MSR in Generation-IV

Delft, July 4-5, 2019
Final SAMOFAR meeting

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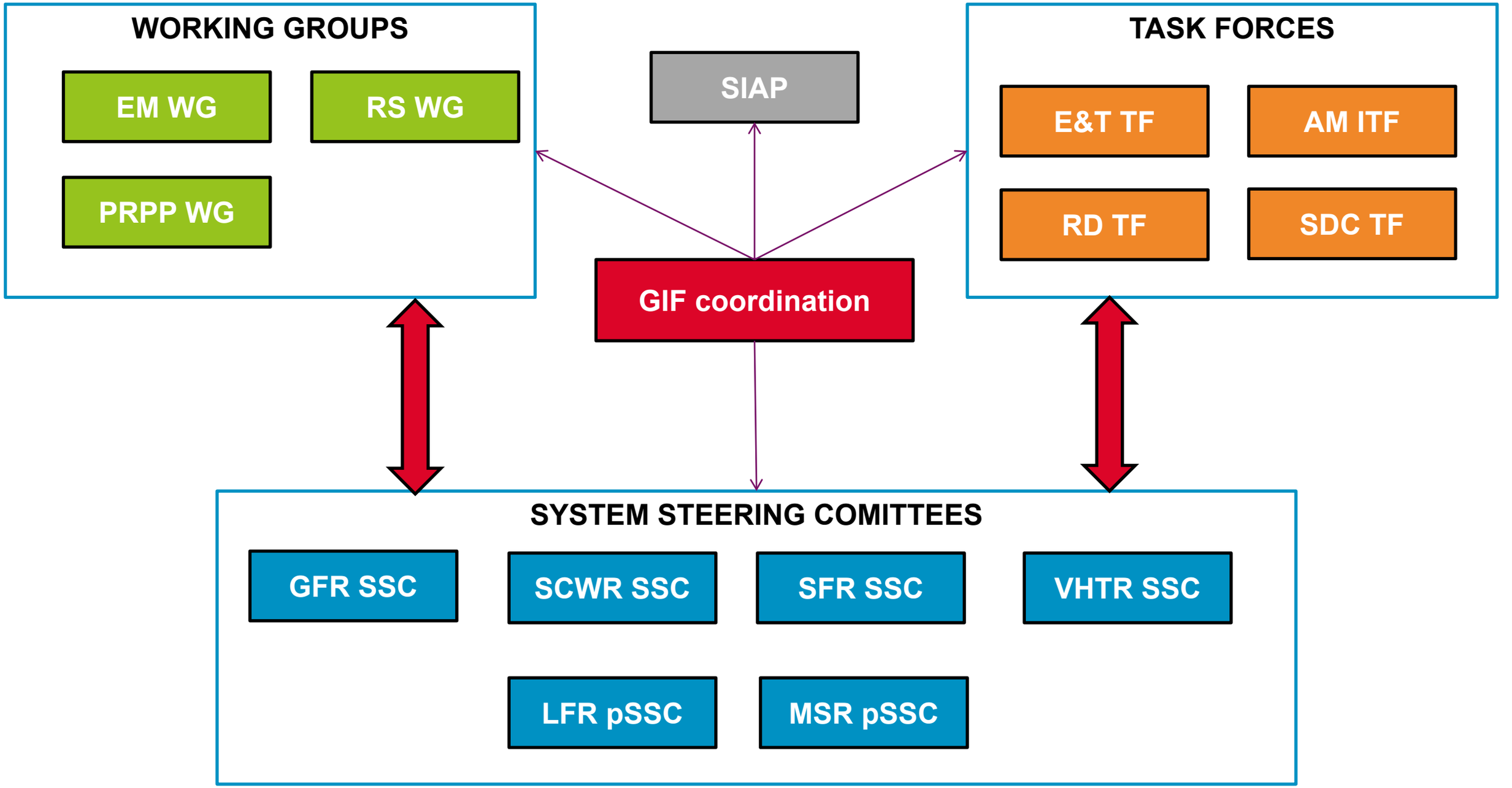
INTRODUCTION

GEN IV FORUM ORGANISATION



GIF members' involvement in Gen IV systems R&D

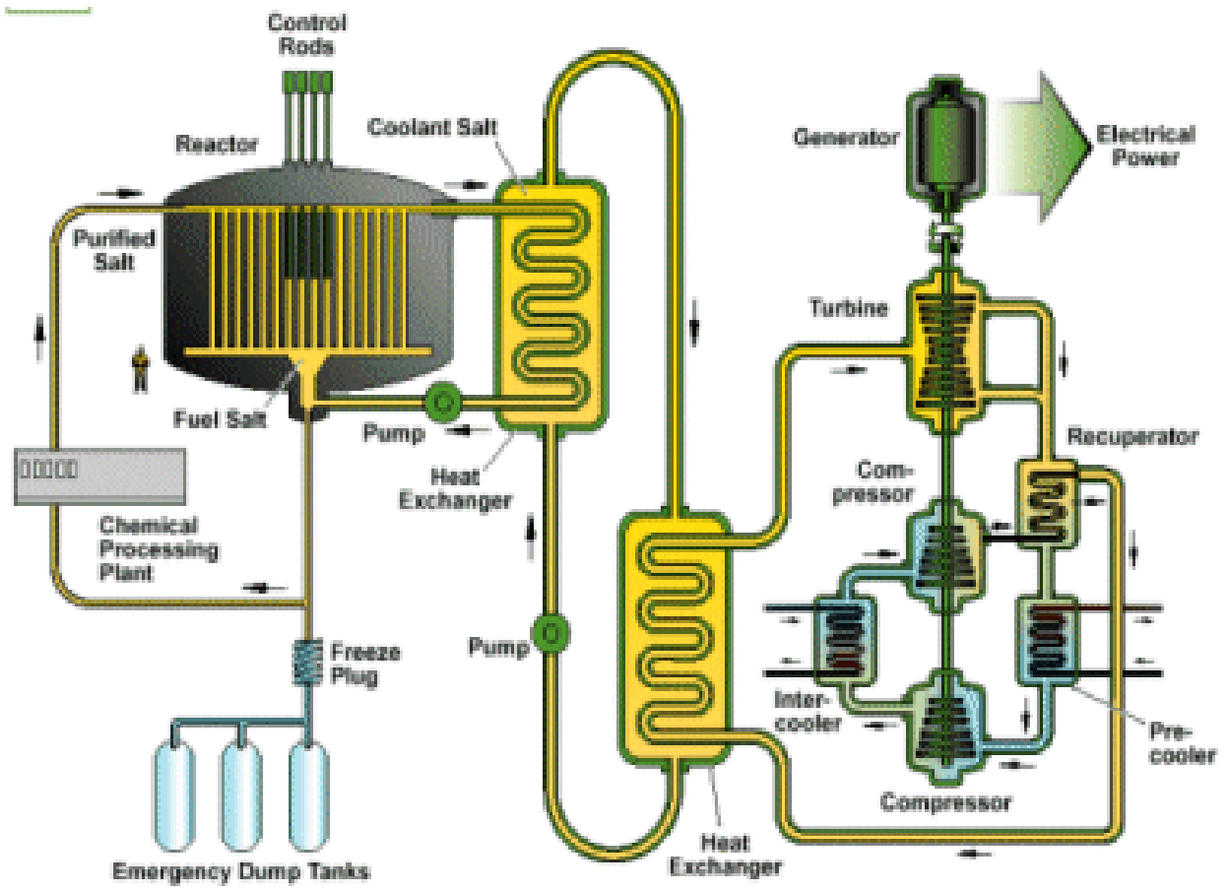
SFR			●	●	●	●	●			●	●	●
VHTR	●	●	●	●	●	●			●	●	●	●
LFR					●	●	●			●		●
SCWR		●	●		●		●					●
GFR				●	●							●
MSR	●	●		●			●		●	●		●

Within the GIF, research is performed on the MSR concepts, under the MOU signed by Australia, Canada, Euratom, France, Russian Federation, Switzerland and USA.
China, Korea, Japan are observers

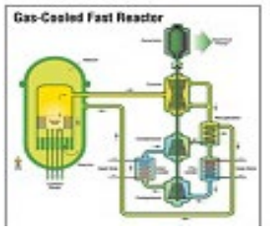
MSR definition and attractivity

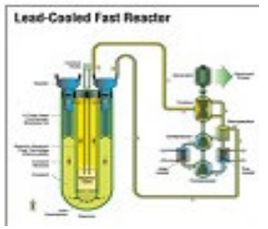
The MSR:

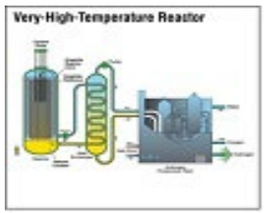
- Uses molten salt as fuel and coolant
- Can reuse fuel from LWR, or burn MA and Pu
- Has increased power conversion efficiency,
- Is operated at low pressure
- Is ackowledged for its passive safety features
- Can be deployed at large scale or as SMR
- Can be operated as a flexible system



The challenge faced by the GEN IV MSR systems







Liquid Fuel MSR

- Thermal
  - U
    - Fluoride
      - Terrestrial Energy IMSR
        Thorcon
        SINAP TMSR-LF1
  - Th/U233
    - Fluoride
      - SINAP TMSR
        Flibe Energy LFTR
- Fast
  - U/Pu
    - Chloride
      - TerraPower
        Elysium MCSFR
    - Fluoride
      - VNIINM FMSR
  - TRU
    - Chloride
      - MOLTEX
    - Fluoride
      - KI MOSART
  - Th/U233
    - Fluoride
      - EURATOM MSFR
        KI MOSART
        BARC IMSBR

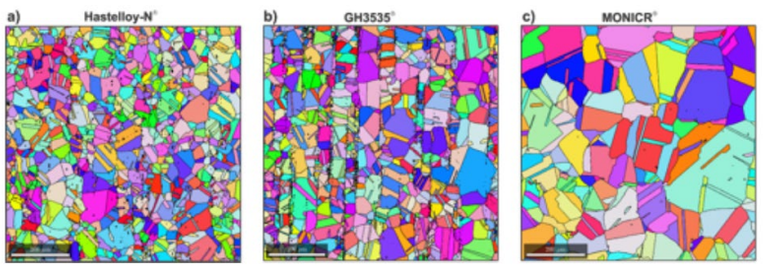
ACTIVITIES

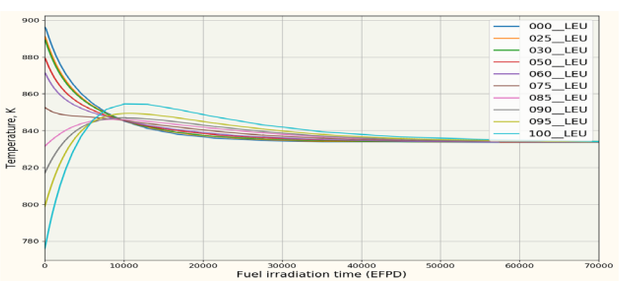
MSR – Past Results

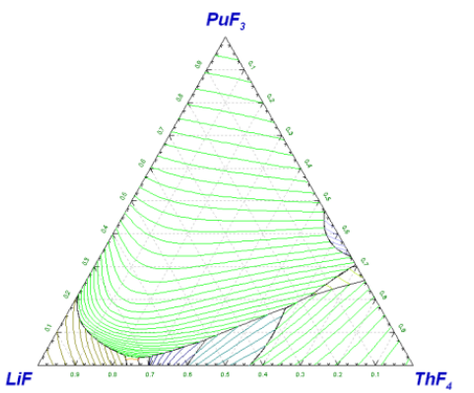
Mainly basic and concept studies

- **Mapping of the different concepts**
  - Fast/thermal, chloride/fluoride
- **Safety**
  - MSR Risk and Safety Assessment White Paper
- **Materials**
  - Advanced alloys
  - Corrosion studies
- **Salts**
  - Physico chemical data acquisition
- **Computational**
  - Neutronics
  - Thermal hydraulics
  - Safety

- Design definition (core and draining system at least)
- Development of simulation tools dedicated (more generic)
- Definition of the normal operation procedures
- Safety evaluation: accident initiators? Accident scenarios?
- Safety approach: severe accident? Barriers? Reactivity control?







MSR – Future R&D Activities

Baseline design of molten salt reactor (liquid fuel)

- Salt and material combinations
- Integrated (physics and fuel chemistry) reactor performance modelling and safety assessment capabilities
- Demonstration of the MSR safety characteristics at laboratory level and beyond
- Establishment of a salt reactor infrastructure and economy that includes affordable and practical systems for the production, processing, transportation, and storage of radioactive salt constituents
- MSR safety approach, licensing and safeguard framework

A key challenge: Constraints on the choice a salt combining reactor, processing and safety requirements

- Melting temperature, volatility, density…
- Corrosion
- Stability domain
- Neutronics
- Actinides and FP solubility
- Behaviour under irradiation
- Interaction with air/water
- Toxicity
- (re)processibility
- Availability/cost

Safety issues!!!

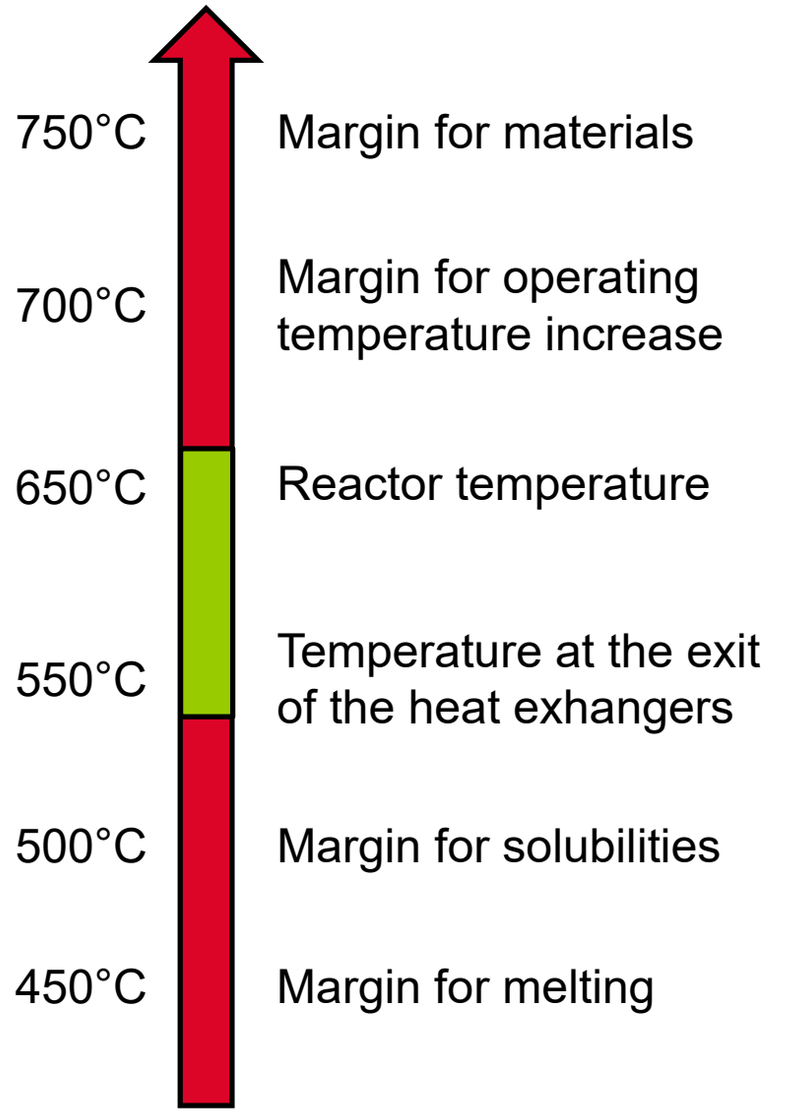


Table 2. Solubilities of PuF_3 and UF_4 in the FLiNaK salt system

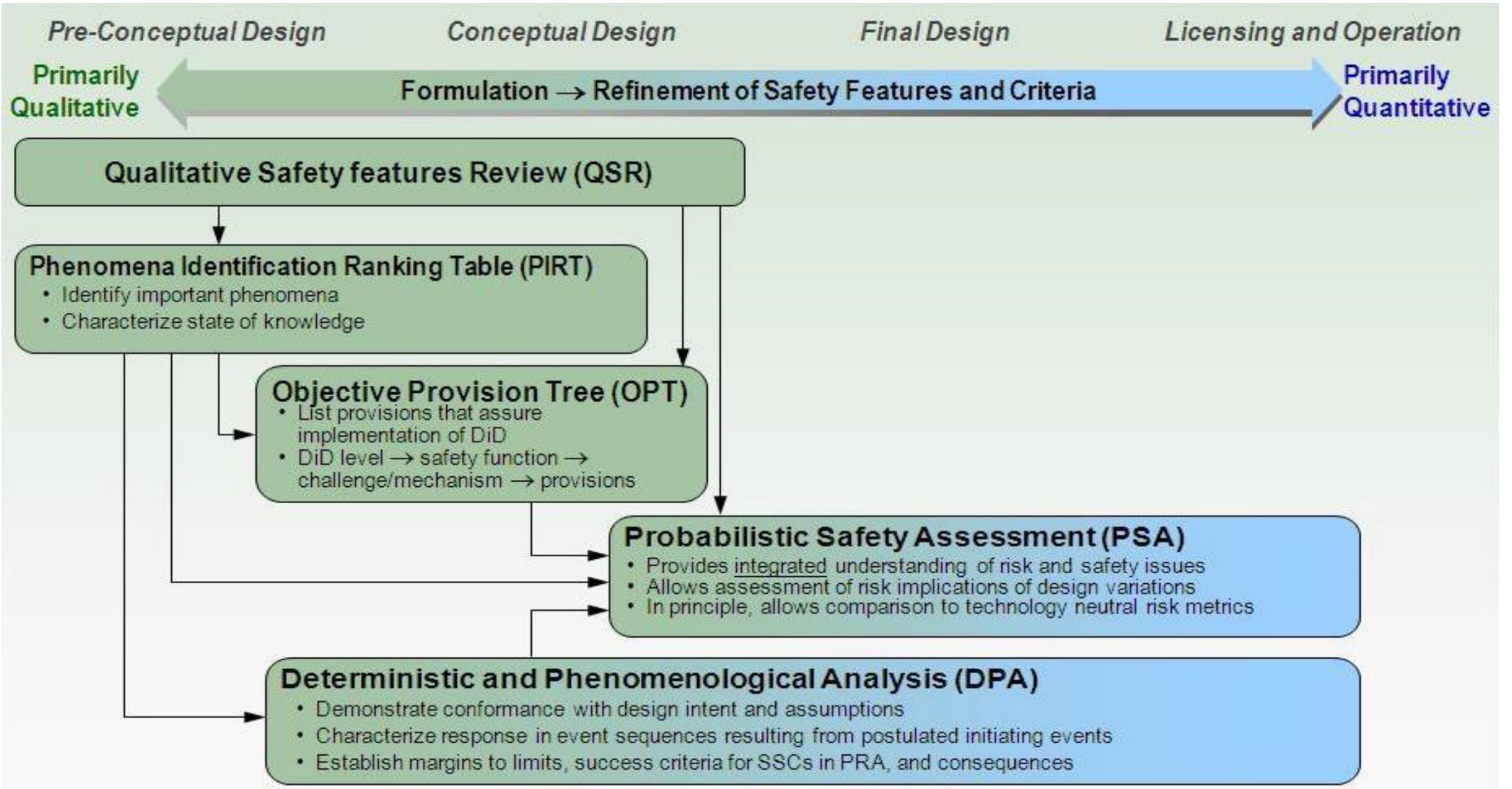
Melting 454°C, (727K)

Temperature, K	Individual solubility [4, 5], mol %		Joint solubility, mol %	
	PuF_3	UF_4	PuF_3	UF_4
550°C 823	6.1 ± 0.6	15.3 ± 0.8	1.16 ± 0.14	1.75 ± 0.26
600°C 873	11.1 ± 1.1	24.6 ± 1.2	2.9 ± 0.3	3.5 ± 0.5
650°C 923	21.3 ± 2.1	34.8 ± 1.7	13.2 ± 1.6	11.0 ± 1.6
700°C 973	32.8 ± 3.3	44.7 ± 2.2	19.1 ± 2.3	17.3 ± 2.6
750°C 1023	No data	No data	21.0 ± 2.5	19.0 ± 2.8
800°C 1073	No data	No data	22.5 ± 2.7	20.0 ± 3.0

UPDATE ON RISK AND SAFETY WORKING GROUP (RSWG) ACTIVITIES

MSR Contribution

GIF Integrated Safety Assessment Methodology (ISAM) Task Flow



Fluid-Fueled MSRs Provide Unique Challenges to Safety Evaluation

1. High boiling point (low pressure)
2. Potentially highly corrosive behavior
   - Compatibility of salts with reactor materials (at high temperatures and radiation conditions)
3. High melting point
4. Large volumetric heat capacity
5. Significant quantities of fuel outside the reactor core
   - Heat exchanger, various tanks, pumps, possible associated fuel processing, possible continuous addition/removal of fuel
6. Distributed delayed neutrons (mobile fuel)
7. Noble gas fission products evolve out of the salt into cover gas; noble metal fission products plate out onto surfaces; fuel salt retains most other fission products
8. Salt vapor deposition in cover gas lines
9. Potential for larger volumes of high activity components (filters and replaced components)
10. Fuel composition continuously changing
11. Fuel performs cooling function
12. Strong prompt negative reactivity feedback with increasing temperature for most designs
13. Tritium production (lithium fuel salts)
14. Presence of bubbles (fission product gasses) passing through the core

MSRs Will Require a Significant Change in Current Regulations and Guidance

- Revision of Advanced Reactor Design Criteria
  - Currently underway as part of ANS 20.2
- Adaption of the LWR or BN Standard Review Plans
- System descriptions and functions will need to be revised
  - Allocation of safety functions will need to be revisited
- Accident sequences and initiators will be unique
- Categorization/classification of equipment
- Fuel qualification
- Mechanistic source terms
- Which regulations apply where? 10 CFR 50, 10 CFR 70, or combinations of both
  - MSR-specific safeguards regulations will also need to be established
- Others will be identified as the MSR designs progress

Update on Proliferation Resistance and Physical Protection (PR&PP) Working Group Activities

MSR Contribution

Objectives of PRPP Working Group

- Facilitate introduction of PRPP features into the design process at the earliest possible stage of concept development
- Assure that PRPP results are an aid to informing decisions by policy makers in areas involving safety, economics, sustainability, and related institutional and legal issues

"Generation IV nuclear energy systems will increase the assurance that they are a very unattractive and the least desirable route for diversion or theft of weapons-usable materials, and provide increased physical protection against acts of terrorism."

PR&PP Methodology Paradigm

CHALLENGES → **SYSTEM RESPONSE** → **OUTCOMES**

Threats

PR
- -Diversion/misuse
- -Breakout
- -Clandestine facility

PP
- -Theft
- -Sabotage

PR & PP

Intrinsic
- Physical & technical design features

Extrinsic
- Institutional arrangements

Assessment

Measures and Metrics

Paradigm is consistent with standard approaches to safety assessment

Status of White Paper Update
Timeline SSCs-PRPPWG Interaction

MSR	Circulating Fuel	MSFR, MOSART, MCFR, etc.	There is a wide variety of MSR technologies, encompassing thermal/fast spectrum reactors, solid/fluid fuel, burner/breeder modes, Th/Pu fuel cycles, and onsite/offsite fissile separation.
		Dual Fluid Reactor	
	Fixed Fuel	Fuel in tubes: Stable Salt Reactor	
		Solid Fuel: TMSR-SF1, Kairos	
	Replaceable Core	IMSR	

MSR – completely new material from the pSSC; created first draft of an update white paper to group design tracks into 3 system options; will send feedback to pSSC after internal review of the draft.

- 2016 Preparation of the Questionnaire
- 2017, April, Workshop with SSCs and PRPPWG, OECD-NEA, Paris. (Internal report with replies to the questionnaire)
- 2017, October, PRPPWG meeting in ISPRA with session LFR & MSR (meeting report, with records of the session)
- 2018, October PRPPWG meeting in Paris with session with SSCs and pSSC (meeting report, with records of the session)
- 2019 Work in progress
- 2020 Finalization

EMWG – SIAP – SSC
Workshop on Flexibility
MSR Contribution

Operational Flexibility (1/2)

- **Maneuverability**
  - *The first MSR concepts were designed to power aircrafts. To prove this concept, the HTRE projects were established. The absence of Xenon poisoning allows high levels of flexibility in the primary circuit. Most of the flexibility limits from an operational point of view come from the steam cycle. Data on flexible operation over a 24-hour cycle is not available at this stage of design.*

- **Ramp rates**
  - *Around 10% minimum*

- **Minimum Power Level**
  - *Around 20%. This operational limit is imposed by the steam cycle.*

- **Primary frequency control**
  - *In principle, yes*

- **Power modulation**
  - *This information is not available at this stage of design.*

- **Is the operational flexibility validated through multi-dimensional physics calculations?**
  - *No*

Operational Flexibility (2/2)

- **Are the reactor designs in your SSC, compatible for integration with hybrid systems with energy storage, topping cycles and/or co-generation using thermal energy? Are there any analyses performed for dynamics of power conversion system?**
  - *The MSR is compatible with hybrid system (e.g. thermal storage of the salt) however, given the early stage of the design, dynamic analyses of power conversion have not been performed yet.*

- **Are there specific R&D being done to address material and component degradation resulting from flexible operation of reactor and power conversion system?**
  - *Not for now but it could be planned.*

- **Describe fuel flexibility aspects of reactor designs in your SSC. Are alternate fuels being considered?**
  - *Liquid fuels provide inherent flexibility capabilities, especially due to the absence of Xenon poisoning. Many different types of fuels cycles can also be considered.*

- **Are the reactors capable of operation in island mode; isolated from regional grid network?**
  - *Yes.*

Deployment Flexibility (1/1)

- **Describe the deployment flexibility aspects of reactor designs in your SSC. Specific questions to consider while describing your systems are as follows.**
  - *Deployment flexibility can be achieved thanks to different reactor sizes and power outputs.*

- **How scalable are the reactor designs? What is the minimum feasible size and maximum size in terms of power output?**
  - *MSR concepts range from 1 MWt to 1-2 GWt The minimum feasible size is 1 MW*

- **Are there any specific siting requirements, considering emergency planning zone, improved safety (underground construction, passive cooling etc.)?**
  - *MSR have similar siting requirement than other Gen IV concepts. Not specific requirements for MSR have been identified.*

- **Are the reactor components, systems amenable to factory fabrication to reduce on-site construction/assembly work?**
  - *Yes, as any other SMR concept, it has potential for improved constructability.*

Product flexibility (1/1)

- **Describe the product flexibility of the reactors designs under development within your SSC?**
  - *MSR reactors can provide both electricity and heat. The heated salt could be also used for thermal storage applications.*

- **Does the reactor design enable additional process heat applications that are not possible with currently deployed reactors? What is the maximum temperature at which the process heat can be supplied to potential industrial user? Are the equipment for heat transfer included in the R&D/design effort? Are there any specific process heat applications (e.g. hydrogen production already identified). Are the reactors capable of producing specific medical or industrial isotopes based on the neutron flux in the reactor core?**
  - *MSR is the Gen IV concept with the highest exergy which means that it can provide high quality heat for industrial application and hydrogen production (i.e. IMSR). The output temperature ranges 600-700°C. Heat transfer components are part of the R&D effort. MSR can also be use for radioisotope production or even as a burner depending on the neutron spectrum (i.e thermal or fast)*

UPDATE ON R&D INFRASTRUCTURE TASK FORCE (GIF RDTF) ACTIVITIES

- Created by the GIF Policy Group in 2017
- Objectives to be accomplished in less than 2 years
- Identify essential large experimental infrastructure needed in support of GEN IV systems R&D activities in terms offeasibility/performance as well as demonstration/deployment.
- Facilitate R&D collaboration across GEN IV systems.
- Promote utilization of experimental facilities for collaborative R&D activities among GIF partners. Facilitate GIF partners' access to the various R&D facilities in the GIF member countries.
- The GIF-RDTF will rely on the GIF Member State's, IAEA' frs and NEA's relevant work in the areas of:
- R&D needs Outlook(s) along with R&D inastructures, databases, reports, compendium and International Cooperation initiatives (e.g. IAEA CRPs, ICERR, NEA Joint Projects, NEST, NI2050, EURATOM Collaborative Projects and so on)

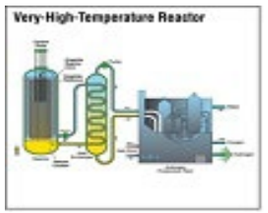
MSR SSC Infrastructure Gaps

The MSR development needs for the 2018 + 10 years period can be expressed in terms of the following grand challenges

- **Identifying, characterizing, and qualifying**
  - successful salt and materials combinations for MSRs.
- **Developing integrated reactor performance modeling and safety assessment capabilities**
  - that capture the appropriate physics and fuel chemistry needed to evaluate the plant performance over all appropriate timescales and to license MSR designs.
- **Demonstrating the safety characteristics of the MSR at laboratory and test reactor levels.**
- **Establishing a salt reactor infrastructure and economy**
  - that includes affordable and practical systems for the production, processing, transportation, and storage of radioactive salt constituents for use throughout the lifetime of MSR fleets.
- **Licensing and safeguards framework development to guide research, development and demonstration.**

TOWARDS A SYSTEM ARRANGEMENT

The challenge faced by the GEN IV MSR systems



Thermal

Liquid Fuel

U

233

Requires transversal Project Arrangements

Fluoride

Chloride

Fluoride

Fluoride

Terrestrial
Th
SINAP T
LF1

MSR
Flibe Energy LFTR

VNIINM FMSR
MOLTEX Energy

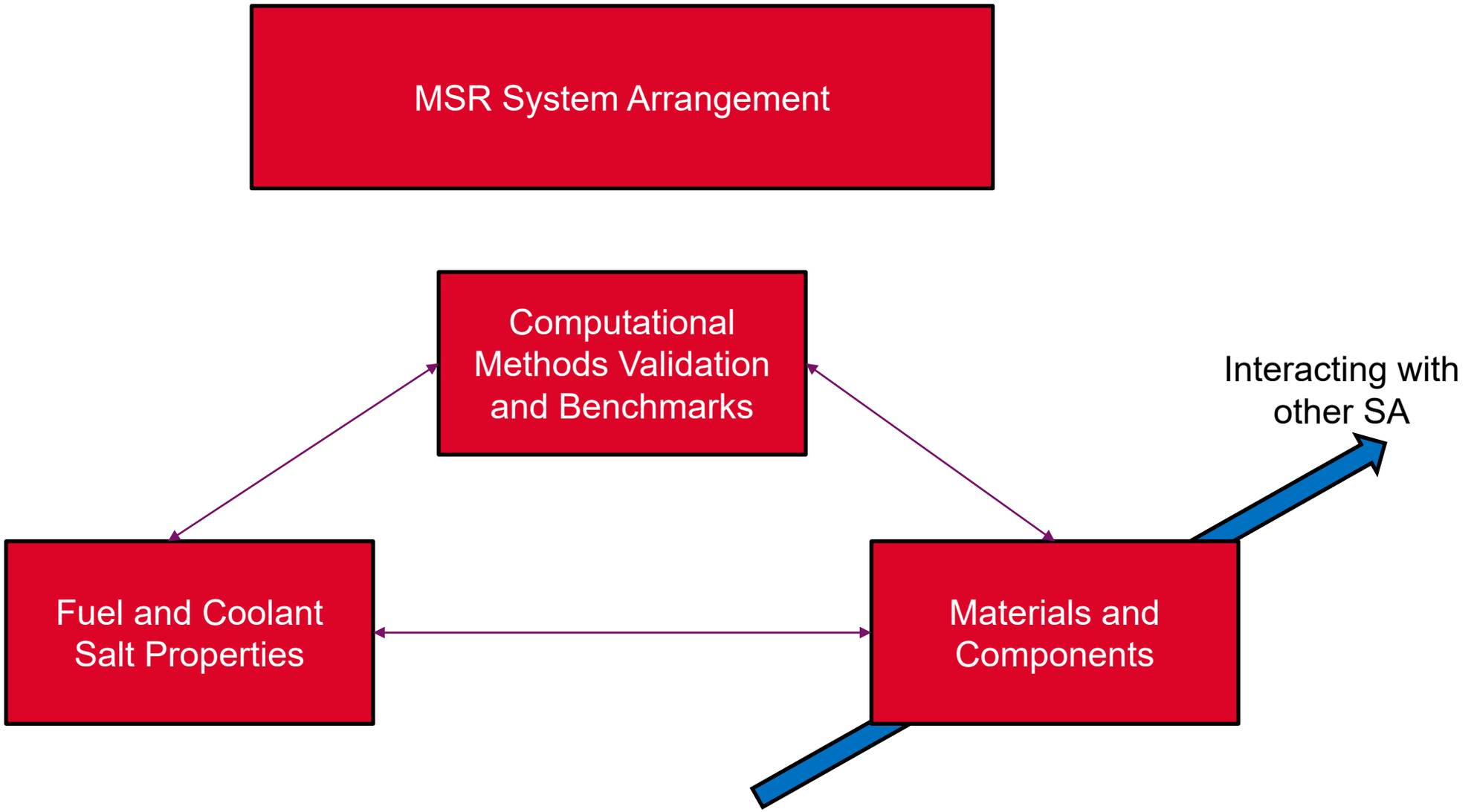
KI MOSART

TerraPower
Elysium MCSFR

Moltex

EURATOM MSFR
KI MOSART
BARC IMSBR

Organisation



PA 1 - Computational Methods Validation and Benchmarks

Task	Title	Sub-tasks to be considered	
1.1	Phenomena Identification and Ranking Table (PIRT)	Task 1.1 Task 1.2	Consolidation of PIRTs on Thermo-Fluid and Safety Behavior Consolidation of PIRTs on Chemistry and Transport
1.2	Multiphysics simulation	Task 2.1 Task 2.2 Task 2.3	Verification and benchmarking of the codes Simulation of selected MSR systems Coupling of thermal-hydraulics with thermo-dynamics
1.3	Reactor core physics and fuel cycle	Task 3.1 Task 3.2 Task 3.3	Verification and benchmarking of the codes Simulation of selected MSR systems Nuclear data evaluation and uncertainties
1.4	Plant dynamics	Task 4.1 Task 4.2 Task 4.3 Task 4.4	Verification and benchmarking of the codes System Studies of the DYNASTY loop experiment, etc. Simulation of selected MSR systems Decay heat removal option for MSR

PA 2 - Fuel and Coolant Salt Properties

	Task	Sub-tasks to be considered
2.1.	Properties of Fuel and Coolant salts	- Experimental validation of relevant data on fuel and coolant salt properties including focus on melting point, vapour pressure, thermal conductivity, heat capacity, density, viscosity, phase behavior of AnF3, oxide behavior in fuel, tritium and PF behavior (solubilities, diffusities etc.) in fuel - Quality assurance plan for the properties investigation - Fuel under extreme conditions - overheating and supercooling - Development of thermodynamic database and uncertainty analysis
2.2.	Retention capacity of Fuel salt	- Systematic studies to investigate retention capacity of the fuel salt with respect to formed fission products with primary focus on volatiles Cs, I, Te and Sr and Ba - Understanding of a fuel salt capacity to serve as a primary barrier
2.3.	Fuel Salt Clean-Up	- Experimental investigation of separation processes and flowsheets for off-line fuel salt clean-up during reactor operation - Experimental investigation of the on-line clean-up scheme
3.4.	Redox control of the Fuel salt	- Investigation of optimal way to measure and control the redox potential of the fuel salt, i.e. inhibit the corrosion of the structural materials

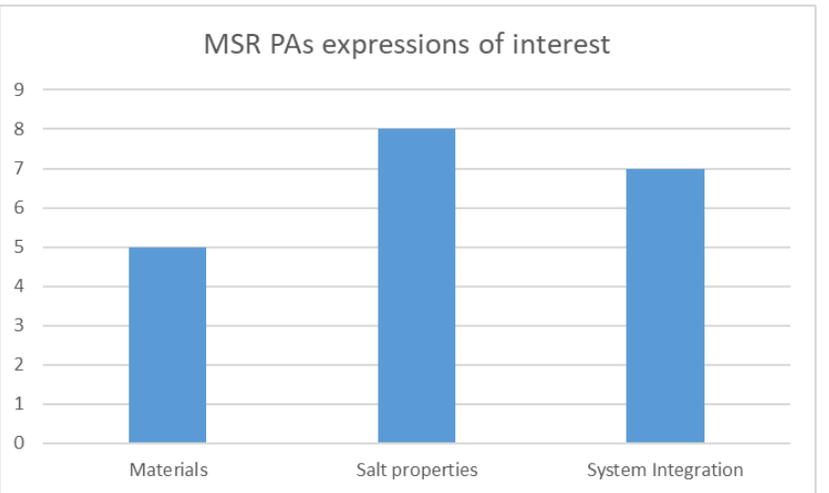
PA 3 - Materials and Components

	Task	Sub-tasks to be considered
3.1	Assessment and evaluation of selected materials and manufacturing methods for the reactor plant and fuel salt processing unit:	- High nickel alloy for primary and intermediate circuits -graphite used for the moderator / reflectors and support structures in the core region - high-temperature control rod cladding and/or guide tube components - ceramic materials for core internals and thermal insulation - graphite, nickel and molybdenum alloys for fuel salt processing unit
3.2	Codification of very-high-temperature mechanical design rules for potential application materials and manufacturing methods. Modeling and description of materials behavior and damage development will provide the basis for codification improvements. This will require information on:	- high-temperature design methodology improvements in structural design methods - materials, components and structure testing and databases - nuclear design codes and standards - high-temperature mechanical properties in potential application salts - environmental degradation processes from exposure to high-temperature salts - long-term irradiation effects on mechanical properties; - high-temperature metallurgical stability (thermal aging effects); - emissivity of the components responsible for passive heat removal - irradiation/corrosion interaction effects (e.g. FP Te intergranular cracking) - advantages/disadvantages

EXPRESSION OF INTEREST

		pSSC Members								Observers				
		Australia	Euratom			France	Russia	US	Switzerland	China	Japan	Korea	Canadian Consortium	
			JRC	TUDelft	CVR								TEI	CNL
L. Edwards	**Materials**	X				X	X						X	X
O. Bennes	**Salt properties**	X	X		X	X	X			X			X	X
J. Krepel	**Computational Methods Validation and Benchmarks**			X		X	X		X		X	X	X	X

- Most of the MSR pSSC members and observers have expressed their interest in the different PAs.
- Interest among PAs is quite “balanced” with « Salt Properties » capturing most of the attention.
- Observers should also join the SA



Conclusion

- 3 transversal project arrangements are under development:
  - Fuel and coolant salt properties – Ondrej BENES
  - Materials and components – Lyndon EDWARDS
  - Computational Methods Validation and Benchmarks– Jiri KREPEL
- The System Research Plan will be updated accordingly
- Canada (TEI) signed the MOU
- Turkey expressed its interest for the MSR system.
- EU SAMOSAFER selected for funding in 2019
- RF MOSART selected for funding in 2019
- White paper on MSR safety published
- Exchange with RSWG for the creation of a task force on MSR safety


THANK YOU