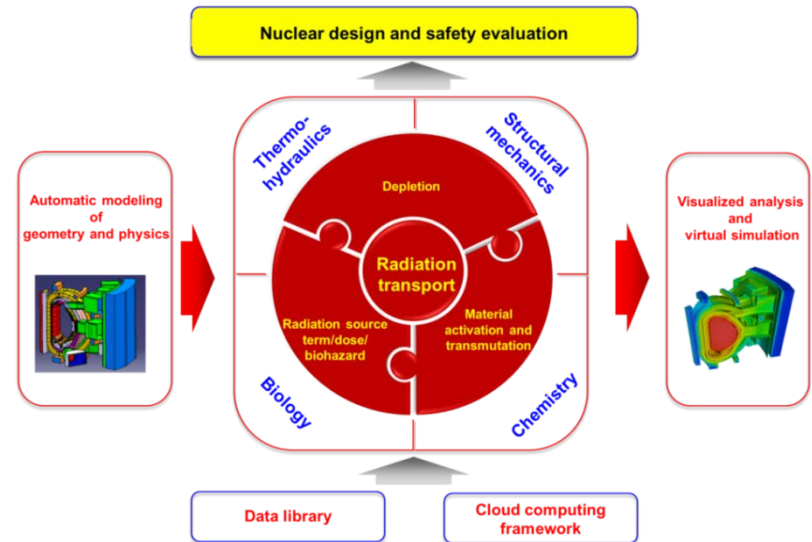
- Development of tritium cycling technologies
- Development of multifunctional experimental platforms (materials, components, nuclear technology applications, etc.)

2. Neutronics Methodology and Simulation

SuperMC: Super Multi-functional Calculation Program for Nuclear Design & Safety Evaluation

20+ years continuous development
400+ person years investment

- **Whole neutronics process simulation:** neutron transport, depletion, activation and dose calculation
- **Multiple physics simulation:** neutronics, thermo-hydraulics, structural mechanics, etc.



SuperMC 3.4 is released in ISFNT-14 (2019)

SueprMC: New Capabilities of SuperMC V3.4

□ Enhancements in neutronics calculation

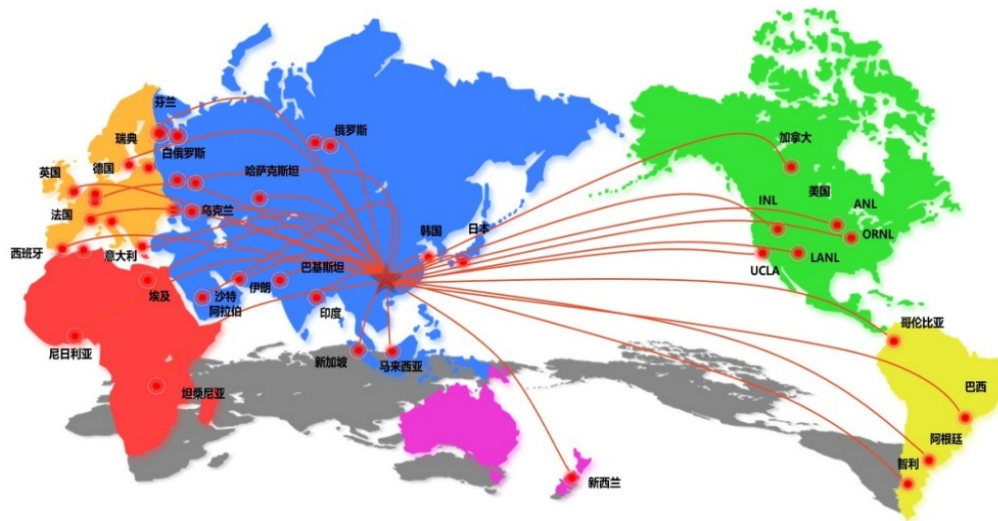
- Shutdown dose rate calculation based on inner-coupling accurate generation of collision response
- Critical search of boron concentration and control rod position based on adjoint flux
- Transport-burnup coupling calculation based on improved semi-predictor-corrector (ISPC), etc.

□ Advances in user-friendliness

- Cloud computing based on mobile phone APP & website
- Physical parameter settings using interactive interface (source, tally, etc.)
- 3D visualization for cell tally results and source distribution, etc.

SuperMC: Widely Applied in the World

- Widely used in the field of nuclear energy (fission/fusion/hybrid system), as well as extended nuclear technology application fields (well logging, nondestructive testing, radiotherapy, etc.)
- Applied in many projects: International Thermonuclear Experimental Reactor (ITER), Joint European Torus (JET), Facility for Rare Isotope Beams, CLEAR, TMSR, etc.



Available from OECD/NEA and RIST/NCC

<http://www.oecd-nea.org/tools/abstract/detail/iaea1437>

<http://www.tokai.rist.or.jp/nucis/codetable.html>

Contact information: SuperMC@fds.org.cn

3. Materials and Blanket

China Low Activation Martensitic steel

CLAM: 0.1C-9Cr-1.5W-0.2V-0.15Ta-0.45Mn

❖ Heat & Irradiation Resistant Design

▪ W content design:

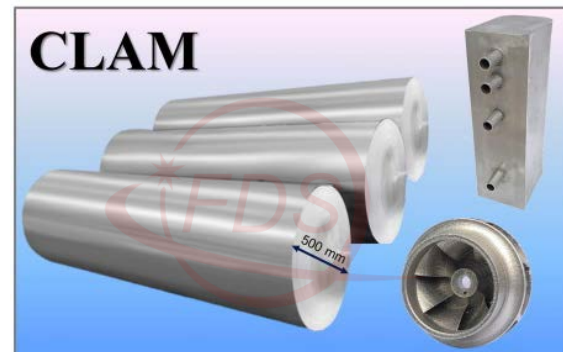
- ✓ High strength with the reduction of brittle Fe₂W formation

▪ Ta content and precipitation design:

- ✓ Relatively high Ta for dispersed nano scale TaC phase
- ✓ Accurate TMT processing for high density of TaC

❖ Component fabrication technologies

- ✓ Fabrication of 1/3 scaled DFLL-TBM by welding technologies
- ✓ Breakthrough in 3D printing of blanket first wall



3x6-ton Ingots & Components

	C	Cr	W	V	Ta	Mn
CLAM	0.10	9.0	1.5	0.20	0.15	0.45
CLF-1	0.11	8.5	1.5	0.30	0.10	0.5
Eurofer97	0.10	9.0	1.1	0.20	0.12	0.4
F82H	0.10	8.0	2.0	0.20	0.03	0.12

Chemical compositions of different RAFM steels

Industry RAFM steel standard based on CLAM has been implemented in 2018 (HJB1016-2018)

Next Generation Structural Material: ODS-CLAM

Supported by National Key Program of China (MCF), 2018-2023

❖ High performance of ODS-CLAM:

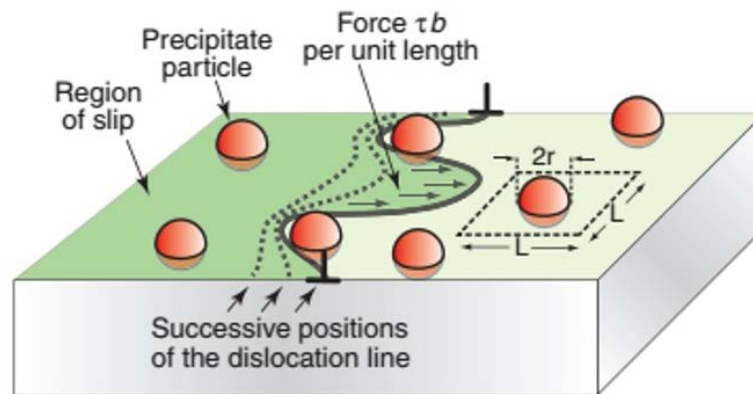
▪ Irradiation resistance:

✓ Swelling after 200 dpa ion irradiation: <0.1%

▪ High temperature strength:

✓ Yield strength at 700 °C: >500 MPa

✓ Creep life at 120 MPa/650°C: >10,000 hr



❖ Smelting mass production technologies

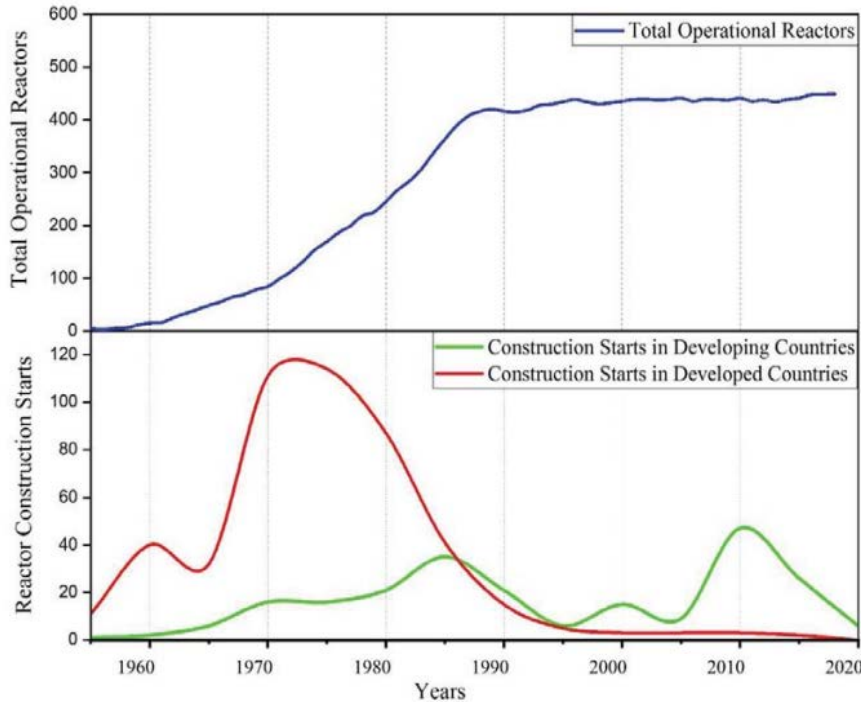
✓ Nanoparticles: <10 nm, $>10^{24} \text{ m}^{-3}$

✓ Complex component fabrication by additive manufacturing

4. Fusion Safety

Nuclear Safety in the Unexpected Second Nuclear Era

Not adequate understanding of nuclear safety even for the fission reactor



Nuclear reactor construction starts & total operational reactors

Nuclear safety in the unexpected second nuclear era

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Edited by M. George Mylonakis, Carnegie Mellon University, Pittsburgh, PA, and approved July 10, 2019 (received for review November 21, 2018)

Nuclear energy development has entered an unexpected second nuclear era, which is mainly driven by developing countries. Despite major efforts to pursue a safe nuclear energy system in the first nuclear era, severe nuclear accidents occurred. A basic problem is that we do not have an adequate understanding of nuclear safety. From the viewpoints of risk and the close coupling of technical and social factors, this paper reexamines the nature of nuclear safety and reviews how previous experts understood it. We also highlight the new challenges that we are likely to confront in the unexpected second nuclear era and clarify some of the refinements that need to be made to the concept of nuclear safety from a sociotechnical perspective. These include the following: 1) Risk decisions should be made based on improving social and technical elements (i.e., “social rationality” 2) risk needs to be controlled based on the “Wabi-Kubi-Kerubi” framework; 3) system thinking should be substituted for reductionist risk assessment and social mechanisms need to be combined to address uncertainties; and 4) public centered risk communication should be established. This contribution can provide a theoretical foundation for improving our understanding of the nature of nuclear safety and for transforming the concept of nuclear safety in the unexpected second nuclear era.

Keywords: nuclear safety, risk, sociotechnical perspective, unexpected second nuclear era

PNAS
Proceedings of the National Academy of Sciences of the United States of America
www.pnas.org

Size evolution of island plants

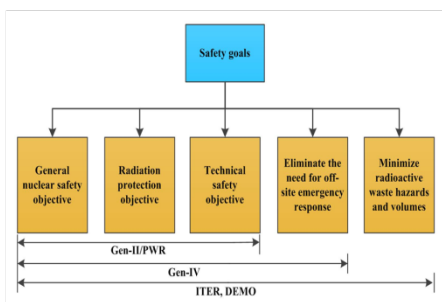
Close coupling of technical and social factors for transforming the concept of nuclear safety

Wu Y. et al. Nuclear Safety in the Unexpected Second Nuclear Era, *PNAS*, 2019, 116(36): 17673-17682

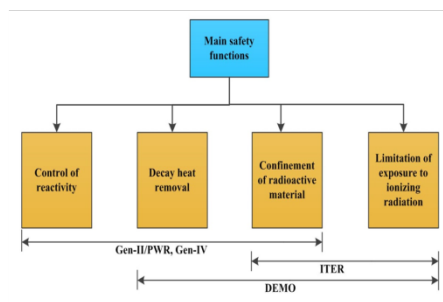
Identification of Safety Gaps for Fusion DEMO Reactors

❖ DEMO safety issues and safety approach, and the international DEMO safety R&D activities are reviewed and safety R&D gaps are presented

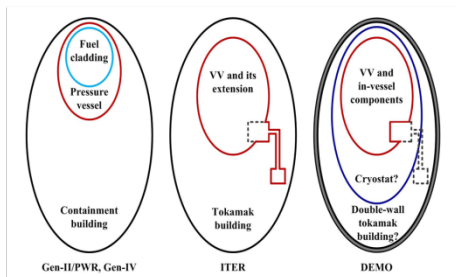
□ Fundamental Safety Objectives



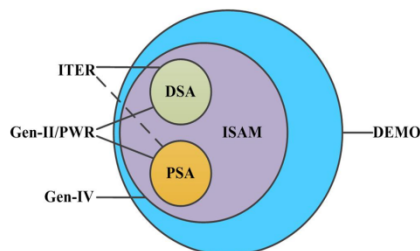
□ Main Safety Functions



□ Defense in Depth and Multiple Barriers



□ Safety Assessment Methodology



nature energy REVIEW ARTICLE
PUBLISHED: 31 OCTOBER 2016 | ARTICLE NUMBER: 16154 | DOI: 10.1038/nenergy.2016.154

Identification of safety gaps for fusion demonstration reactors

Y. Wu^{1*}, Z. Chen¹, L. Hu¹, M. Jin¹, Y. Li¹, J. Jiang¹, J. Yu¹, C. Alejandre², E. Stevens³, K. Kim⁴, D. Maisonnier⁵, A. Kalashnikov⁶, K. Tobita⁷, D. Jackson⁸ and D. Perrault⁹

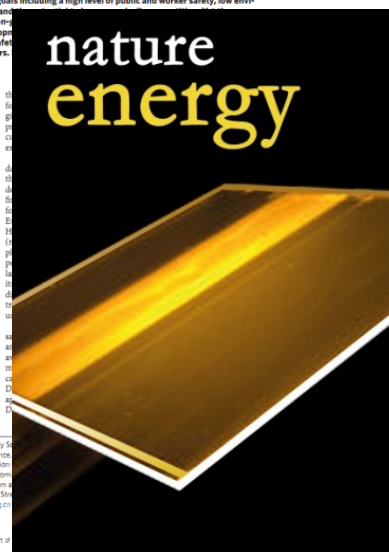
To assist in the development of nuclear fusion as a viable commercial power source, preparation is underway for the fusion demonstration reactor (DEMO), which will build on the work of ITER, the international experimental fusion reactor. Like other advanced nuclear energy systems, DEMO must satisfy several goals including a high level of public and worker safety, low environmental impact, high reactor availability, a closed fuel cycle and still large scientific and technological safety gaps between the two. Here we review international fusion safety research and development from ITER. We identify the main scientific and technological safety gaps for the design and operation of DEMO.

With greenhouse gas emissions across their total lifecycle similar to those of other renewable energy sources and much lower than for fossil fuels, nuclear power can play an important role in efforts to decarbonize the production of electricity¹. According to statistics from the Nuclear Energy Agency of the Organisation for Economic Cooperation and Development (OECD/NEA)², nuclear fusion power accounted for about 11% of world electricity generation in 2013, and could increase to 17% by 2050. Meanwhile, fusion power — in which light atomic nuclei bind into single, heavier nuclei, releasing a large amount of energy — offers the promise of being the ultimate energy source, mainly owing to the abundance of the fuel, absence of high-level radioactive waste and low greenhouse gas emissions. However, despite extensive research and development being conducted in the fusion community, it remains decades away from deployment.

Safety is considered the top priority in nuclear energy development, in particular after the Chernobyl nuclear accident in 1986 and the Fukushima nuclear accident in 2011. The Chernobyl and Fukushima nuclear reactor accidents date from the 1970s and are classified as Generation II (see Box 1 for a description of nuclear reactor generations). Since then, in the further development of Generation III and IV reactors, significant improvements have been proposed and implemented in terms of enhanced safety, minimized waste, high economic competitiveness and proliferation resistance. Fusion energy systems, which will be categorized as the next generation reactor beyond Generation IV, must be even more attractive regarding safety, environmental impact and economic competitiveness if fusion energy development is not to fail in the long run.

A collaboration between 35 nations, the International Thermonuclear Experimental Reactor (ITER)³ is one of the most ambitious energy projects in the world today. It is intended to be

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Wu Y. et al. Identification of safety gaps for fusion demonstration reactors.

nature energy 1, 16154, doi:10.138/nenergy.2016.154 (2016).

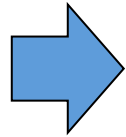
Quantitative Safety Goals for Fusion Reactors (accidents an example)

Facility	Safety requirement	Emergency evacuation guidelines
AP1000	EPRI URD ^[1]	10 mSv (24 hours, site boundary), frequency 10^{-6}
ITER	France ASN ^[2]	sheltering: 10 mSv (48 hours); evacuation: 50 mSv
Fusion facility	U.S. DOE ^[3]	sheltering/evacuation: 10 mSv (7 days)

[1]URD,1999; [2]ASN report,2015; [3]DOE-STD-6002,1996

* Calculated according to DOE-STD-6002 (1996) and INEEL/EXT-03-00405 (2003).

Public Evacuation Dose limit:
 Early dose (7 days) for most exposed individual at site boundary, 10 mSv



Implication on DEMO and FPP:

- ✓ Hugely reduce inventories of radioactive materials in VV (e.g. 33 g tritium for 100% release)
- ✓ Decrease release fraction as large as possible (e.g. 330g tritium for 10% release)

Outline

- I. Highlights of Fusion R&D Activities
- II. International Communication and Collaboration

International Cooperation on Fusion Nuclear Technology and Safety

□ IEA-ESEFP ExCo Chair (2013.9-2018.1)

□ IEA-NTFR ExCo Chair (2019.09-)

ExCo Members from:

1. MOST, China (INEST being the representative)
2. EC, Europe
3. IPR, India
4. QST, Japan
5. NFRI, Korea
6. ROSATOM, Russia
7. DOE, USA

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2019 IEA ESEFP ExCo Meeting



2019 IEA NTFR ExCo Meeting

World Summit on Nuclear Energy Safety Technology (10-16 May 2020)

□ Satellite Meetings

- **SNINS: Symposium on Neutronics and Innovative Nuclear Systems**
- **CASLER: International Co-operative Alliance for Small LEad-based Fast Reactors**
- **CAS-RAS Bilateral Meeting on ALIANCE**
- **INEST International Advisory Board**

Fliers on the registration desk



Institute of Nuclear Energy Safety Technology, CAS · FDS Team

Pre-announcement of the 4th World Summit on Nuclear Energy Safety Technology

In order to advance the sustainable development of nuclear energy and promote wider application of nuclear technology, the World Summit on Nuclear Energy Safety Technology (SNEST) is initiated by the Institute of Nuclear Energy Safety Technology (INEST), Chinese Academy of Sciences, and organized by INEST and other international organizations of the field. Nowadays SNEST has been recognized as one of the premier international gatherings for nuclear energy safety technology, promoting the exchange of information on all scientific, engineering and other technical aspects of the fields.

The 4th SNEST will be held in Hefei, China from May 10 to 16, 2020. Many Nobel Laureates, leaders of international organizations and top 500 enterprises of the world, would be on hand for the prestigious event that will bring collaborations among international scientists and engineers. The topics of 4th SNEST provide the excellent opportunity for discussing and exchanging the nuclear energy safety issues, and identifying means to resolve these issues. In addition, a number of satellite meetings, workshops and related academic activities will also be held linking to the 4th SNEST.

Thanks to the support of International Atomic Energy Agency (IAEA), International Energy Agency (IEA), Nuclear Energy Agency in Organization for Economic Cooperation and Development (OECD/NEA), International Thermonuclear Experimental Reactor organization (ITER), Ministry of Science and Technology of China (MOST), Chinese Academy of Sciences (CAS), Chinese Academy of Engineering (CAE) etc., the SNEST has been successfully held three times, and attracted extensive attention of scientists and celebrities in the world.



Contact information

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15th International Symposium on Fusion Nuclear Technology

13-17 September 2021, Hefei, China

Hosted by the Institute of Nuclear Energy Safety Technology, CAS
(INEST)



Summary

1. In the field of fusion research, INEST concentrates on the Nuclear Technology and Safety.
2. In 2019, INEST has made good progress on neutron source, neutronics software, fusion safety, material development, etc.
3. INEST is always open to domestic & international cooperation.

Thanks for Your Attention!



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