State of the Art of the Molten Salt Reactors Research

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Problems of the contemporary nuclear power

- Safety
- Nonproliferation
- ^{235}U resources
- Nuclear fuel cycle closing
- Radwaste handling
- Minor actinides incineration

Trends to overcome the problems

To create the inherently safe fast reactor with closed nuclear fuel cycle

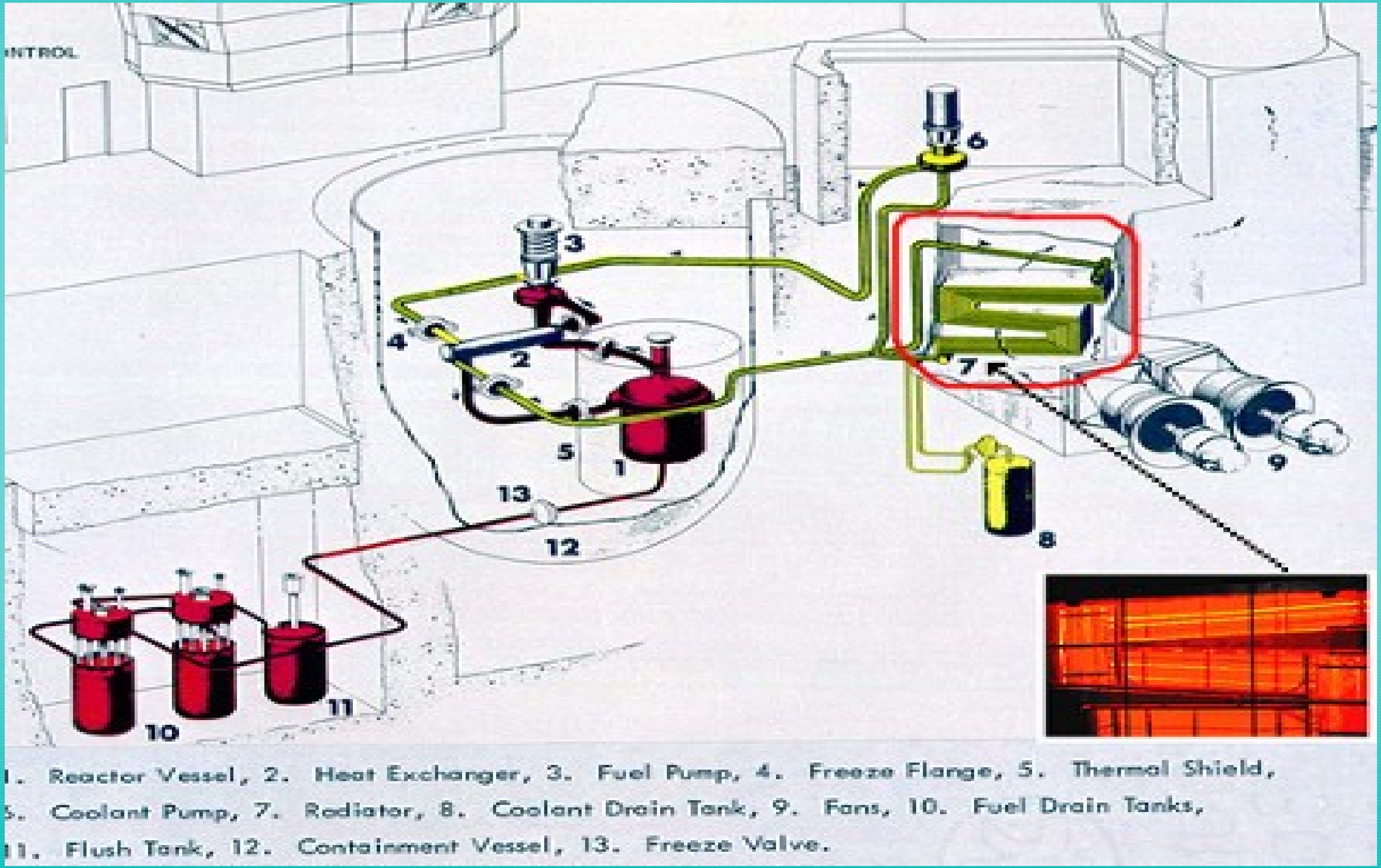
Advantages of Molten Salt Reactor

- It is inherently safe
- There is no fuel elements fabrication and utilization
- There are no restrictions on the fuel burning depth
- The closed nuclear fuel cycle is essentially simplified

Additionally - for Fast MSR:

- There is no restrictions of the fuel resources
- The natural way of the minor actinides incineration

MSRE


NTROL
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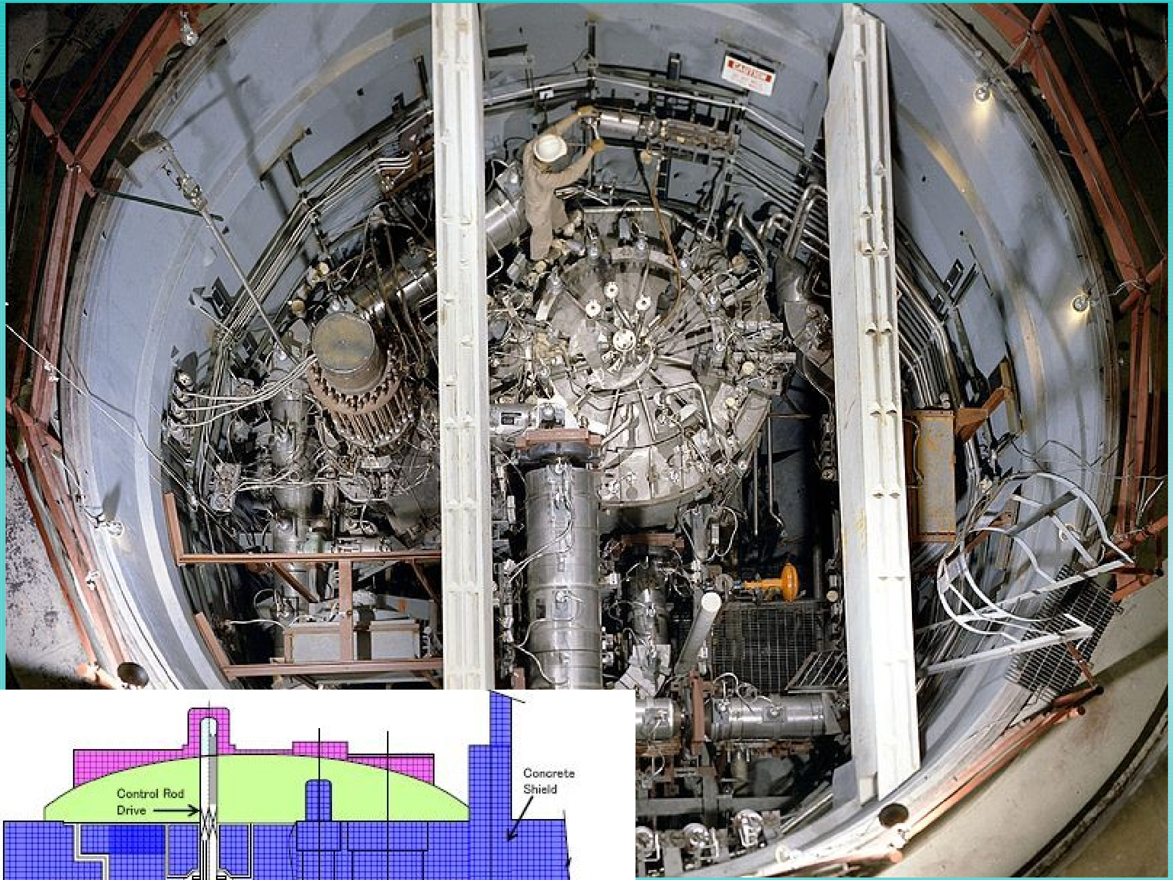
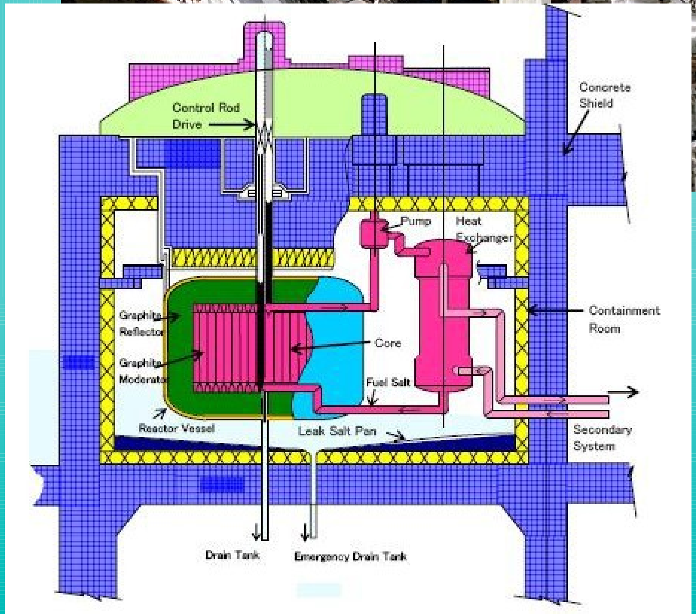
1. Reactor Vessel, 2. Heat Exchanger, 3. Fuel Pump, 4. Freeze Flange, 5. Thermal Shield,
6. Coolant Pump, 7. Radiator, 8. Coolant Drain Tank, 9. Fans, 10. Fuel Drain Tanks,
11. Flush Tank, 12. Containment Vessel, 13. Freeze Valve.

MSRE





MSRE core

Technical Meeting on the Status of Molten Salt Reactor Technology (Vienna 31.10. – 03.11.2016)

- 36 participants +10 IAEA staff;
- 16 countries:
- Canada
- China
- Czech
- EU
- France
- India
- Indonesia
- Italy
- Japan
- The Netherlands
- Russian Federation
- Switzerland
- Turkey
- United Kingdom
- USA
- Venezuela

GAIN MSR Technical Working Group Includes Developers and Utilities

ONE	TWO	THREE	FOUR	FIVE	SIX
TerraPower	**Thorcon**	**Terrestrial Energy**	**Flibe Energy**	**Transatomic Power**	**Elysium Industries**
Fast Breeder Liquid Fuel Salt Cooled Uranium (Could use Th)	Thermal Burner Liquid Fuel Salt Cooled Thorium	Thermal Burner Liquid Fuel Salt Cooled Uranium (Could use Th)	Thermal Breeder Liquid Fuel Salt Cooled Thorium	Hybrid Burner Liquid Fuel Salt Cooled Uranium	Liquid Fuel Salt Cooled

Southern Company

EPRI

NEI
NUCLEAR ENERGY INSTITUTE

Exelon.

DUKE ENERGY.

DOE's Focused Investment in FHRs Remains Primarily Through University Research

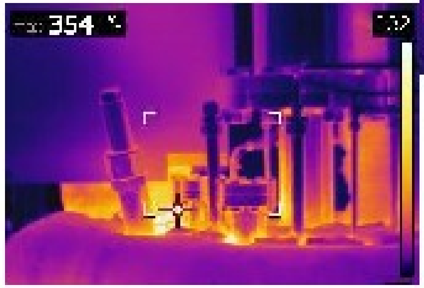
- **In 2011, DOE funded a multi-university (Massachusetts Institute of Technology [MIT], University of California, Berkeley [UC-B], and University of Wisconsin [UW]) integrated research project on FHR concept and technology development**
  - Thermal hydraulics and safety tests (UC-B)
  - Material and component selection and performance (UW)
  - Coolant/material tests in MIT research reactor (MIT)
  - FHR test reactor functional requirements and pre-conceptual design (MIT)
  - Commercial reactor conceptual design (UC-B)
  - Developing potential commercialization strategies linked to specific strengths of molten salt systems (MIT)
- **In 2014, DOE funded two additional integrated research projects on FHRs one led by Georgia Tech and the other by MIT**
  - Projects were focused on resolving FHR technology issues
  - Joint planning has occurred to minimize overlap and emphasize synergy

MSRs Benefit From Multiple DOE Supported Projects

Tritium Management	• Tritium stripping comparison/demonstration • Multiple university-based tritium removal projects
Structural Ceramics	• SiC channel boxes for BWRs • SiC leaf springs for LWR fuel assemblies • ASTM and ASME standards
Safety & Licensing	• DOE-NRC joint initiative on advanced reactor design criteria • ANS standards on MSR & FHR design safety
Fuel Cost and Qualification	• Mo & SiC accident tolerant cladding for LWRs • AGR TRISO testing
^{7}Li Cost	• Innovative separation technique • Higher separation coefficient materials

ORNL FLiNaK Test Loop Has Started-Up

- **Loop originated in ORNL LDRD, was expanded through DOE-NE, and brought into operation under SINAP**
- **Versatile liquid salt test loop embodies multiple innovative technologies providing a technology demonstration platform**
  - Integration of ceramic and metal components
  - Molten salt compatible gaskets (all prior loops have relied on welded joints)
  - Liquid salt instrumentation
    - *Ultrasonic flow meter*
    - *Radar level gauge*
  - Integration of salt cleaning with loop
- **First hot functional testing performed in June 2016**
- **SINAP staff have been participating in the measurements**



Thermal images of loop containing hot salt

Presentation to IAEA MSR Workshop
1st Nov 2016

An Overview of the Integral Molten Salt Reactor

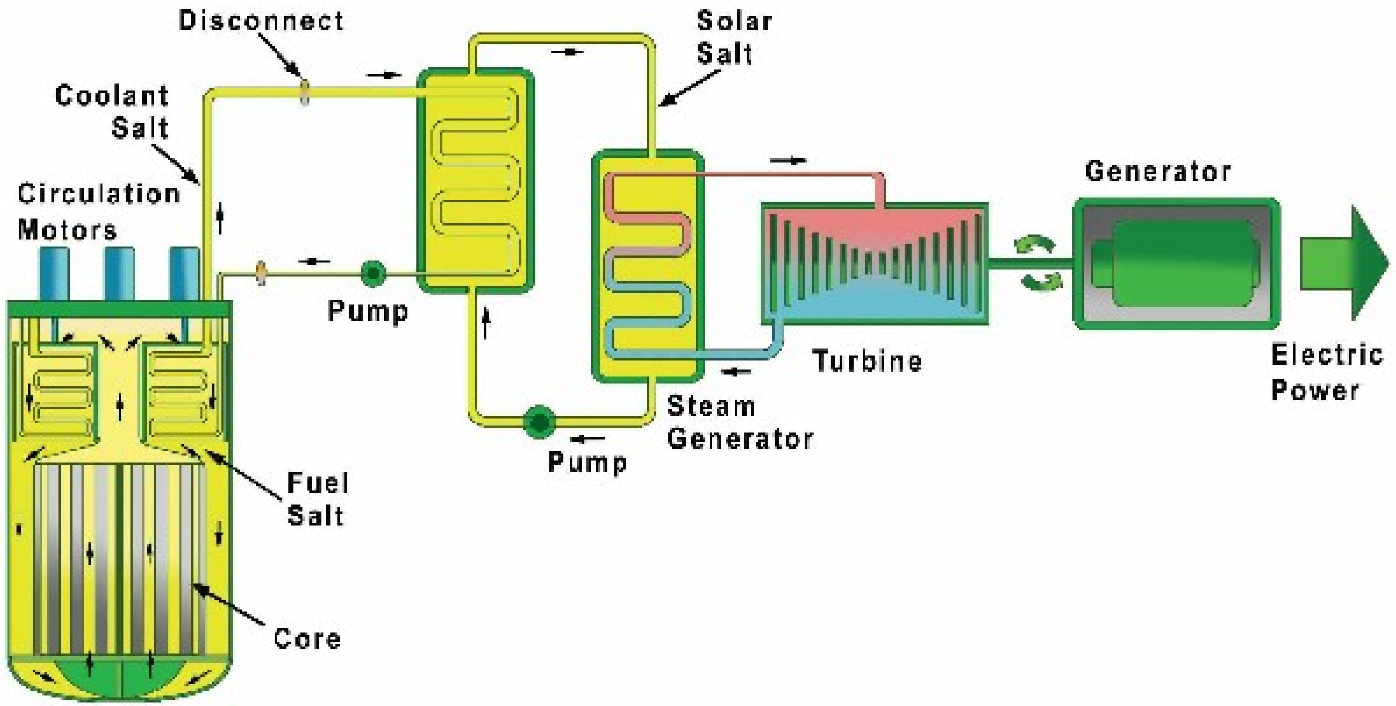
TERRESTRIAL ENERGY

TERRESTRIAL ENERGY'S CORPORATE INDUSTRIAL ADVISORY BOARD

- Power Utilities
  - Duke Energy owns and operates six nuclear power stations in North Carolina and South Carolina, USA.
    - Represented by John W. (Bill) Pitesa, Chief Nuclear Officer
  - Energy Northwest operates the Columbia Generating Station, located in Richland, Washington, USA.
    - Represented by Mark Reddemann, Chief Executive Officer
  - NB Power owns and operates the Point Lepreau Nuclear Generating Station, New Brunswick, Canada.
    - Represented by Gaëtan Thomas President and Chief Executive Officer
  - Ontario Power Generation owns and operates the Pickering and Darlington Nuclear Power Stations in Ontario, Canada.
    - Represented by Jeff Lyash, President and Chief Executive Officer
  - PSEG Nuclear operates the Salem and Hope Creek Nuclear Generating Stations in Lower Alloways Creek, New Jersey, USA, and is a part owner of the Peach Bottom Nuclear generation station in Delta, Pennsylvania, USA.
    - Represented by William Levis, PSEG Power, President and Chief Operating Officer
  - Southern Nuclear Operating Company operates the Alvin W. Vogtle Electric Generating Plant near Waynesboro, Georgia, USA, and the Edwin I. Hatch Nuclear Plant near Baxley, Georgia, USA, and the Joseph M. Farley Nuclear Plant near Dothan, Alabama, USA.
    - Represented by Stephen Kuczynski, Chairman, President and Chief Executive Officer
- Industrial
  - Caterpillar is the leading manufacturer of construction and mining equipment, diesel and natural gas engines, industrial gas turbines and diesel-electric locomotives.
    - Represented by Dan Henderson – Director of Research and Advanced Engineering

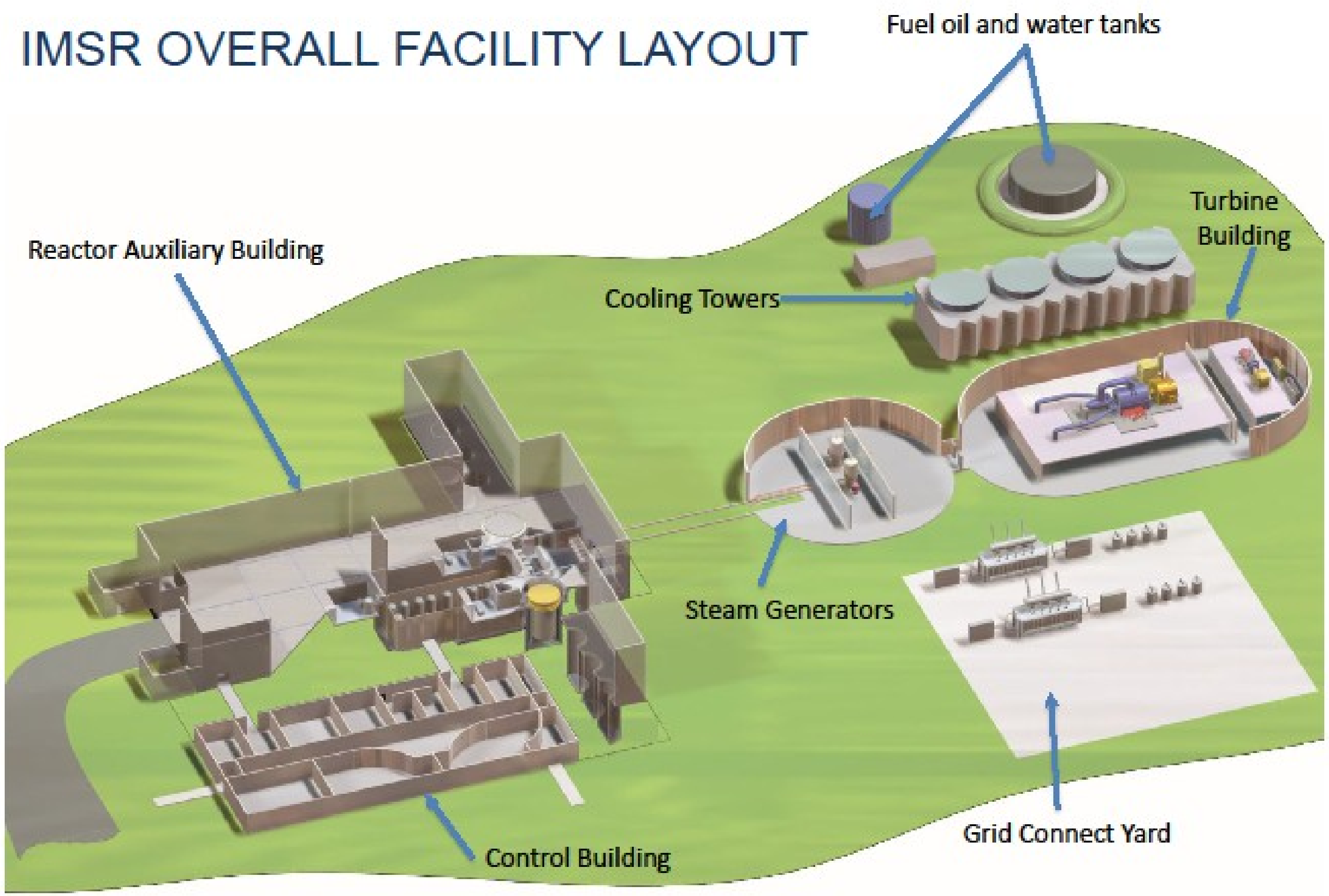
TERRESTRIAL ENERGY

SCHEMATIC VIEW OF IMSR POWER TRAIN



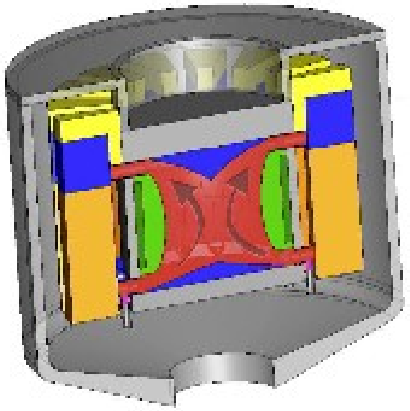
TERRESTRIAL ENERGY

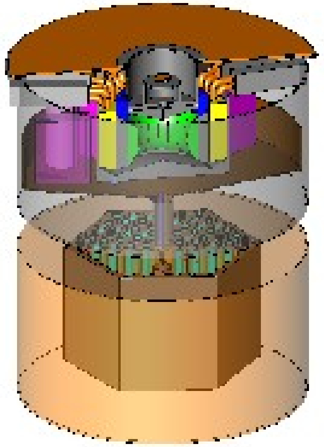
IMSR OVERALL FACILITY LAYOUT



TERRESTRIAL ENERGY

Concept of Molten Salt Fast Reactor





'MSFR Team' - M. ALLIBERT, M. BROVCHENKO, S. DELPECH,
D. GERARDIN, D. HEUER, A. LAUREAU, E. MERLE
Reactor Physics Group – LPSC Grenoble (CNRS-IN2P3 / Grenoble INP - PHELMA)
and IPN Orsay (CNRS-IN2P3)

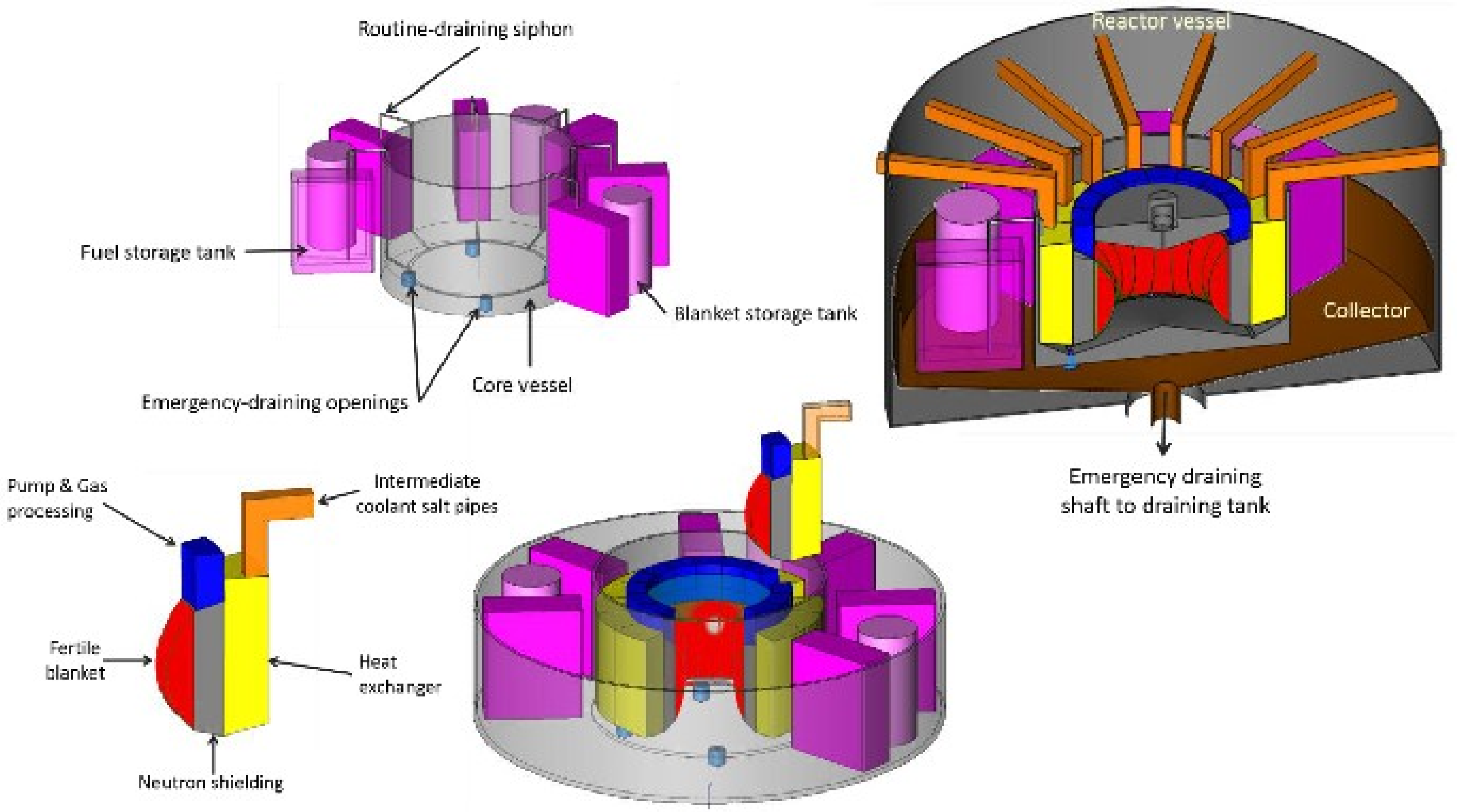
With the support of the IN2P3 institute and the PACEN and NEEDS Programs of CNRS, Grenoble Institute of Technology, and of the EVOL and SAMOFAR Euratom Projects

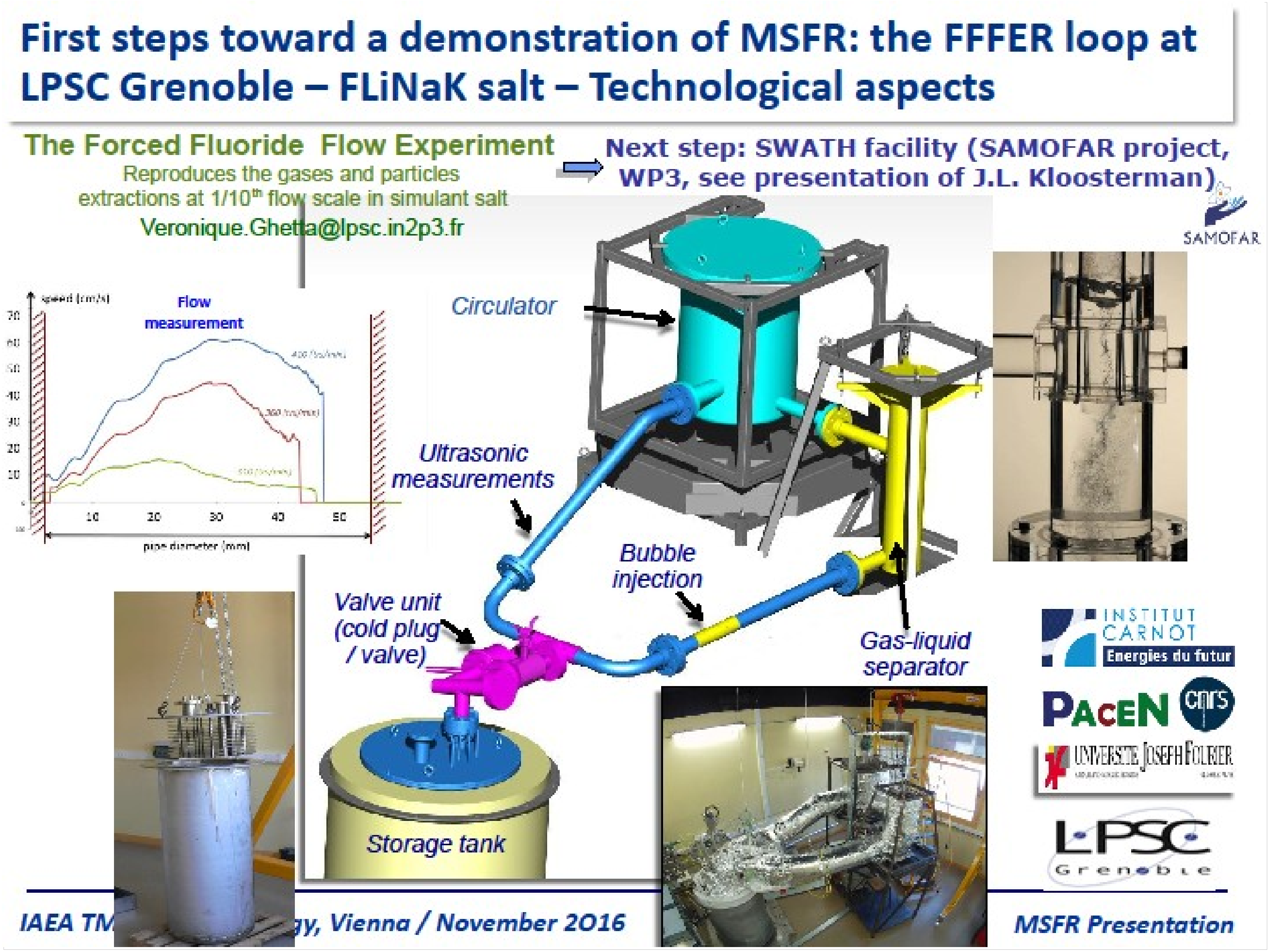
SAMOFAR

In2p3

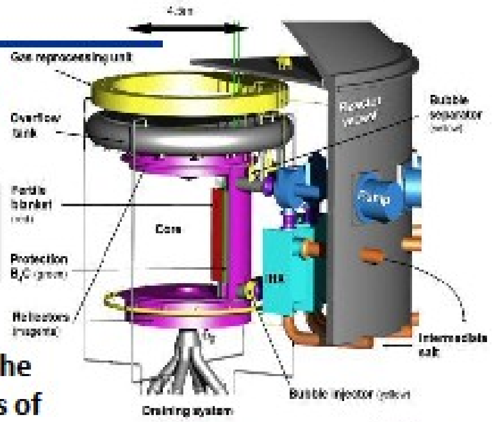
Concept of MSFR: Fuel salt loop (fuel circuit)

Segmented geometry (SAMOFAR proposal):




First steps toward a demonstration of MSFR: the FFFER loop at LPSC Grenoble – FLiNaK salt – Technological aspects
The Forced Fluoride Flow Experiment
Reproduces the gases and particles extractions at 1/10th flow scale in simulant salt
Veronique.Ghetta@lpsc.in2p3.fr
Next step: SWATH facility (SAMOFAR project, WP3, see presentation of J.L. Kloosterman)
SAMOFAR
speed (cm/s)
Flow measurement
pipe diameter (mm)
Circulator
Ultrasonic measurements
Bubble injection
Valve unit (cold plug / valve)
Gas-liquid separator
Storage tank
INSTITUT CARNOT
Energies du futur
PACEN
cnrs
UNIVERSITE JOSEPH FOURIER
LPSC
Grenoble
IAEA TM
gy, Vienna / November 2016
MSFR Presentation

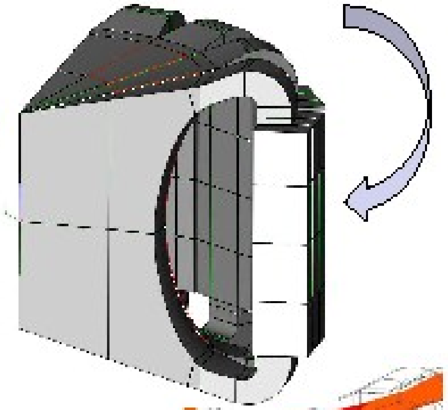
MSFR and the European project EVOL



European Project "EVOL" Evaluation and Viability Of Liquid fuel fast reactor - ***FP7 (2011-2013): Euratom/Rosatom cooperation***

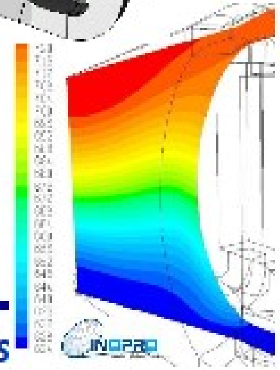
Objective : to propose a design of MSFR by end of 2013 given the best system configuration issued from physical, chemical and material studies

- Recommendations for the design of the core and fuel heat exchangers
- Definition of a safety approach dedicated to liquid-fuel reactors - Transposition of the defence in depth principle - Development of dedicated tools for transient simulations of molten salt reactors
- Determination of the salt composition - Determination of Pu solubility in LiF-ThF4 - Control of salt potential by introducing Th metal
- Evaluation of the reprocessing efficiency (based on experimental data) – FFFER project
- Recommendations for the composition of structural materials around the core



⇒ EVOL { **WP2: Design and Safety**
WP3: Fuel Salt Chemistry and Reprocessing
WP4: Structural Materials

12 European Partners: France (CNRS: Coordinateur, Grenoble INP , INOPRO, Aubert&Duval), Pays-Bas (Université Techno. de Delft), Allemagne (ITU, KIT-G, HZDR), Italie (Ecole polytechnique de Turin), Angleterre (Oxford), Hongrie (Univ Techno de Budapest)
+ 2 observers since 2012 : Politecnico di Milano et Paul Scherrer Institute



+ Coupled to the MARS (Minor Actinides Recycling in Molten Salt) project of ROSATOM (2011-2013)

Partners: RIAR (Dimitrovgrad), KI (Moscow), VNIITF (Snezinsk), IHTE (Ekateriburg), VNIKHT (Moscow) et MUCATEX (Moscow)

12 MS

Some PhD Thesis in France on MSR

Axel LAUREAU, ***"Développement de modèles neutroniques pour le couplage thermohydraulique du MSFR et le calcul de paramètres cinétiques effectifs"***, PhD Thesis, Grenoble Alpes University, France (2015)

Mariya BROVCHENKO, ***"Etudes préliminaires de sûreté du réacteur à sels fondus MSFR"***, PhD Thesis, Grenoble Institute of Technology, France (2013)

Xavier DOLIGEZ, ***"Influence du retraitement physico-chimique du sel combustible sur le comportement du MSFR et sur le dimensionnement de son unité de retraitement"***, PhD Thesis, Grenoble Institute of Technology and EDF, France (2010)

Elsa MERLE-LUCOTTE, ***"Le cycle Thorium en réacteurs à sels fondus peut-il être une solution au problème énergétique du XXIème siècle ? Le concept de TMSR-NM"***, Habilitation à Diriger les Recherches, Grenoble Institute of Technology, France (2008)

Ludovic MATHIEU, ***"Cycle Thorium et Réacteurs à Sel Fondu: Exploration du champ des Paramètres et des Contraintes définissant le Thorium Molten Salt Reactor"***, PhD Thesis, Grenoble Institute of Technology and EDF, France (2005)

Jorgen FINNE, ***"Chimie des mélanges de sels fondus - Application à l'extraction réductrice d'actinides et de lanthanides par un métal liquide"***, PhD Thesis, EDF-CEA-ENSCP, Paris, France (2005)

Fabien PERDU, ***"Contributions aux études de sûreté pour des filières innovantes de réacteurs nucléaires"***, PhD Thesis, Grenoble Institute of Technology, France (2003)

Alexis NUTTIN, ***"Potentialités du concept de réacteur à sels fondus pour une production durable d'énergie nucléaire basée sur le cycle thorium en spectre épithermique"***, PhD Thesis, Grenoble I University and EDF, France (2002)

Available on http://lpsc.in2p3.fr/index.php/fr/38-activites-scientifiques/physique-des-reacteurs-nucleaires/183-msfr-bibliographie or 'MSFR LPSC' in google search

SAMOFAR

Jan Leen Kloosterman, TU Delft
on behalf of all SAMOFAR partners

Concept of Molten Salt Fast Reactor (MSFR)

SAMOFAR Project – Horizon2020
Safety Assessment of a MOlten salt FAst Reactor

SAMOFAR

4 years (2015-2019), 3,5 M€

Partners: TU-Delft (leader), CNRS, JRC-ITU, CIRTEN (POLIMI, POLITO), IRSN, AREVA, CEA, EDF, KIT + PSI + CINVESTAV

SAMOFAR will deliver the experimental proof of the following **key safety features**:
The **freeze plug** and draining of the fuel salt
New materials and new coatings to materials
Measurement of safety related data of the fuel salt
The dynamics of **natural circulation** of (internally heated) fuel salts
The **reductive extraction processes** to extract lanthanides and actinides from the fuel salt

5 technical work-packages:

WP1 Integral safety approach and system integration

WP2 Physical and chemical properties required for safety analysis

WP3 Proof of concept of key safety features

WP4 Numerical assessment of accidents and transients

WP5 Safety evaluation of the chemical processes and plant

THE FRAMEWORK PROGRAMME FOR RESEARCH AND INNOVATION
HORIZON 2020

→ **+ See presentation by Jan-Leen Kloosterman**

SAMOFAR partners

Number	Organisation	Country
1 (Coord)	Technische Universiteit Delft (TU Delft)	The Netherlands
2	Centre National de la Recherche Scientifique (CNRS)	France
3	JRC – Joint Research Centre– European Commission (JRC)	Germany
4	Consorzio Interuniversitario Nazionale per la Ricerca Tecnologica Nucleare (CIRTEN)	Italy
5	Institut de Radioprotection et de Sûreté Nucléaire (IRSN)	France
6	Centro de Investigaciony de Estudios Avanzados del Instituto Politecnico Nacional (CINVESTAV)	Mexico
7	AREVA NP SAS (AREVA)	France
8	Commissariat a l'Energie Atomique et aux Energies Alternatives (CEA)	France
9	Electricité de France S.A. (EDF)	France
10	Paul Scherrer Institute (PSI)	Switzerland
11	Karlsruher Institut für Technologie (KIT)	Germany

SAMOFAR

2

Aim of the project

- The grand objective of SAMOFAR is to:
  - prove the innovative safety concepts of the MSFR,
  - deliver breakthrough in nuclear safety and waste management
  - create a consortium of stakeholders to demonstrate the MSFR beyond SAMOFAR

- Main results are:
  - experimental proof of concept
  - (integral) safety assessment of the MSFR
  - update of the conceptual design of the MSFR
  - roadmap and momentum among stakeholders

SAMOFAR

3

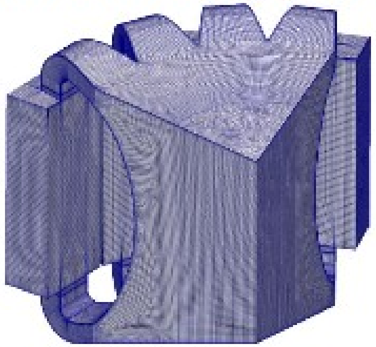
Technical Meeting on the Status of Molten Salt Reactor Technology   Vienna, 2nd November, 2016

Modelling and experimental activities on Molten Salt Reactors (MSRs) developed at Politecnico di Milano in Italy

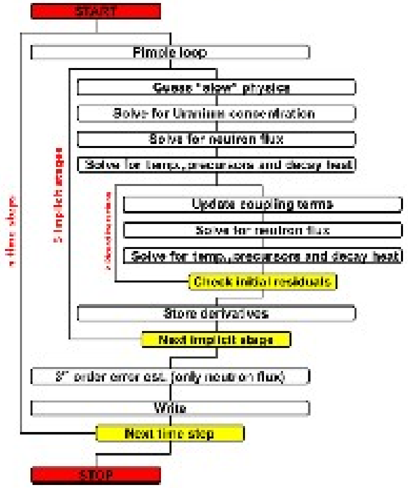
Stefano Lorenzi, A. Cammi, L. Luzzi, M. E. Ricotti

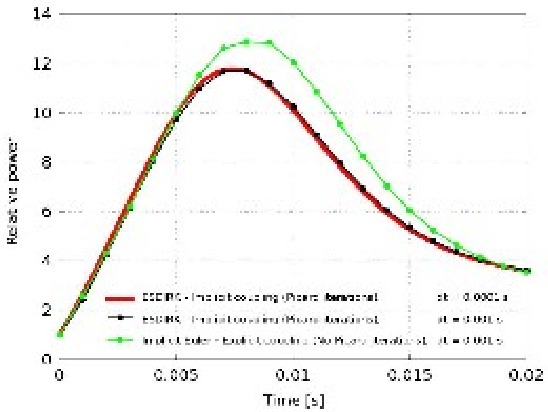
Nuclear Reactors Group

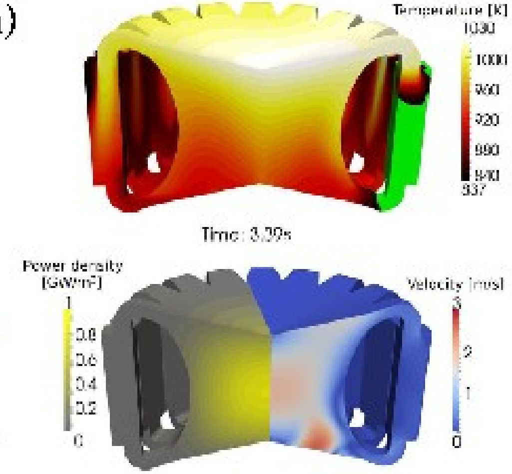
MSFR reactor



. **Transient analysis of the MSFR reactor** (3D) with MPM based on FV solver (OpenFOAM)
. Fluid dynamics (incompressible RANS realizable k-ε + Boussinesq approx) + heat transfer (conjugate heat transfer and decay heat) + neutronics (1 group diffusion)
. **New high-order integration** method (ESDIRK) for implicit neutronics-thermal hydraulics coupling
. HPC-friendly (**parallelization**)



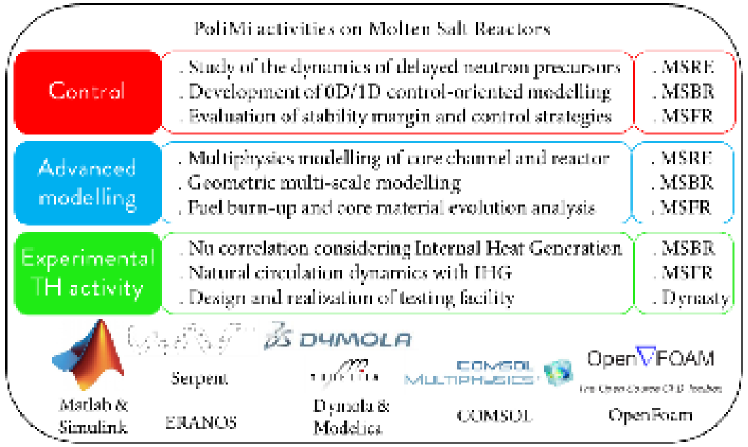




Aufiero, M., Cammi, A., Geoffroy, O., Losa, M., Luzzi, L., Ricotti, M.E., Rouch, H., 2014b. Development of an OpenFOAM model for the Molten Salt Fast Reactor transient analysis. Chemical Engineering Science 111, 390–401.

Future perspectives

10 years of research activities @ PoliMi on MSR



Modelling & Simulation:
. Control
. Advanced modelling (Multiphysics)
. Influence of Internal Heat Generation on thermal-hydraulics

Experimental:
. DYNASTY testing facility

Planned and future activities

Modelling:
. Development of MSFR plant simulator
. Definition of operational modes of MSFR
. Improvement of the Multiphysics modelling (OpenFOAM)
. Reduced Order Methods

Experimental:
. Testing with DYNASTY facility
. Extension of the facility (eDYNASTY)

R&D activities on Molten Salt Reactors @ PoliMi-NRG

Projects:

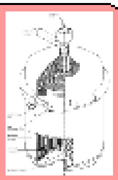
. EVOL (observer)

. SAMOFAR

. 2 x FARB (PoliMi)

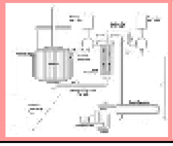
. IAEA CRP T12026

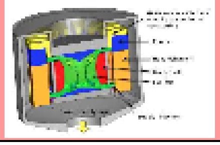
Reactors:



. Graphite-moderated (MSBR and MSRE)

. Fast system (MSFR)





Collaboration:

. TU-Delft

. PSI

. CNRS-Grenoble

. KIT

. Westinghouse

. VTT Technical Research Centre of Finland

. JRC - Karlsruhe

People:

. Prof. Marco Enrico Ricotti

. Prof. Antonio Cammi

. Prof. Lelio Luzzi

. Stefano Lorenzi (PostDoc)

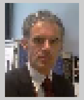
. Alessandro Pini (PhD student)

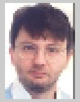
. Marco Tudor Cauzzi (PhD student)

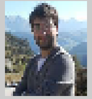
. Alberto Tosolin (PhD student)

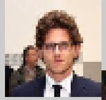
. Eric Cervi (PhD student)

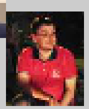
. 5 PhD theses + 15 MSc thesis

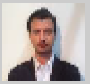


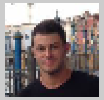












Current Research Activity on MSR in Japan

Committee and Meeting

① Research Committee on Molten Salt Technology in AESJ (Yamawaki)
② International Thorium Molten-Salt Forum at Atomic Energy Committee

Elemental Research

③ Arita (Fukui U.) : Volatile FP Release from Molten Salts
④ Fukumoto (Fukui U.) : Molten Salt Corrosion of Hastelloy-N
⑤ Terai (U. Tokyo) : Molten Salt Chemistry for Nuclear Systems
⑥ Koyama, Uozumi (CRIEPI) : Pyro-reprocessing of Molten Salt Fuel
⑦ Sagara (NIFS) : FLiNaK-loop for Fusion Technology

Conceptual Design

⑧ Yamawaki (Fukui U.) : New Conceptual Design of MSR: S-MSR
⑨ Mitachi (Former Toyohashi I. T.) : Pu/MA Processing Scenario
Hirose (Former Hitachi) : Molten Salt Fuel Design and Processing Scenario

Private Companies

⑩ Kinoshita (TTS) : "Reactor in Reactor" Concept
⑪ Kamei (Kyoto Neutronics) : "UNOMI"
⑫ Manufacturers of MSR Key Elements

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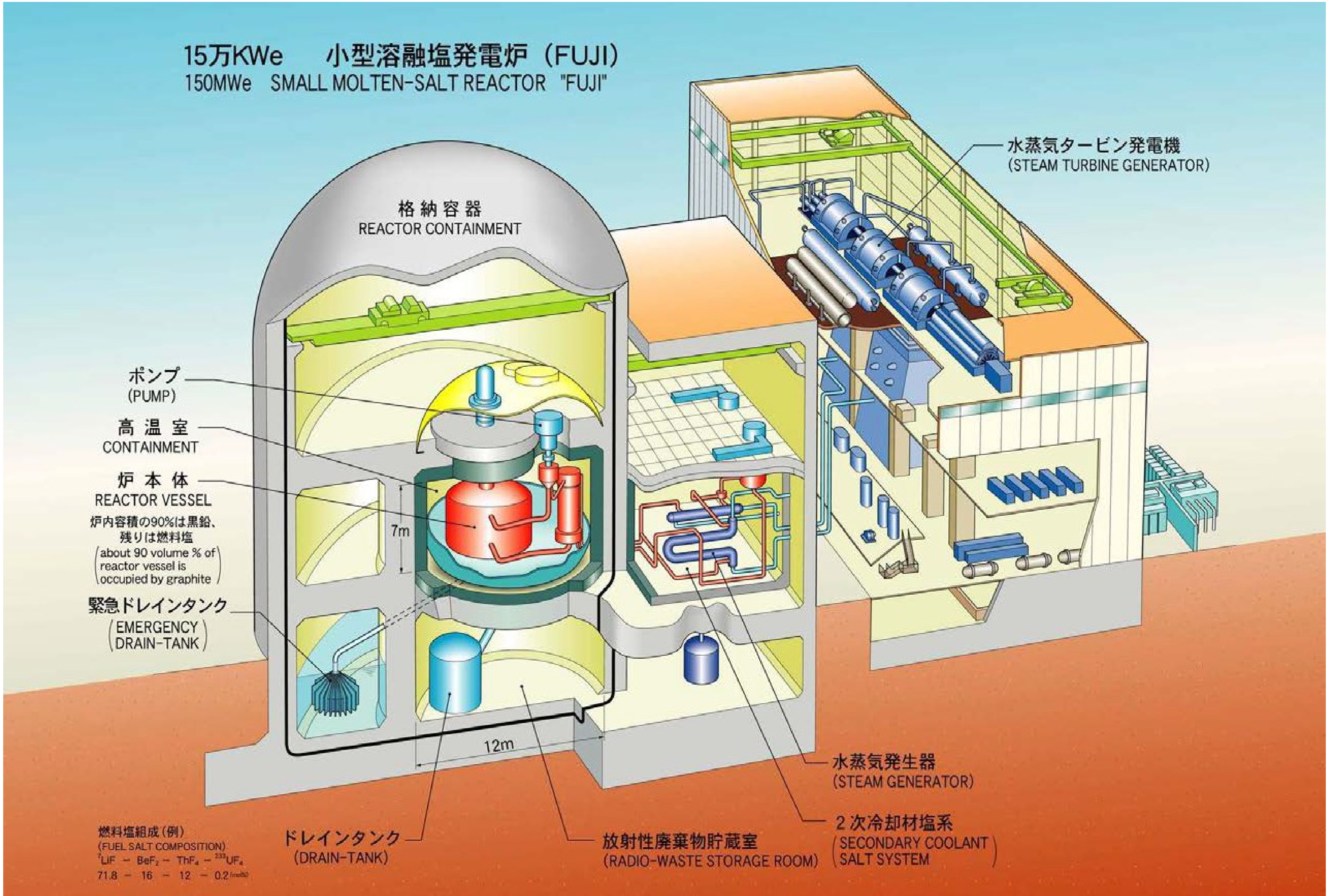
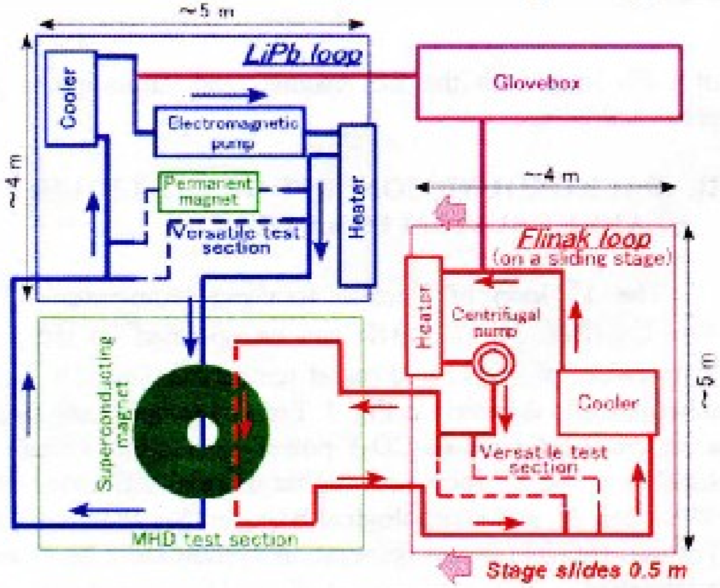
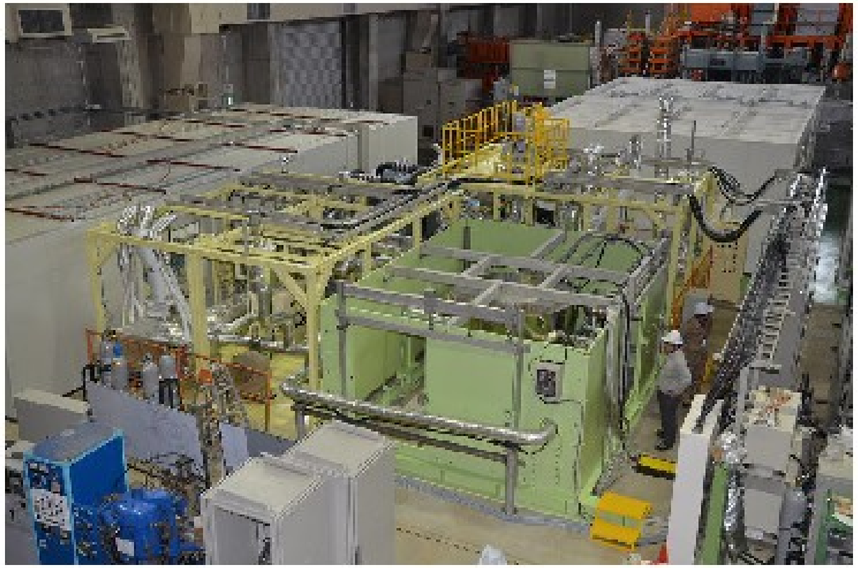

15万KWe　小型溶融塩発電炉（FUJI）
150MWe SMALL MOLTEN-SALT REACTOR "FUJI"
水蒸気タービン発電機
(STEAM TURBINE GENERATOR)
格納容器
REACTOR CONTAINMENT
ポンプ
(PUMP)
高 温 室
CONTAINMENT
炉 本 体
REACTOR VESSEL
炉内容積の90%は黒鉛、
残りは燃料塩
(about 90 volume % of reactor vessel is occupied by graphite)
7m
緊急ドレインタンク
(EMERGENCY DRAIN-TANK)
12m
水蒸気発生器
(STEAM GENERATOR)
2次冷却材塩系
(SECONDARY COOLANT SALT SYSTEM)
燃料塩組成（例）
(FUEL SALT COMPOSITION)
$^{7}LiF - BeF_2 - ThF_4 - {}^{233}UF_4$
71.8 − 16 − 12 − 0.2
ドレインタンク
(DRAIN-TANK)
放射性廃棄物貯蔵室
(RADIO-WASTE STORAGE ROOM)

⑦FLiNaK-loop for Fusion Technology (Sagara, NIFS)

NIFS (National Institute for Fusion Science)'s loop: Orosh^{2}i-2 (Operational Recovery Of Separated Hydrogen and Heat Inquiry)



	FLiNaK	LiPb
	LiF-NaF-KF (46.5-11.5-42 mol %)	$Li_{15.7}Pb_{84.3}$
Inventory	: ~100 L	~100 L
Pump	: Centrifugal	Electromagnetic
Pipe material	: Inconel	SUS 316
Inner diameter	: 25.4 mm	40.8 mm/25.4 mm
Velocity	: 1.5 m/s	1.5 m/s
Temperature	: 500 °C	350 °C



A. Sagara, et al. "First Operation of the FliNaK/LiPb Twin Loop Orosh^{2}i-2 with a 3T SC Magnet for R&D of Liquid Blanket for Fusion Reactor", *Fusion Science and Technology*, Vol.68 (2015)

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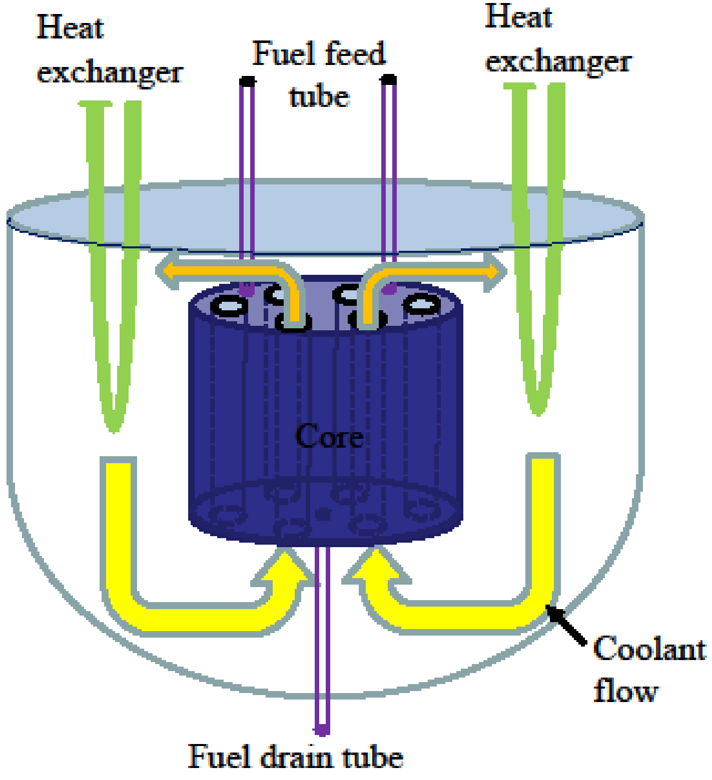
⑧Proposal of a New Design of S-MSR
(Yamawaki, Fukui U.)

Fuel salt is maintained in a core tank, so that it is safer in terms of severe accident and delayed neutron.

Rad-waste nuclear transmutation : contriving scenario and efficiency evaluation are under way.



Schematic Figure of S-MSR

M. Yamawaki et al. (Univ. of Fukui), ICONE23, Chiba, May 17-21, 2015

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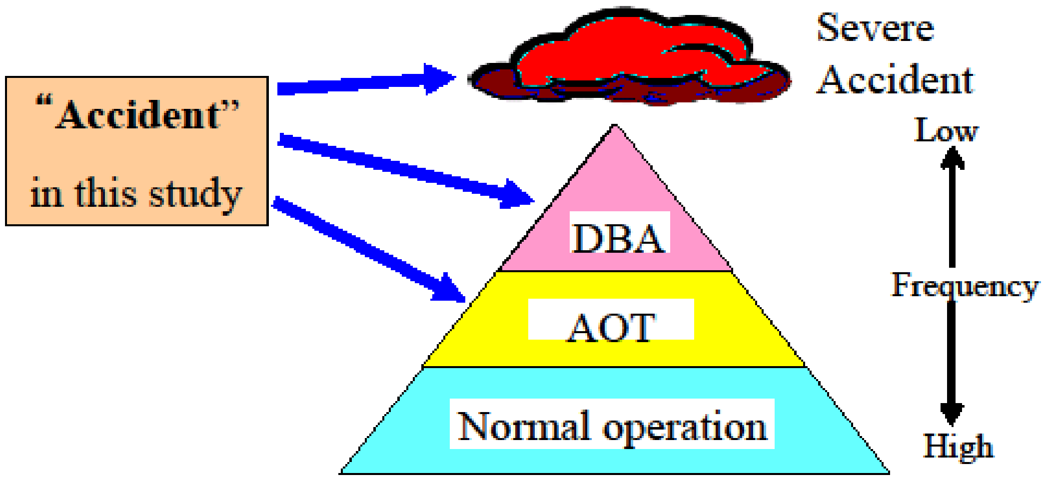
Classification of Reactor Status



Severe Accident	Events beyond DBA, which will cause core melt-down for LWR and/or large release of radioactivity.
Design Basis Accident (DBA)	Events beyond AOTs, which will cause LWR fuel failure.
Abnormal Operating Transient (AOT)	Anticipated events to occur once or more during a plant service life. Initiated by single equipment malfunction, or single operator error.
Normal operation	Reactor shutdown or startup, besides operation at power

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Conclusion

1	40 possible accidents for MSR are specified.
2	In several accidental scenarios, fuel-salt must be transferred to a drain-tank, and this system assures high safety of MSR. However, its consequence depends on freeze valve function, because its operation is slow, and this means that some verification is required.
3	Also, some other accidents need quantitative evaluation.
4	As a summary of this report, it can be concluded that MSR has superior safety, and it may be concluded that MSR has an intrinsic safety, after completion of these evaluations.

Safety Concept, Safety Criteria, and GDC (General Design Criteria) are proposed in a separate paper.

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Technical Meeting on the Status of Molten Salt Reactor Technology
(622-I3-TM-52244)， IAEA Headquarters， Vienna, Austria
Thorium Molten Salt Reactors
(TMSR) Development in China
Dai Zhimin, Zou Yang, Chen Kun
Institute of Advanced Nuclear Energy（ANEI), CAS
SINAP
中国科学院上海应用物理研究所
Shanghai Institute of Applied Physics, Chinese Academy of Sciences

China Restarted TMSR Program

- January, 2011, Chinese Academy of Sciences (CAS) initiated (restarted) “Thorium Molten Salt Reactor Nuclear Energy System” (TMSR) Strategetic Pioneer Sci.&Tech. Project.
- August, 2013, TMSR was one of the National-Energy Major R&D projects of Chinese National Energy Administration (CNEA)。
- May, 2015, TMSR was one of the Major S&T Projects by Shanghai Local Government for “Development of Global S&T Innovation Center” .

TMSR Development Strategy

R&D、Design、Licensing → Demonstration → Commercial

- Simulator (2017)
- Test Reactor (2020)
- Demonstration Reactor (2025)
- Commercial Reactor (2030)

Key technology and component development, Simulator (mock-up) (TMSR-SF0)

2MWth liquid-fuel test reactor (TMSR-LF1)

10MWth Solid-fuel test reactor (TMSR-SF1)

168MWe liquid-fuel demonstration reactor (TMSR-LF2)

168MWe solid-fuel demonstration reactor (TMSR-SF2)

CAS TMSR Project (2011-2018): 2.17B RMB
Shanghai Local Government (2015-2017): 115M RMB

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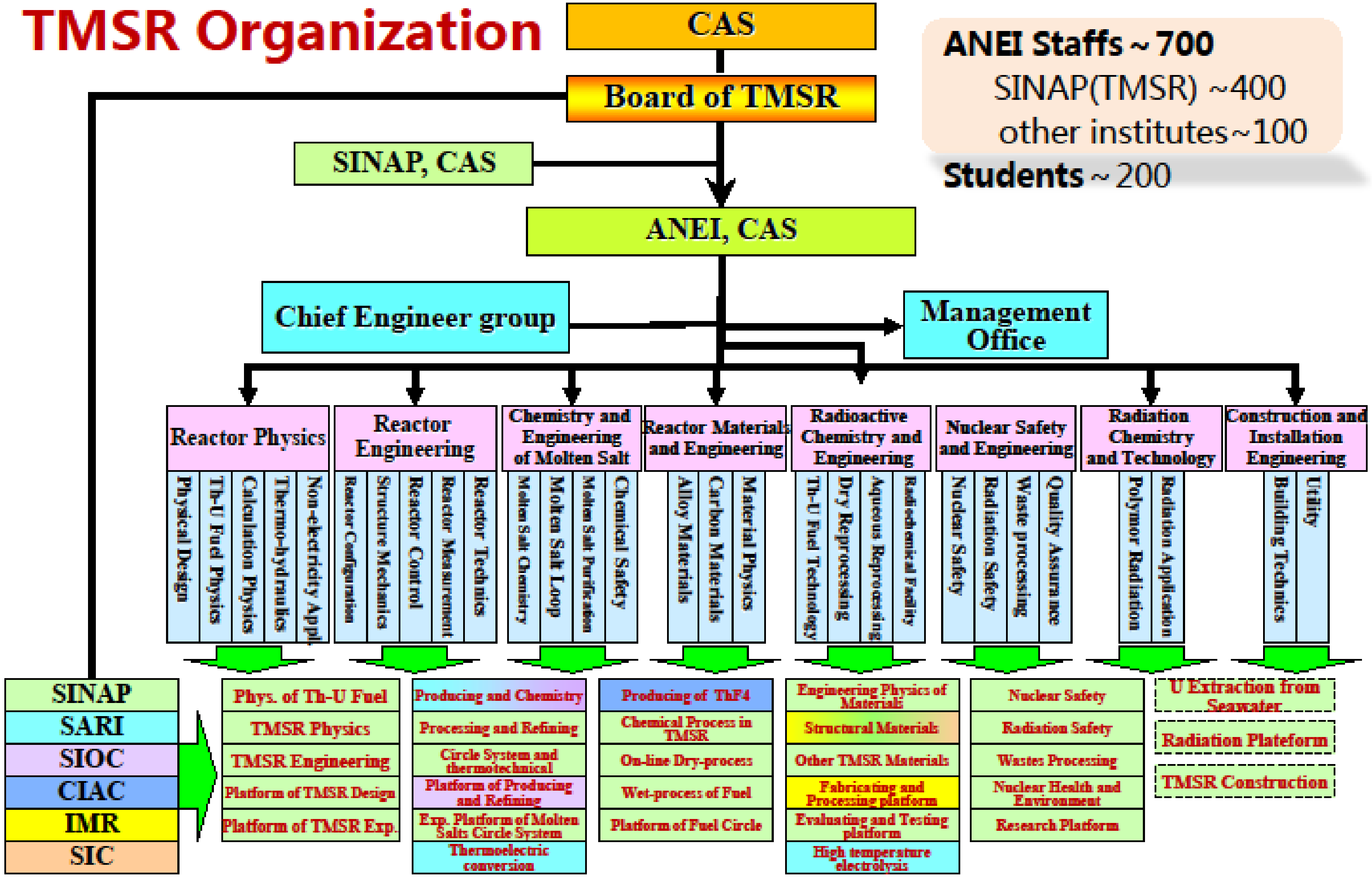
Institute of Advanced Nuclear Energy

- **The Institute of Advanced Nuclear Energy （ANEI）is an organization established by CAS for leading the TMSR program**
  - **There are 7 institutes of CAS involved in TMSR program**
  - **There are about 500 staffs and 200 graduatestudents of ANEI, in which ~400 staffs from SINAP and ~100 staffs from other institutes**

Research institutes	Tasks in TMSR program
Shanghai Institute of Applied Physics	• undertakes more than 80% of the R&D work with about 80% of the funding
Shanghai Institute of Organic Chemistry	• Extraction methods for lithium isotope separation
Shanghai Advanced Research Institute	• Thermal power conversion technology • Production of methanol with CO_2
Institute of Metal Research	• R&D of nickel-based alloy with corrosion resistance to molten salt
Changchun Institute of Applied Chemistry	• Production of nuclear grade thorium
Shanghai Institute of Ceramics	• R&D of SiC-SiC composite materials and carbon-based materials
Institute of Coal Chemistry	• R&D of new grade of nuclear graphite

TMSR Organization

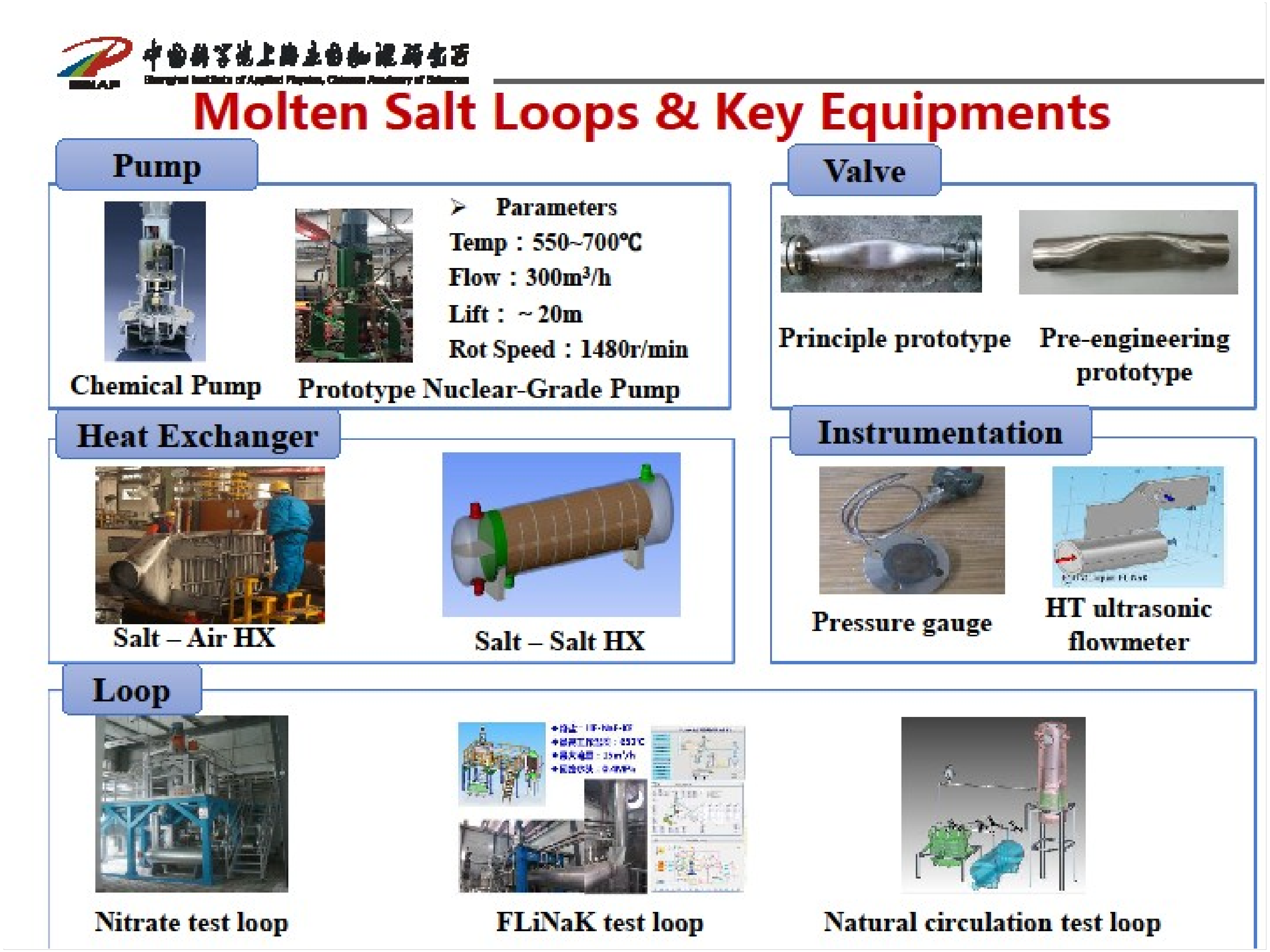


ANEI Staffs～700

SINAP(TMSR) ~400

other institutes～100

Students～200


Molten Salt Loops & Key Equipments
Pump
Parameters
Temp：550~700℃
Flow：300m³/h
Lift： ~20m
Rot Speed：1480r/min
Chemical Pump
Prototype Nuclear-Grade Pump
Valve
Principle prototype
Pre-engineering prototype
Heat Exchanger
Salt – Air HX
Salt – Salt HX
Instrumentation
Pressure gauge
HT ultrasonic flowmeter
Loop
Nitrate test loop
FLiNaK test loop
Natural circulation test loop

It Appears We Have Come Full Circle from the Late 1960s on MSRs

From the Preface of a Series of Papers Published in *Nuclear Applications & Technology* on MSRs from 1969 by Alvin M. Weinberg:

The tone of optimism that pervades these papers is hard to suppress. And indeed, the enthusiasm displayed here is no longer confined to Oak Ridge. There are now several groups working vigorously on molten salts outside Oak Ridge.

MSRE showed that MSRs are possible today's efforts are to prove they are practical

Fast Molten Salt Reactor with U-Pu Fuel

L.I. Ponomarev

A.A.Bochvar High Technology Research Institute of Inorganic Materials, Moscow

- Problems of the contemporary nuclear power
- Preferences of molten salt reactors
- Fast neutron spectrum vs thermal one
- U-Pu vs Th-U fuel cycle
- Solubility of PuF_3 in the eutectic LiF-NaF-KF
- U-Pu FMSR
- FMSR-burner of Am

MSR fuel and neutron spectrum

- Traditionally Th-U MSR fuel is considered and it is reasonable for the thermal neutron spectrum: in this case Th-U fuel has advantages in comparison with U-Pu fuel.
- But for the breeding and MA incineration the fast neutron spectrum is preferable.
- Neutron balance of U-Pu fuel with the fast spectrum is essentially more attractive in comparison with Th-U fuel.
- Fast neutron spectrum in liquid fuel is formed if the concentration of heavy elements (Th, U, Pu) in molten salt is ≥ 10 at.%.

Th-U fuel vs U-Pu fuel

	Thermal spectrum (0.025 eV)				Fast spectrum (2 MeV)			
	ν	α	η	δ	ν	α	η	δ
^{235}U	2.43	0.167	2.07	1.07	2.67	0.09	2.38	1.38
^{238}U	-	-	-	-	2.64	5.9*	0.45	-0.55
^{239}Pu	2.88	0.358	2.12	1.12	3.18	0.025	3.10	2.10
^{232}Th	-	-	-	-	2.41	12.5*	0.18	-0.82
^{233}U	2.49	0.085	2.29	1.29	2.67	0.041	2.56	1.56

$\eta = 1/(1+\alpha)$

$\delta = \eta - 1$

$\alpha = \sigma_c/\sigma_f$

*Taking into account neutron inelastic scattering on ^{238}U and ^{232}Th

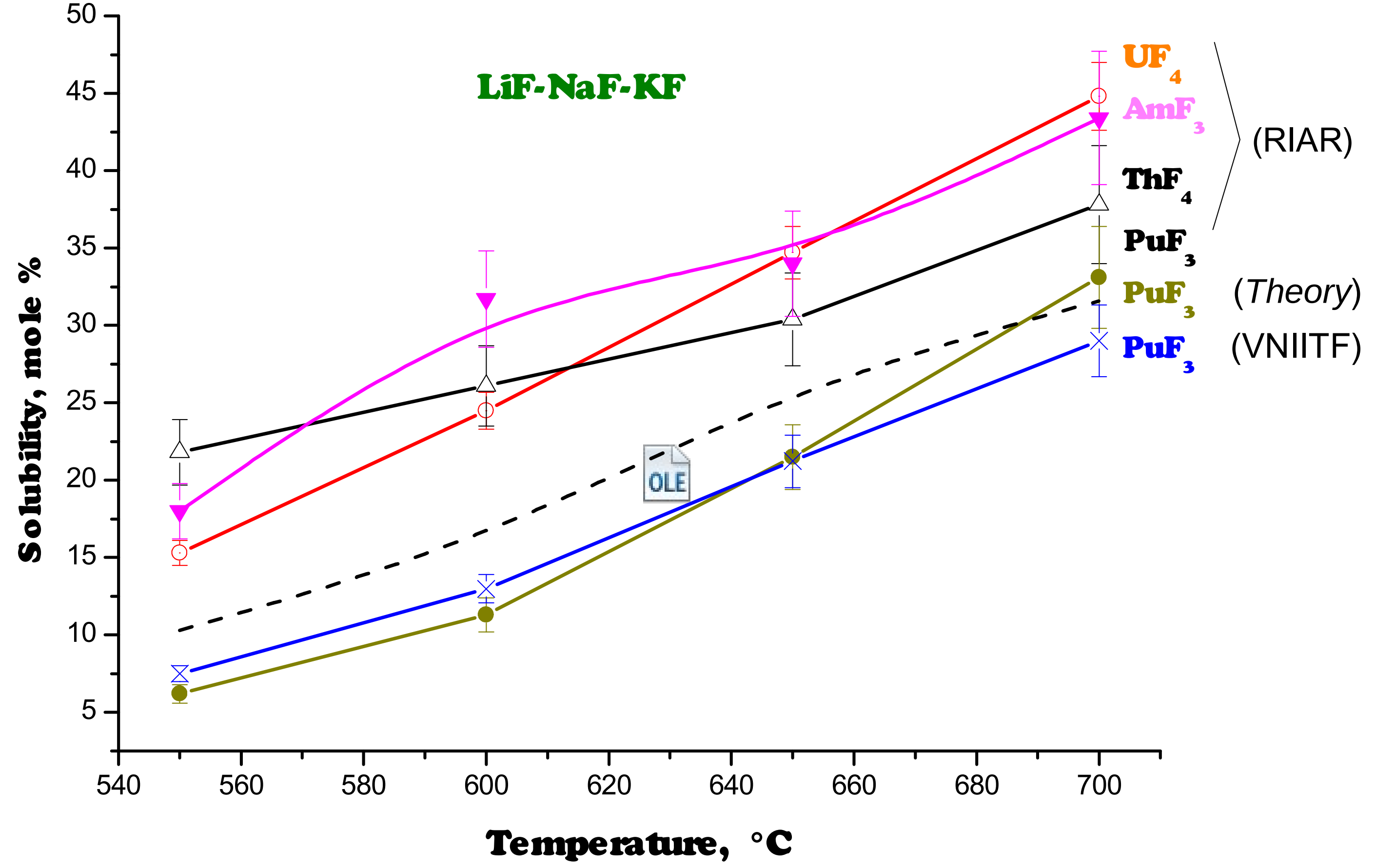
PuF_3 solubility (mole %)

	T_m, °C	Temperature, °C			Ref.
		550	**600**	**650**	
$67LiF\text{-}33BeF_2$	**460**	0,31	0,45	**0,88**	Barton et al., 1958
$66,7LiF\text{-}33,3BeF_2$	**460**	0,39[β]	0,58	**0,83**	Barton, 1960
$17,5LiF\text{-}56,5NaF\text{-}26BeF_2$	**505**	1,56	1,56	**2,80**	Barton, 1960
$15LiF\text{-}58NaF\text{-}27BeF_2$	**480**	1,33	1,94	**2,89**	Ignatiev et al., 2006
$70LiF\text{-}10BeF_2\text{-}20UF_4$	–	1,27	1,70	**2,48**	Thoma, 1958
$72LiF\text{-}16BeF_2\text{-}12ThF_4$	–	1,17	1,78	**2,57**	Bamberger et al., 1970
$75LiF\text{-}20BeF_2\text{-}5ThF_4$	–	–	2,88	–	Iyer et al., 1973
$75LiF\text{-}5BeF_2\text{-}20ThF_4$	--	--	2,9	**3,8**	Sood et al., 1975
$75LiF\text{-}5BeF_2\text{-}20ThF_4$	–	–	3,16	**3,98**	Ignatiev et al., 2012

PuF_3 solubility (mole %) in molten salts

Salt (mole %)	T_{melt}, °C	Temperature. °C				Ref.
		550	**600**	**650**	**700**	
$LiF–BeF_2$ (67-33)	**460**	0.31	0.45	0.84	–	Barton, 1958
$LiF–NaF–BeF_2$ (15-58-27)	**480**	1.33	1.94	2.89	–	Ignatiev at al., 2006
LiF–NaF–KF (46.5-11.5-42)	**454**	**6.8**	**12.7**	**21.2**	**31.1**	RIAR, VNIITF, 2013

Actinides solubility in FLiNaK



Consequences

- The extremely high PuF_3 solubility in FLiNaK allows to combine three ideas:

  liquid nuclear fuel;

  fast neutron spectrum;

  U-Pu fuel cycle.

- This experimental fact opens the way for the development of the fast molten salt reactor with the closed U-Pu fuel cycle as well as the effective reactor-burner of Am.

- In the case of success U-Pu FMSR can solve the main problems of the contemporary nuclear power.

Fast molten salt reactor with U-Pu fuel (U-Pu FMSR)

Power, *MWth*	3200
Volume, m^3	21,2
Specific power, W/cm^3	150
Average neutron flux, $cm^{-2}s^{-1}$	10^{15}
Initial fuel loading U/Pu/Am, Cm, *tons*	68,5/ 15/ 0
Equilibrium fuel U/Pu/Am, Cm, *tons*	68,6/20,9/1,4
UF_4 /PuF_3 equilibrium concentration, *mole %*	21/7
Pu/Am, Cm equilibrium concentration, *mole %*	7,0/ 0,5
Fraction of delayed neutrons, β%	0,34
Void coefficient, $dk_{ef}/(d\rho/\rho)$	- 0,06
Temperature coefficient $[d\,k_{ef}/(d\rho/\rho)]\cdot[(d\rho/\rho)/dT]$, K^{-1}	$-2,4 \cdot 10^{-5}$

Transition of U-Pu FMSR to the equilibrium mode

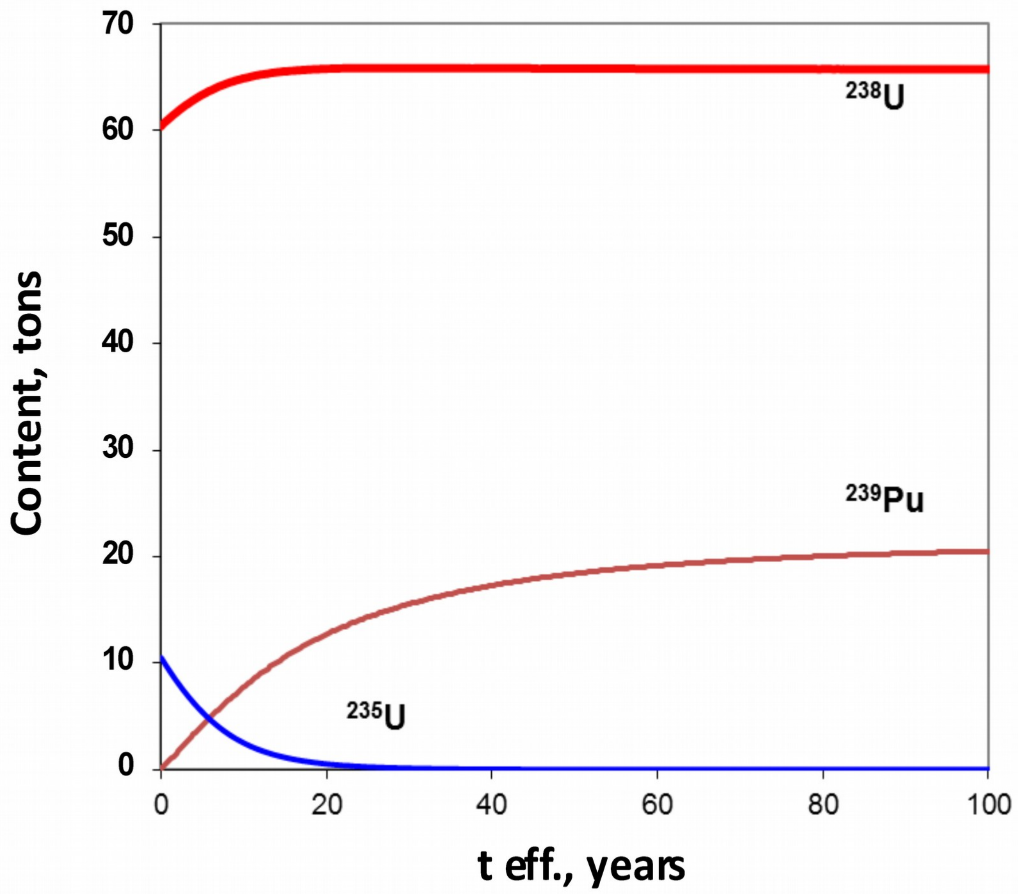
- In the equilibrium mode the Pu production rate is equal to the rate of its burning, i.e. reactor consumes ^{238}U **only.**
- The initial loading:

$0.13\ ^{235}U + 0.87\ ^{238}U$.

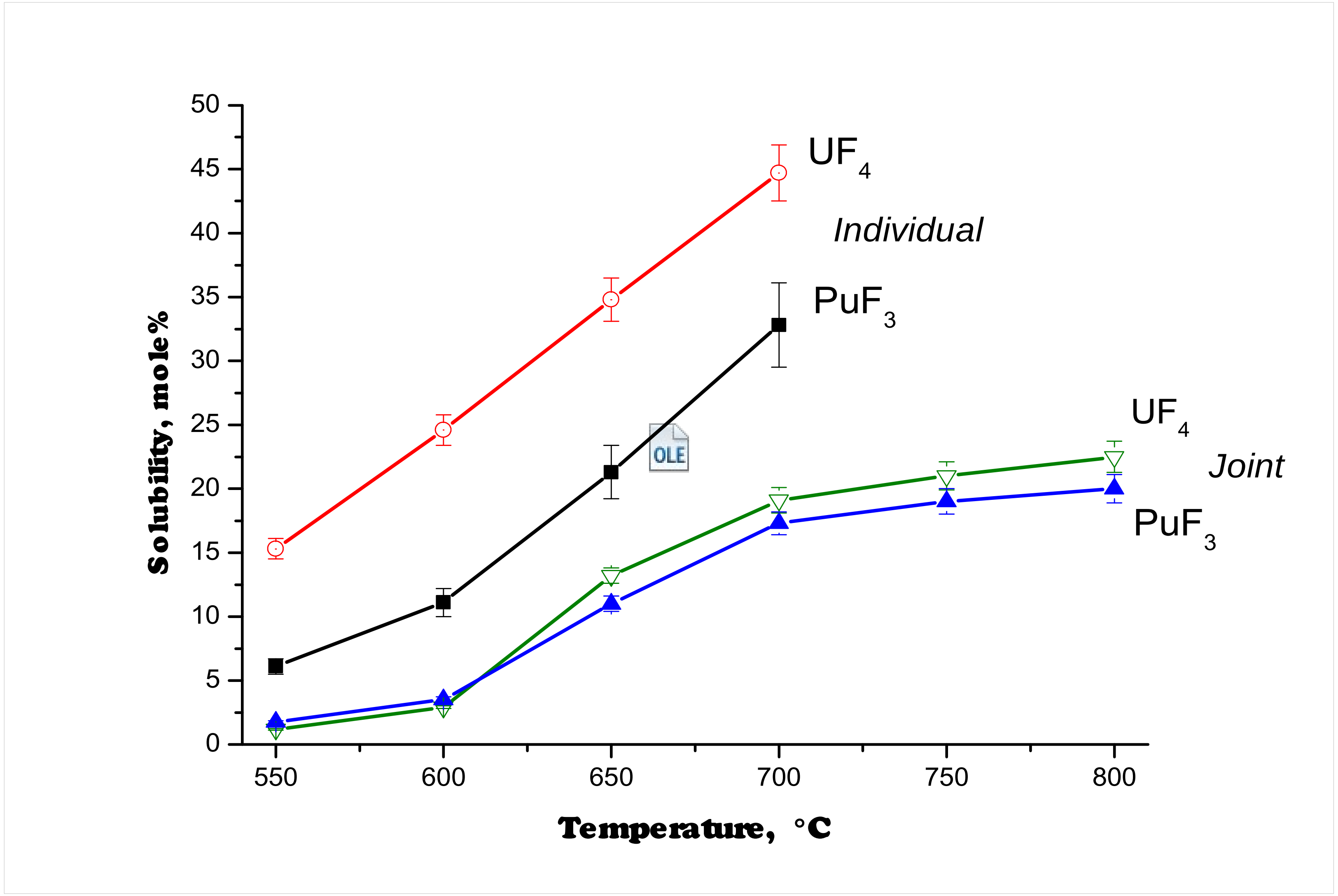
- **Equilibrium fuel:**

UF_4 – 22 mole %,

PuF_3 - 7 mole %.



Joint solubility of UF_4 and PuF_3



Parameters of FMSR vs the lead cooled FR

Parameter	FMSR	BREST-1200
Reactor power W_b, *MWth*	3200	2800
Full loading U/Pu/MA, *t*	68.6/21/1.4	60/5.7
UF_4, *mole* %	21	-
MAF_3, *mole* %	7	-
Specific power, *W/cm*^{3}	150	143
Volume of reactor V, *m*^{3}	21.2	19.5
Radius/height of reactor, *cm*	150/300	238/110
Effective fuel density, *g/cm*^{3}	3.1	3.4

Minor actinides incineration

- There are no problems with minor actinides in U-Pu FMSR:
  the concentrations of Np, Am and Cm do not exceed 0.4 mole %;
- There are problems with minor actinides in the spent fuel storages: one year spent fuel production of one 1GWe power plant after 30 year storage contains ~ 20 kg Am. All the world spent fuel (~ 300 000 tons) contains ~ 6 000 tons of Am.
- Due to the extremely high solubility of AmF_3 in LiF-NaF-KF
  U-Pu FMSR-burner based on FLiNaK can solve effectively
  the problem of Am incineration from the spent fuel storages.

FMSR MA-burner

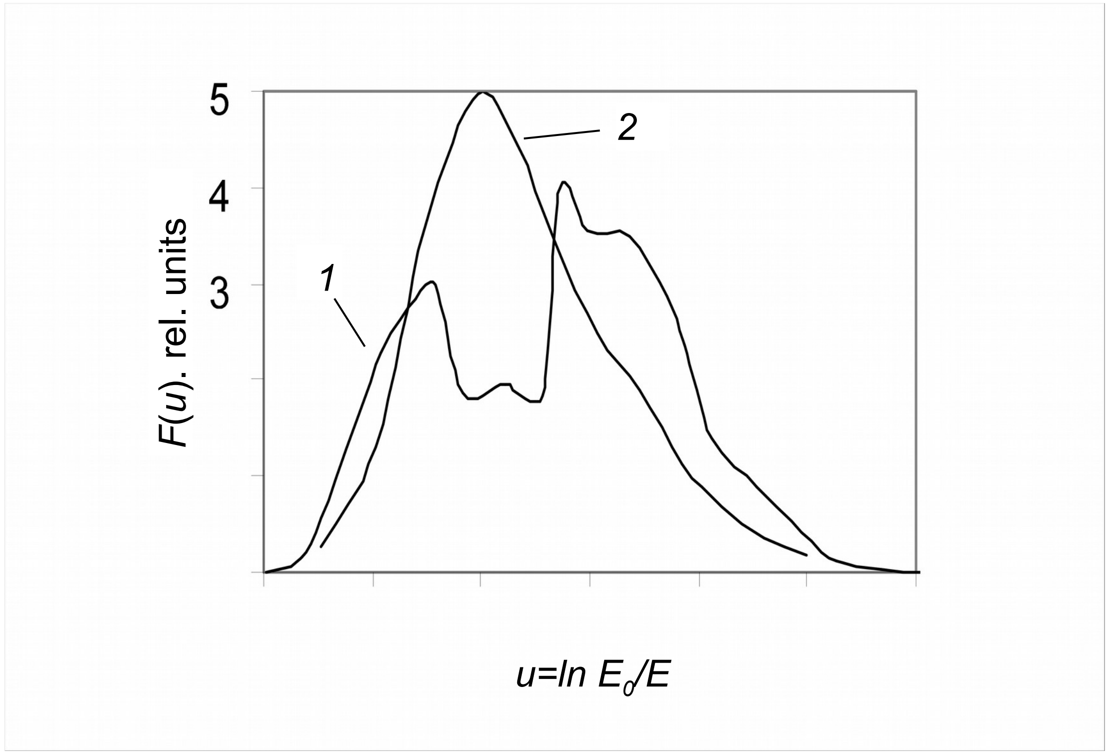
Using the new results on the solubility PuF_3 and AmF_3 the calculations of the subcritical MSR-burner have been performed.

Efficiency:
q_{Am} ~ **300** kg Am/year·GWth;

Pu consummation:
$\varepsilon = Pu / Am \approx \mathbf{0}$;

Transmutation time:
$\tau = Q_{Am}/q_{Am} \approx$ **20** years;

Q_{Am} is *Am* mass in the equilibrium mode.



1 – neutron spectrum by MSR-burner;
2 – neutron spectrum by fast reactor.

Parameters of FMSR-burner

Power, *MWth*	1650	495
Accelerator power, *MW* [a]	10	3
Subcriticality, Δk [b]	0.01	0.01
Average neutron flux, $cm^{-2}\cdot s^{-1}$	$2.2\cdot10^{15}$	$2.2\cdot10^{15}$
Height /radius, *m*	1.74/0.94	1.16/0.63
Fuel salt loading, m^3	8.27	2.48
active core	4.74	1.42
first loop	3.3	1.0
regeneration loop	0.2	0.06
Transuranium part, *mole %*	14	14
Fuel loading total, *tons*	10.7	3.21
U/Np/Pu/Am, Cm	0.05/0.01/5.26/5.39	0.014/0.003/2.31/1.61
Pu/Am, Cm: loading	0.975	1.75
feeding	0.	0.59
Rate of Am burning, *kg/year*	520	98
Normalized rate burning, *Am kg / year·GWth*	~300	~200
Time of the initial loading burning, τ_{in}, *years*	21	33

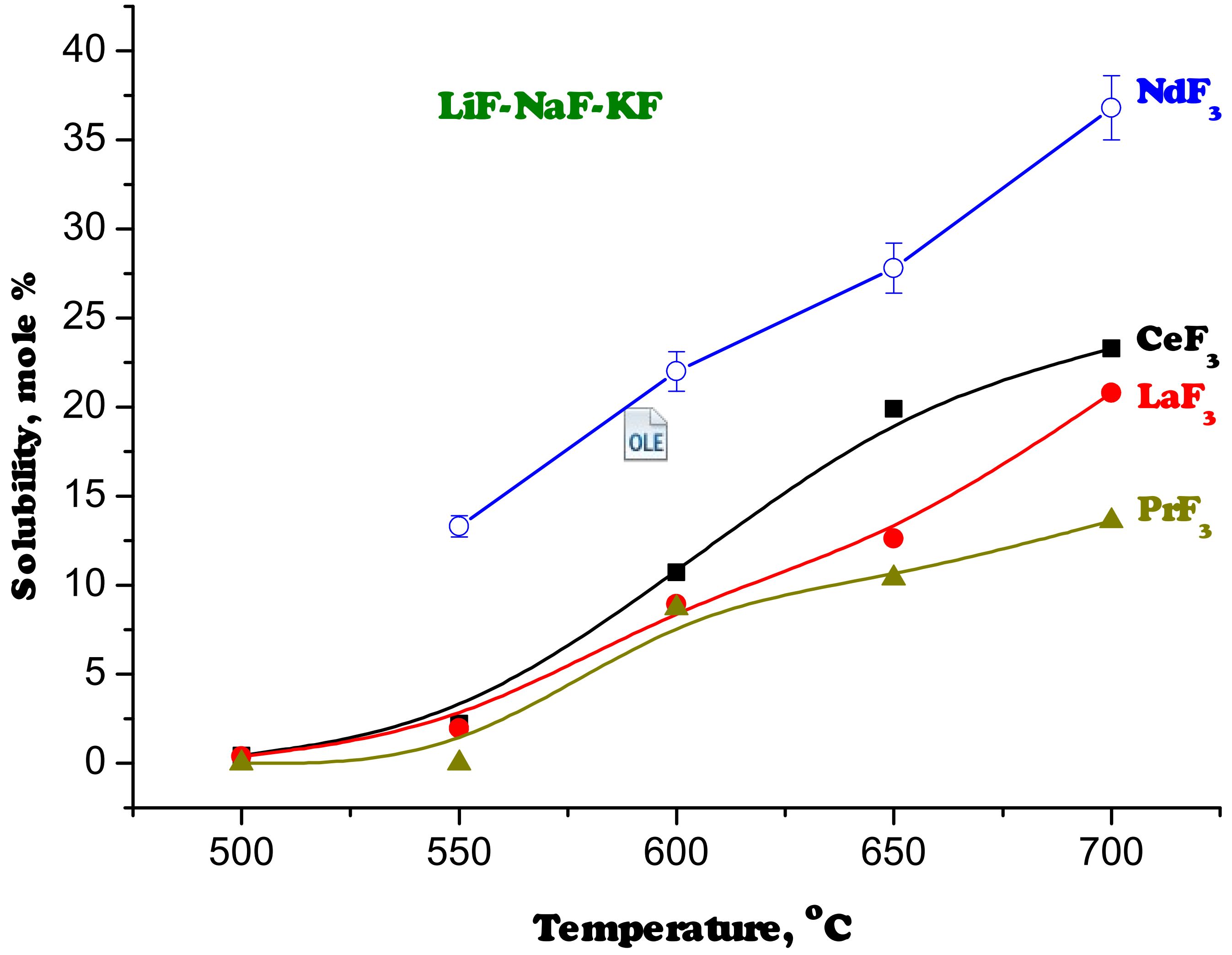
[a] The neutron multiplication is ≈ 20.

[b] At the subcriticality Δk = 0.03 the accelerator power is 3 times more.

Fuel composition of U-Pu FMSR (at. %)

Element	U-235 Initial loading	Pu initial loading	Equilibrium concentration		
F	64.47	63.80	63.78	Am (total)	0.10
^{7}Li	12.39	12.26	11.85	^{241}Am	0.060
K	11.19	11.07	10.71	^{242m}Am	0.003
Na	3.06	3.03	2.93	^{243}Am	0.037
U (total)	8.89	7.91	7.65	Zr	0.09
^{234}U	-	-	0.008	Nd	0.08
^{235}U	1.32	-	0.002	Ce	0.06
^{238}U	7.57	7.91	7.631	Cm (total)	0.06
Pu (total)	-	1.936	2.41	^{244}Cm	0.034
^{238}Pu	-	0.032	0.053	^{245}Cm	0.011
^{239}Pu	-	1.264	1.112	Sr	0.05
^{240}Pu	-	0.463	0.963	Cs	0.04
^{241}Pu	-	0.069	0.149	Pr	0.03
^{242}Pu	-	0.108	0.133	Sm	0.02
^{237}Np	-	-	0.01	La	0.02
Ba	-	-	0.12	^{231}Np	0.01
Total	100	100	-		100

Lanthanides solubility in FLiNaK



Co-precipitation of U and Nd from LiF-NaF-KF

Element		Na_2O stoichiometry to total amount of metals, %		
	Ref. in FLiNaK (mole %)	80 precipitation, %	200 precipitation, %	800 precipitation, %
U	1.57	45	84	72
Nd	2.06	85	97	97

Fuel cycle closing

The method of the actinide and lanthanide oxides co-precipitation with stoichiometric Na_2O stress:

$$UF_4 + 2\ Na_2O \rightarrow UO_2 + 4\ NaF;$$

$$2\ NdF_3 + 3\ Na_2O \rightarrow Nd_2O_3 + 6\ NaF$$

was suggested for the U-Pu FMSR hot spent fuel cleaning from lanthanides.

FMSR fuel cycle economics evaluation

- Due to the absence of solid fuel elements fabrication and utilization the price for the fuel cycle closing can be reduced by 3-4 times.
- The amount and price of the construction elements burial are reduced several times.

Main publications of U-Pu FMSR conception

Degtyarev, A.M. and Ponomarev, L.I. (2012) "LiF-NaF-KF Molten salt reactor with a fast neutron spectrum", Atomic Energy, vol. 112(6), pp. 451-453.

Degtyarev A., Myasnikov A., Ponomarev L. (2015) "Molten salt fast reactor with U-Pu fuel cycle", Progr. Nucl. Energy, vol. 82, pp. 33-36.

Ponomarev L.I. and Fedorov Yu.S. (2015) "U-Pu Fast Molten Salt Reactor and its Fuel Cycle", Proc. GLOBAL-2015, Sept.20-24, 2015, Paris, France, paper 5336.

Degtyarev A.M., Kolyaskin O.E., Myasnikov A.A., Ponomarev L.I., Karmanov F.I., Seregin M.B., Sidorkin S.F. (2013) "Molten salt subcritical transplutonium actinide incinerator", Atomic Energy, vol. 114 (4), pp. 225-232.

Problems of U-Pu FMSR

The problems of U-Pu FMSR are common to all MSR ones:

- Safety and maintenance need the special attention and probably the revision of safety criteria developed for the solid fuel reactors;
- The new construction materials resistant to the fast neutron irradiation and corrosion with the fuel composition at high temperature ~700˚C should be developed.
- All these problems are common also for all MSR projects with Th-U fuel, and the years of experience in this field could be (and must be) used in U-Pu FMSR development.

Задачи

- Расчёт равновесного режима U-Pu БЖСР с топливом из хранилищ ОЯТ.
- Расчёт подкритического БЖСР-сжигателя Am без мишени.
- Выбор схемы теплоотвода и тепло-гидравлический расчёт БЖСР.
- Исследование диаграммы состояния топливной композиции FLiNaK-UF_4-PuF_3.
- Измерения режимов растворимости смеси UF_4-PuF_3 в LiF-NaF-KF.
- Измерения растворимости PuF_3 в эвтектике 0,504NaF-0,216KF-0,280UF_4 (T_m 490˚C).
- Разработка схемы переработки горячего ОЯТ БЖСР.

Спасибо!