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Testing Activities for Design's Verification and Validation of integral-PWR type SMR Technology Development

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CeSNEF-Nuclear Engineering division



IAEA

International Atomic Energy Agency

Vienna, Austria

First Meeting of the Technical Working
Group on Small and
Medium Sized or Modular Reactor
(TWG-SMR)

IAEA Headquarters, Vienna
23 – 26 April 2018

- ① **Fuel + Integrated components**
(pumps, steam generators, CRDMs, pressurizer)
- ② **Safety systems** (passive, natural circulation, two-phase flow systems)
- ③ **Integral layout:** integration of components + safety systems (+ containment)

Separate Effects Test (SET)

Integral Effects Test (IET)

Main goals:

- i) to test **safety** effectiveness & **performance**
- ii) to **validate codes & models**
- iii) to train & educate

Fuel power	AP1000	NuScale	CAREM	SMART	mPower	WEC-SMR	Holtec
Linear [kW/m]	19	8	11	11	12	14	14
Active length	14ft	6.5ft	4.5ft	6.5ft	8ft	8ft	12ft

standard-based, reduced length, reduced power density

➤ mixed convection heat transfer (CFD)

*“Potential deteriorated turbulent heat transfer (DTHT) when moving from fully turbulent to mixed convection regime: **current correlations** for mixed convection **could be limited**, suitable (anisotropic) turb. models (wall effects) are needed for CFD calculations”*

Wibisono et al. (KAIST), A v^2 -f model assessment for mixed convection in water-cooled SMR configuration, ICAPP 2014

SMR – iPWRs TH investigation & testing: SET facilities

FUEL

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Fuel power	AP1000	NuScale	CAREM	SMART	mPower	WEC-SMR	Holtec
Linear [kW/m]	19	8	11	11	12	14	14
Active length	14ft	6.5ft	4.5ft	6.5ft	8ft	8ft	12ft

standard fuel-based, reduced length, reduced power density

- mixed convection heat transfer (CFD)
- specific CHF and hydraulic testing (fretting)



SMART: CHF test section-freon (FTHEL facility)



NuScale: CHF test section (Stern Labs)

SMR – iPWRs TH investigation & testing: SET facilities

FUEL

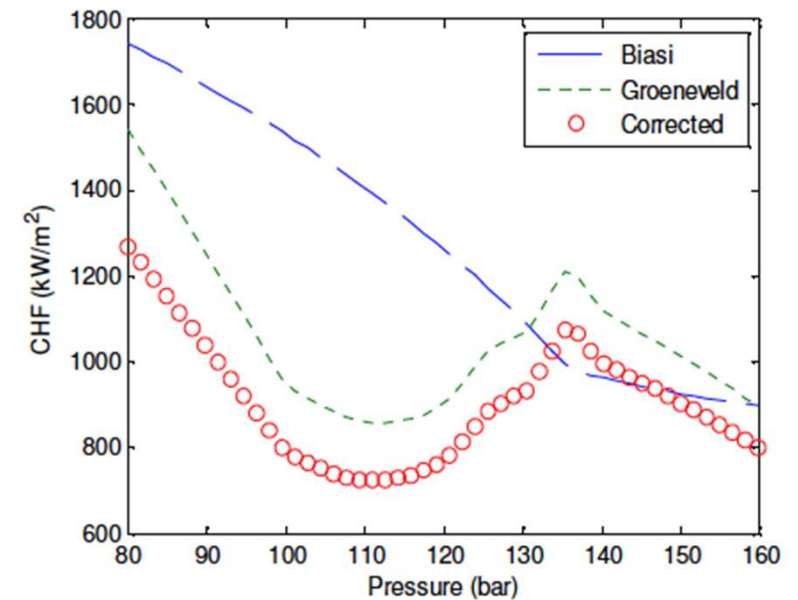
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Fuel power	AP1000	NuScale	CAREM	SMART	mPower	WEC-SMR	Holtec
Linear [kW/m]	19	8	11	11	12	14	14
Active length	14ft	6.5ft	4.5ft	6.5ft	8ft	8ft	12ft



Pressure (bar)	Mass Flux (kg/m ² s)	Inlet Subcooling (°C)
80, 100, 120, 140, 160	100, 450, 800, 1150, 1500	10, 30, 50, 70

Scott, Corradini et al., Study of critical heat flux for a four rod bundle at Small Modular Reactor operating conditions, NURETH15, 2014

SMR – iPWRs TH investigation & testing: SET facilities

FUEL

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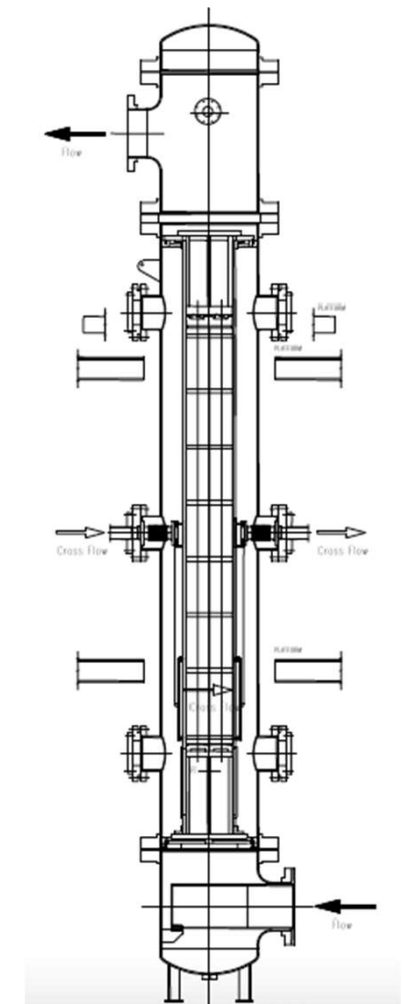
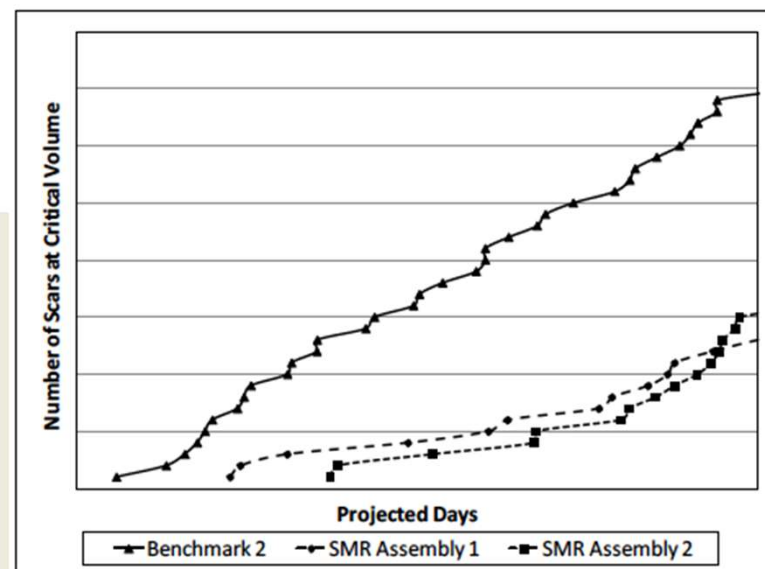
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Active length	14ft	6.5ft	4.5ft	6.5ft	8ft	8ft	12ft

“Grid-to-rod fretting wear test (one of the major failure mechanisms for PWR fuel): wear scars identification”

M.E. Conner et al., Fuel Assembly Hydraulic Testing for Westinghouse Small Modular Reactor, ICAPP 2014



WEC: VIPRE
hydraulic test loop

SMR – iPWRs TH investigation & testing: SET facilities

MODULAR STEAM GENERATORS (OT, Helical Coil)

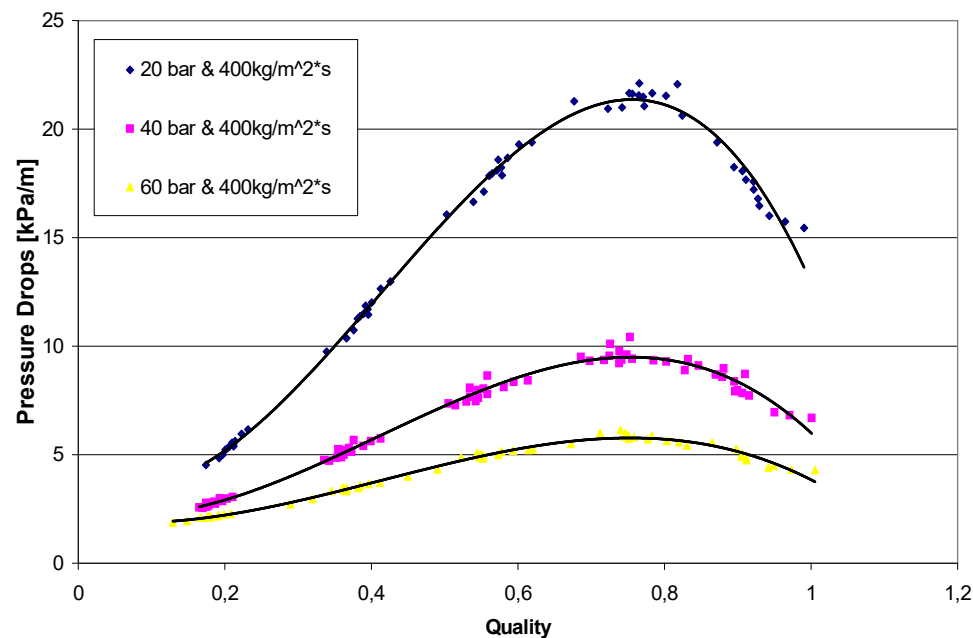
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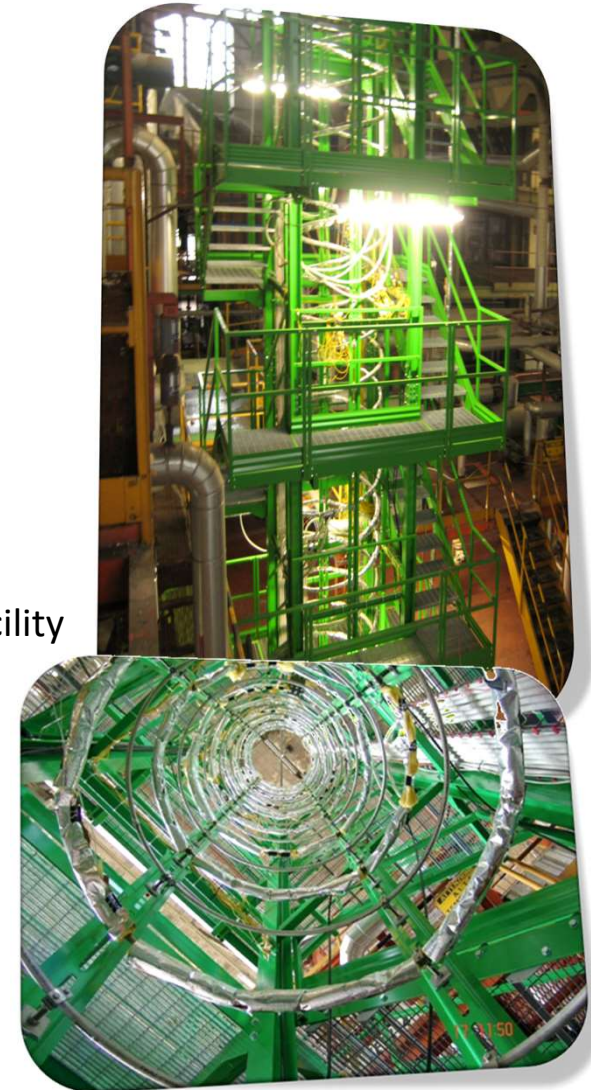
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➤ Two-phase flow pressure losses



Pressure drops vs Quality @ different system pressure

POLIMI HCSG test facility



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MODULAR STEAM GENERATORS (OT, Helical Coil)

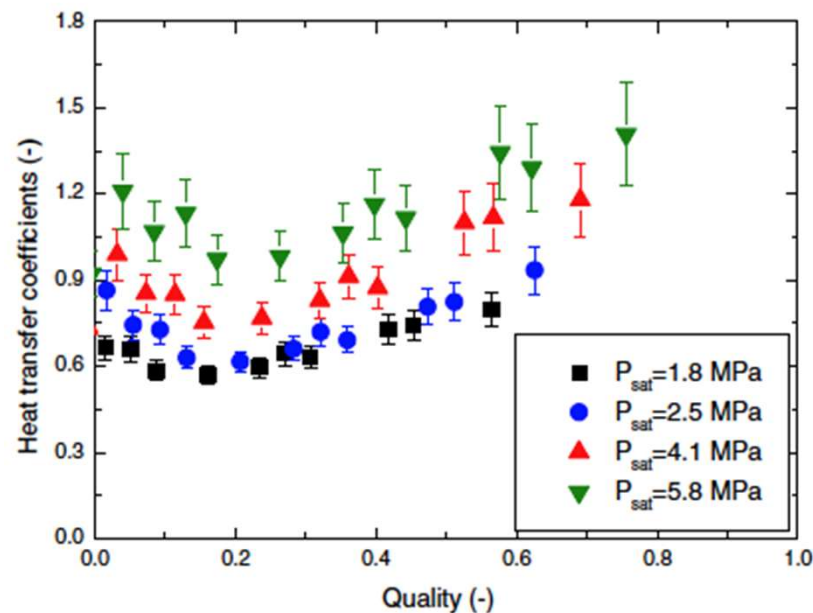
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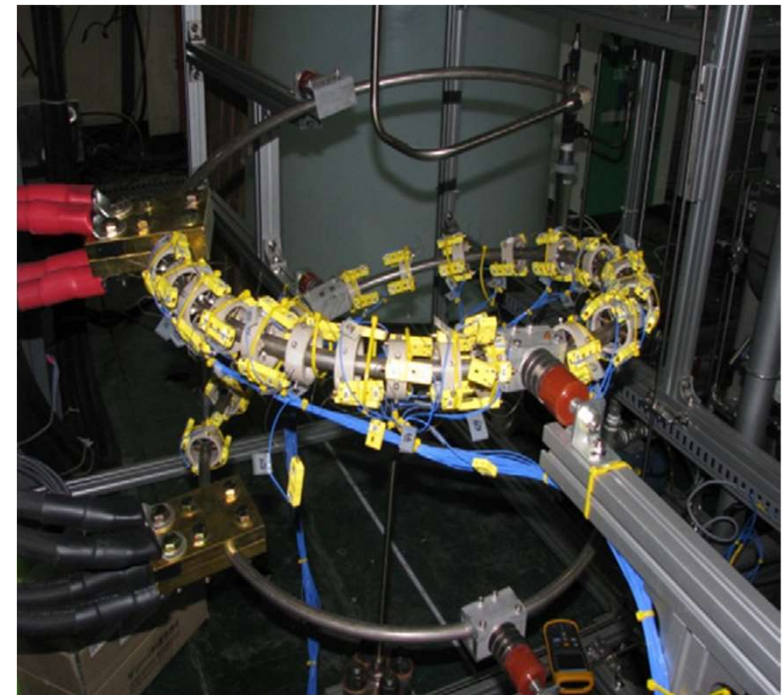
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- Two-phase flow pressure losses
- Dryout conditions (2D)



(a) $Q=82$ kW and $m=0.06$ kg/s



SMART: HCSG test facility

Chung et al., Boiling heat transfer and dryout in helically coiled tubes under different pressure conditions, Ann.Nucl.En., 2014

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MODULAR STEAM GENERATORS (OT, Helical Coil)

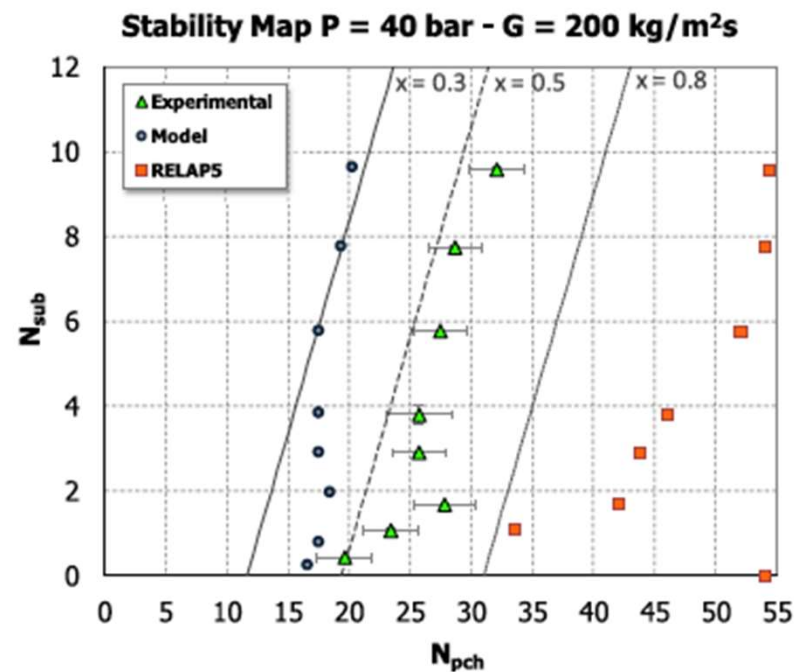
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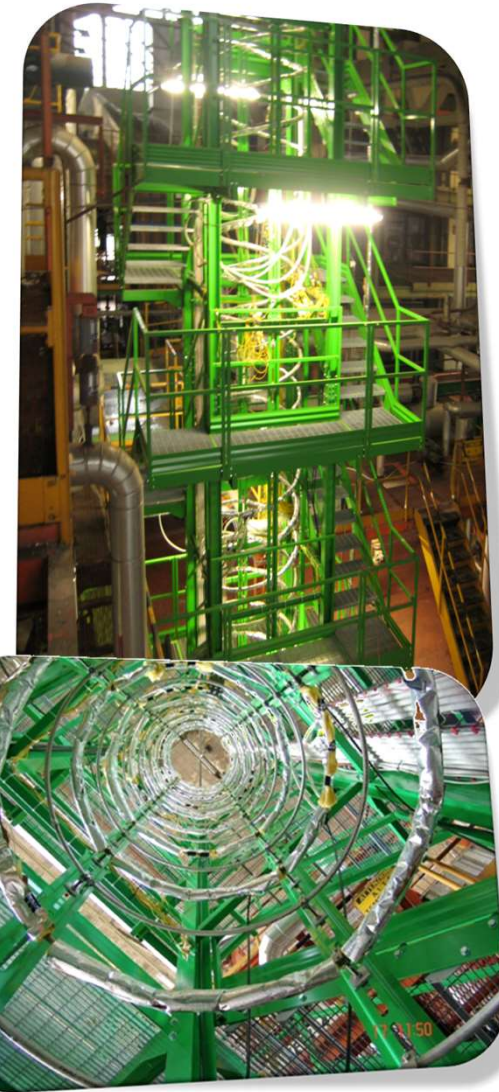
9

- Two-phase flow pressure losses
- Dryout conditions (2D)
- Instabilities (parallel tubes)



Papini et al., Experimental and theoretical studies on density wave instabilities in helically coiled tubes, Int.J.H&MT, 2014

POLIMI HCSG test facility



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MODULAR STEAM GENERATORS (OT, Helical Coil)

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- Two-phase flow pressure losses
- Dryout conditions (2D)
- Instabilities (parallel tubes)
- Flow-Induced Vibrations

NuScale: full scale, prototypical
HCSG test facility



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INTERNAL CONTROL ROD DRIVE MECHANISMS

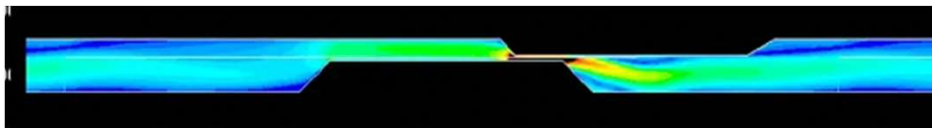
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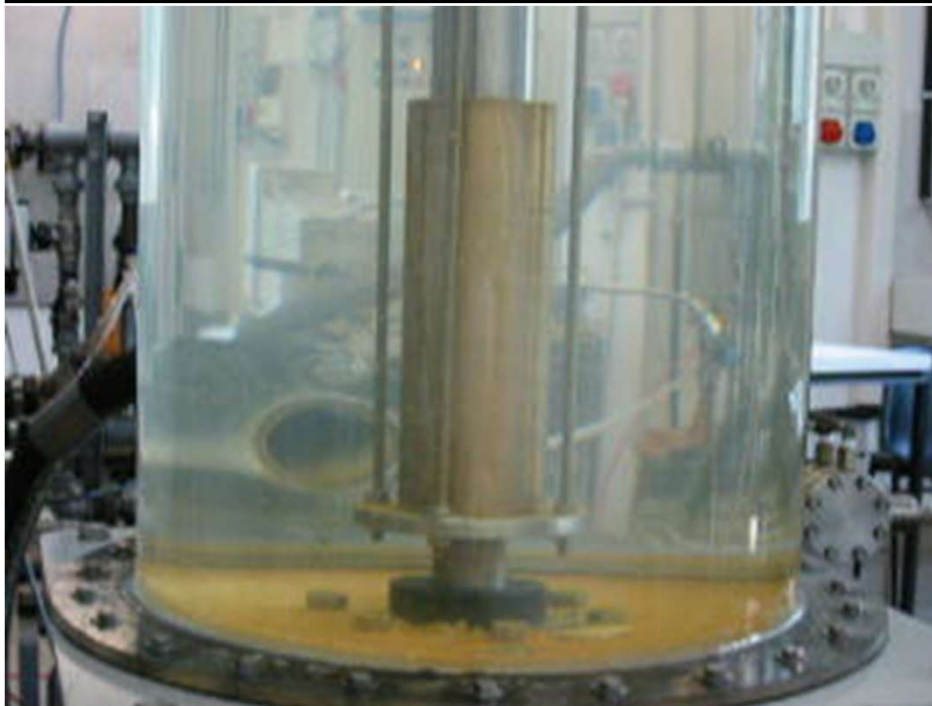
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- Hydraulically driven
- Electro-magnetic

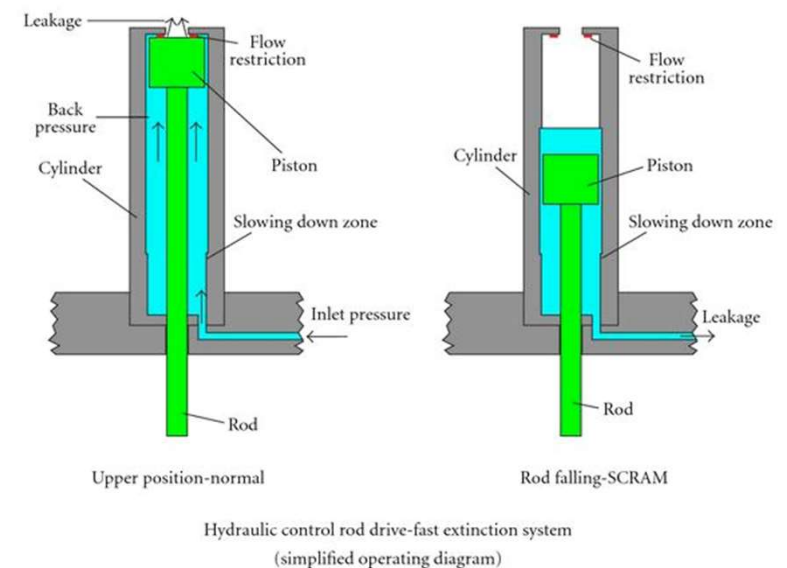


CFD



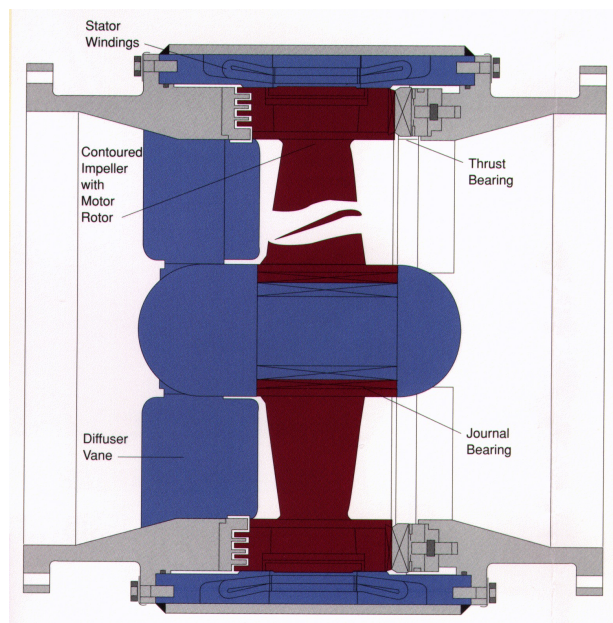
Exp. Test

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HDCR
Low P, T
facility

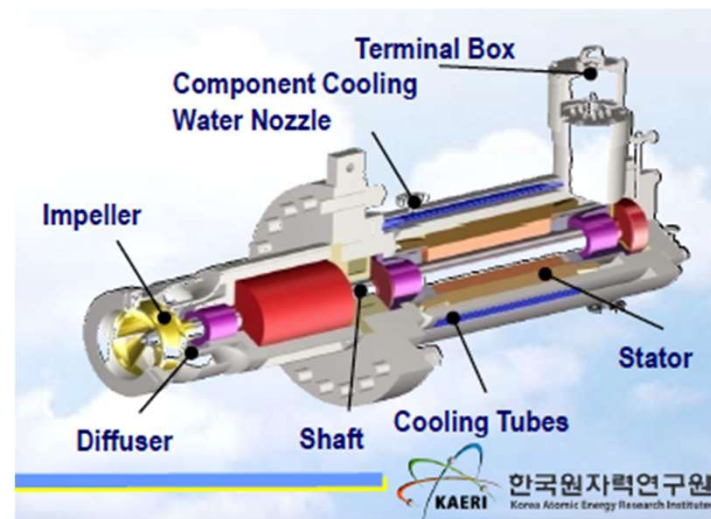


CAREM25: high-pressure and high-temperature rig for testing the innovative hydraulic control rod drive mechanism

- RPV mounted/Canned-motor pumps
- Fully internal pumps



Spool pump design
(Curtiss-Wright
EMCorp patent)

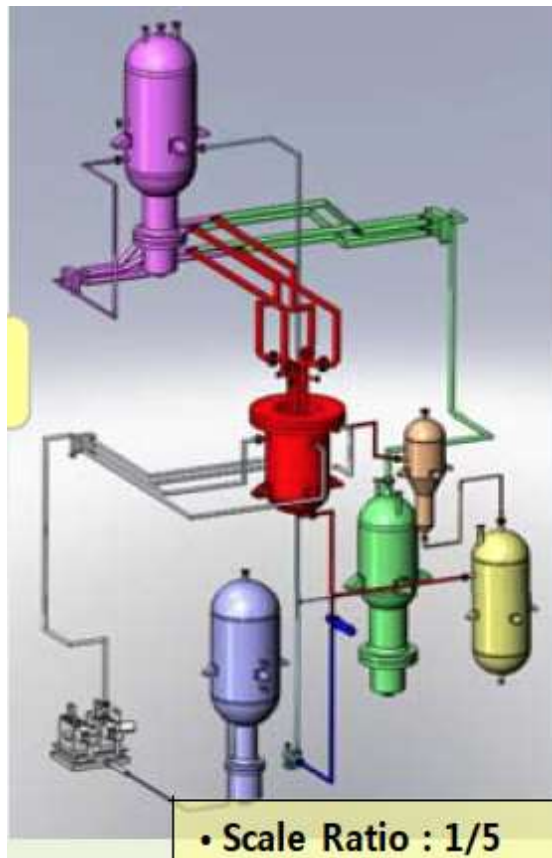


SMART: Canned
motor pump test



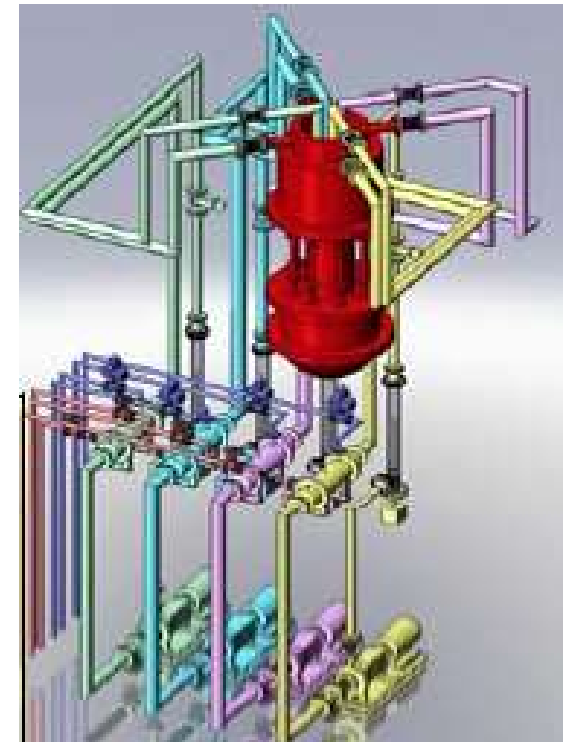
mPower: Reactor
Coolant Pump test

- Downcomer / Lower Plenum mixing
- Safety injection (SBLOCA)



SMART: RPV Assembly flow distribution test (SCOP facility)

SMART: Safety Injection two-phase choking test (SWAT facility)



Yi et al., Major results of thermal-hydraulic validation tests for the SMART design licensing, NURETH15, 2013

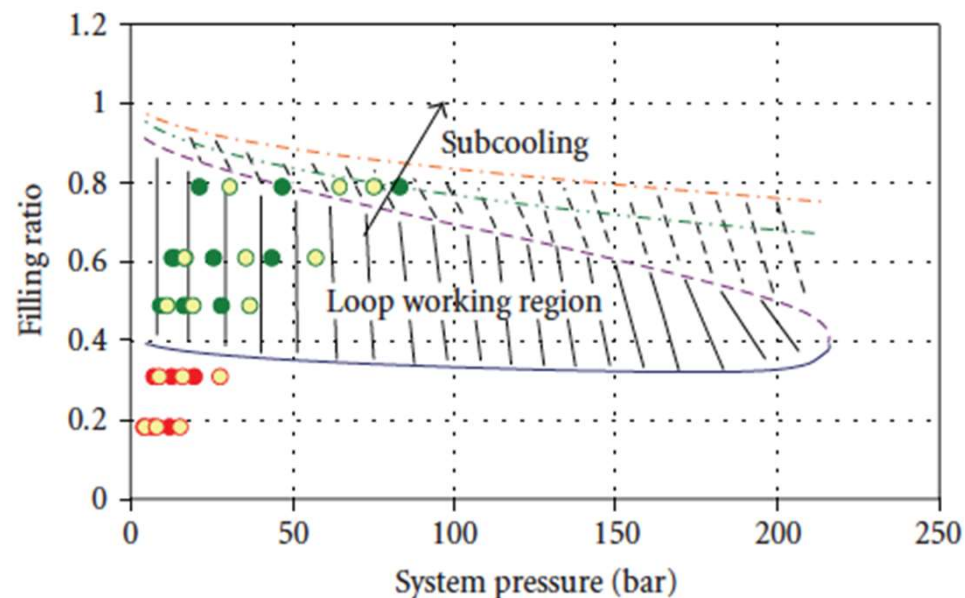
SMR – iPWRs TH investigation & testing: SET facilities

SAFETY COMPONENTS / SYSTEMS

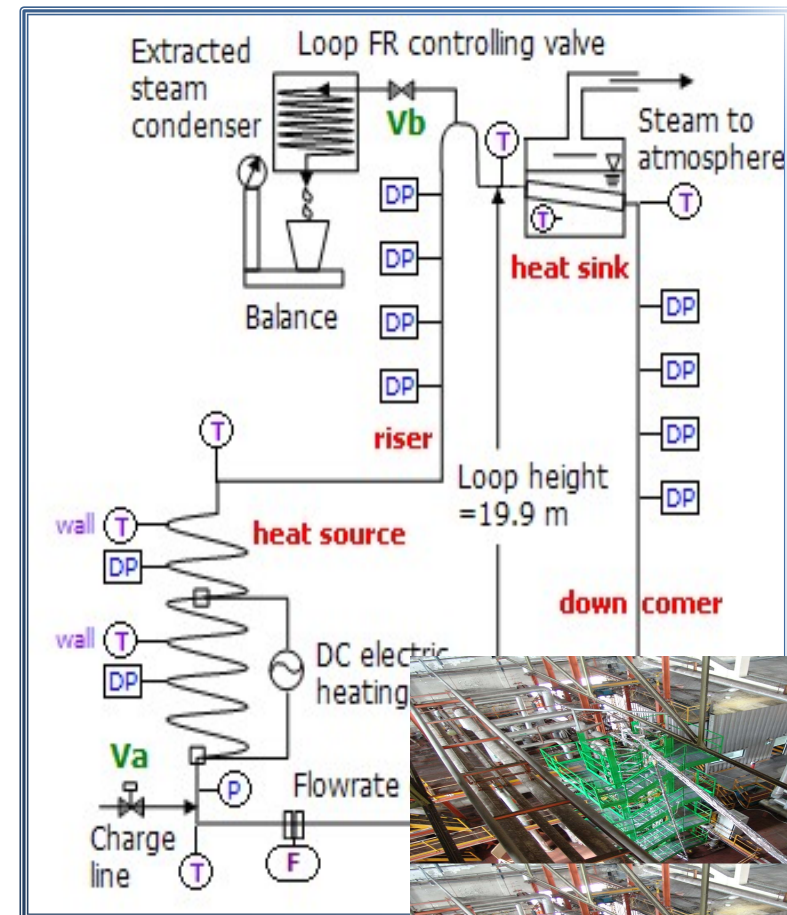
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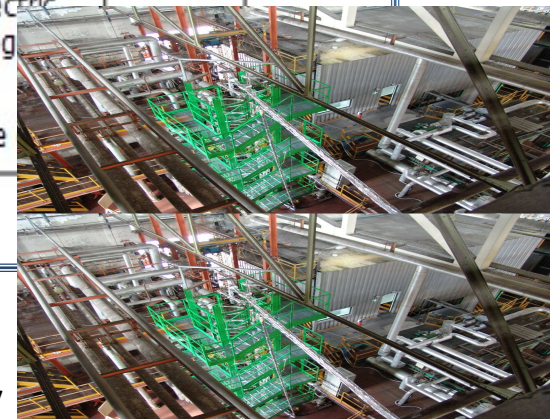
- Downcomer / Lower Plenum mixing
- Safety injection (SBLOCA)
- Natural Circulation DHR systems



Santini et al., Experim. characterization of a Passive Emergency Heat Removal System for a GenIII+ Reactor, STNI, 2010



POLIMI
passive
loop facility



Introductory open literature about IET in general:

17 papers:

- PWR (8)
- VVER (4)
- BWR (3)
- SMR-iPWR (2)

Hindawi Publishing Corporation
Science and Technology of Nuclear Installations
Volume 2012, Article ID 826732, 3 pages
doi:10.1155/2012/826732

Editorial
**Integral Test Facilities and Thermal-Hydraulic System Codes
in Nuclear Safety Analysis**

Klaus Umminger¹ and Alessandro Del Nevo²

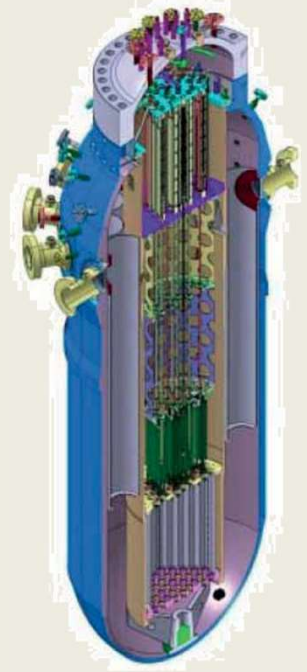
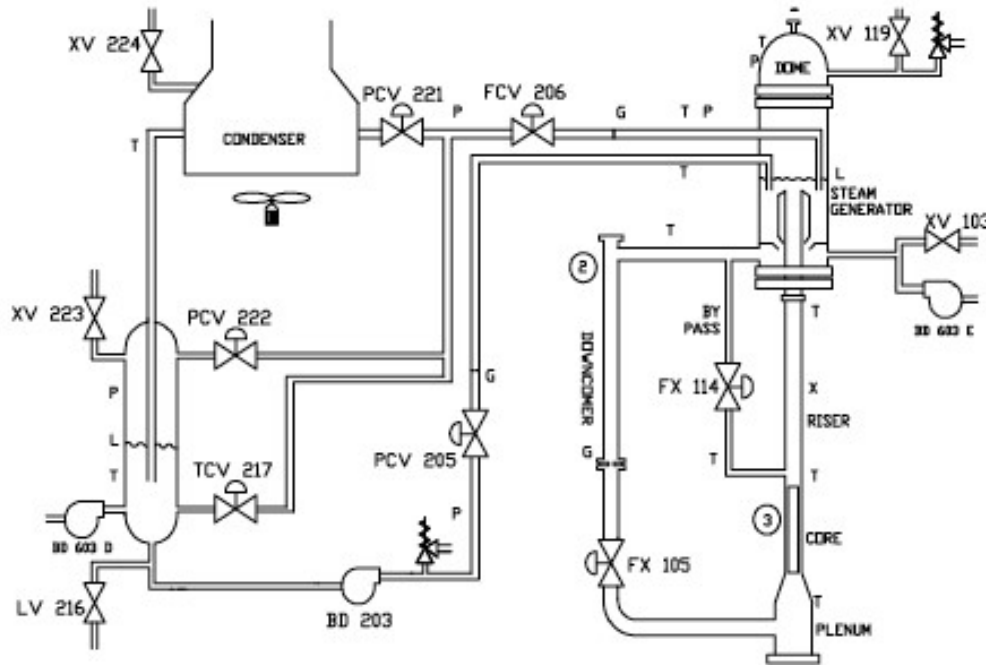
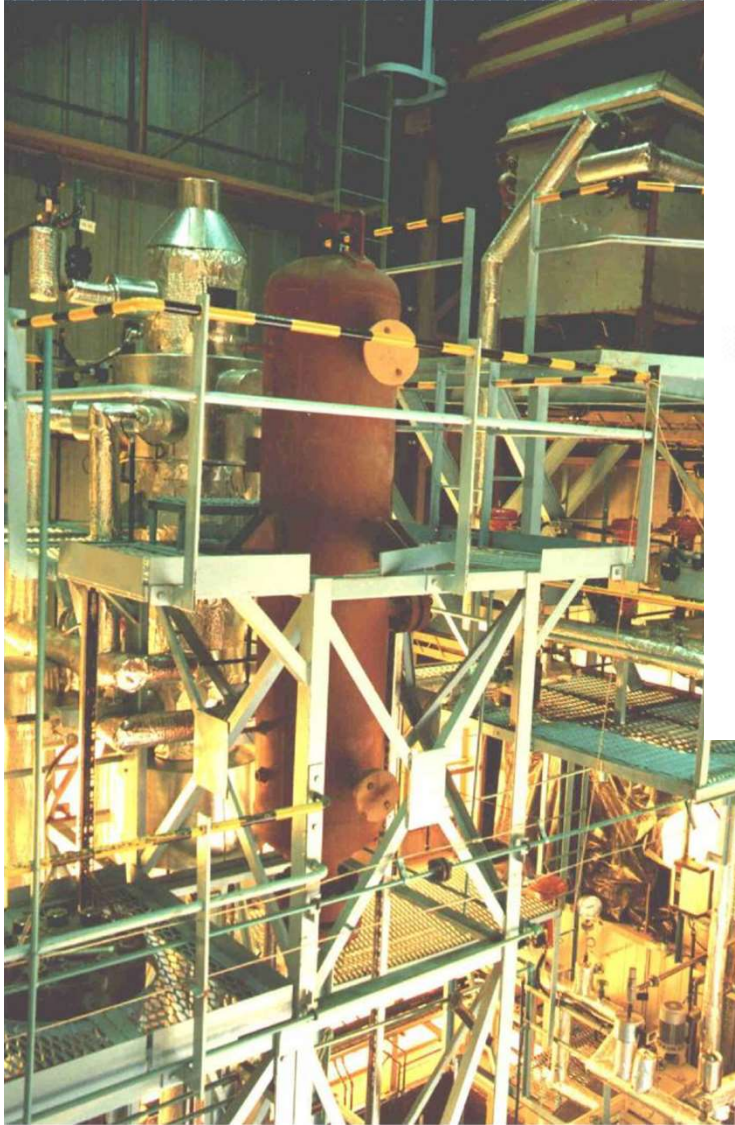
¹ AREVA NP GmbH, Paul-Gossen Strasse 100, 91052 Erlangen, Germany
² ENEA UTIS-TCI, C.R. Brasimone, 40032 Camugnano (Bo), Italy

SMR – iPWRs: Integral Effect Test (IET) facilities

CAREM

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CAPCN facility, TH dynamics in conditions similar to CAREM-25 operational states

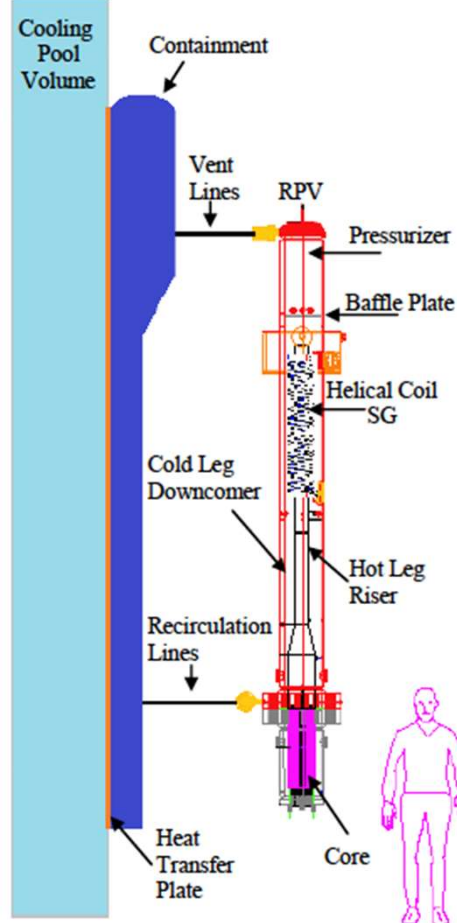
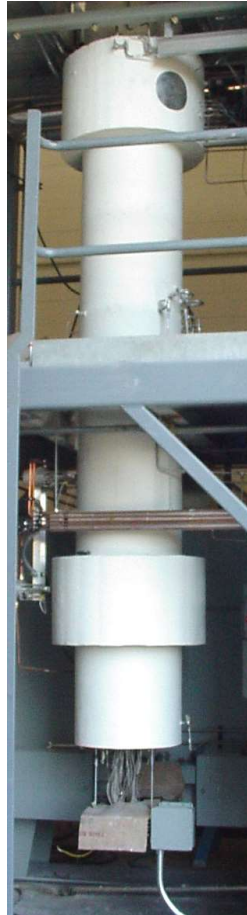
(1:1 in height and P, T; 1:335 in power)

SMR – iPWRs: Integral Effect Test (IET) facilities

NuScale

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NuScale Integral System Test (NIST) facility

(1:1 in P, T; 1:3 in height, 1:253 in volume, 1:1 in time)

SMR – iPWRs: Integral Effect Test (IET) facilities mPower

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Integrated Systems Test (IST) facility

(1:1 in height and P, T; 1:375 in power)

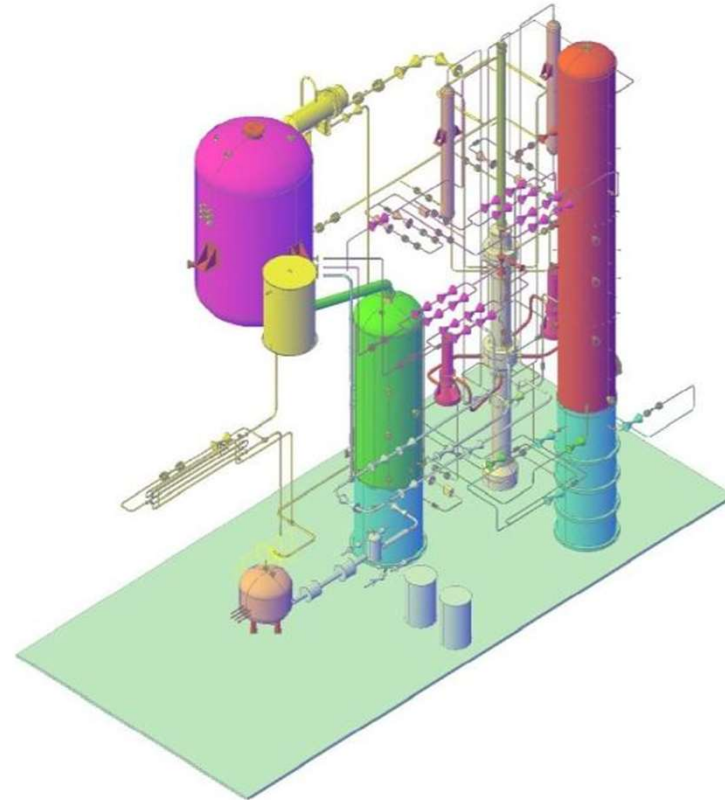


SMR – iPWRs: Integral Effect Test (IET) facilities

ACP100

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Core Cooling and REsidual heat removal
System Test facility (CREST)

(1:1 in height and P, T; 1:37 in volume;
1:100 in power)



SMR – iPWRs: Integral Effect Test (IET) facilities

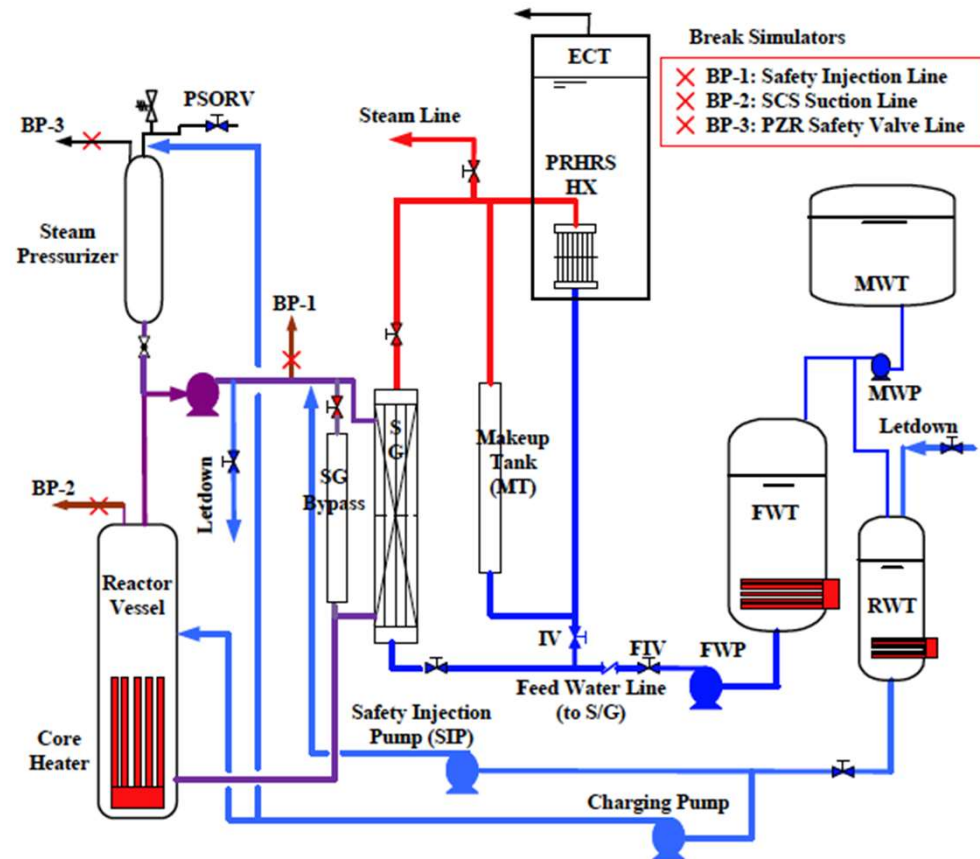
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VISTA (Experimental Verification by Integral Simulation of Transients and Accidents) integral test facility

(1:2.8 in height, 1:1 in P, T; 1:473 in power)

SMR – iPWRs: Integral Effect Test (IET) facilities

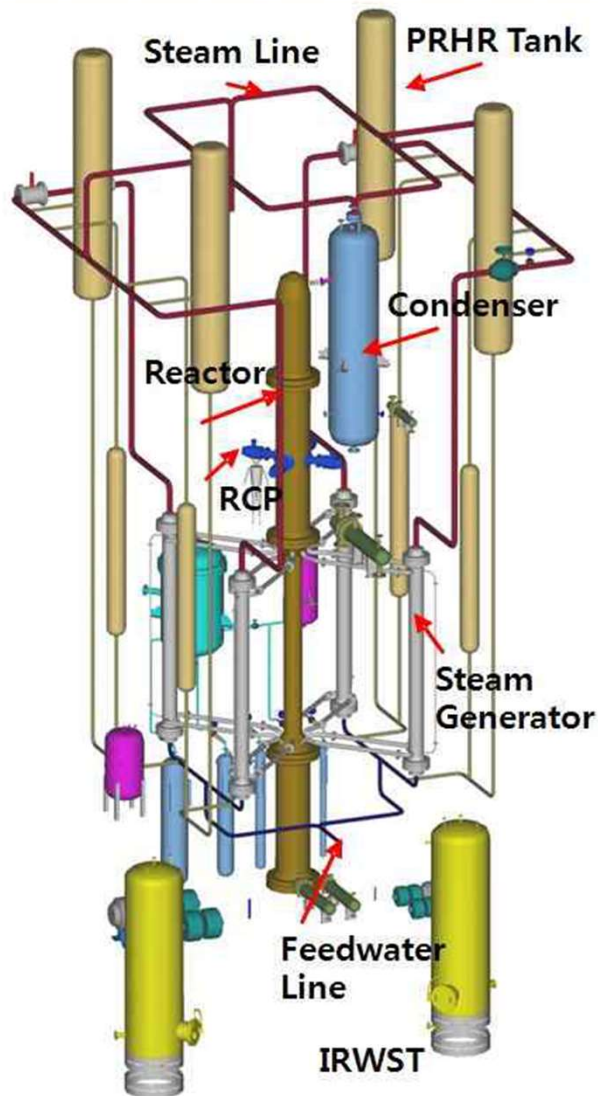
SMART

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SMART-ITL (Integral Test Loop) large scale integral test facility

(1:1 in height, 1:1 in P, T; 1:49 in power/volume)

SMR – iPWRs: Integral Effect Test (IET) facilities

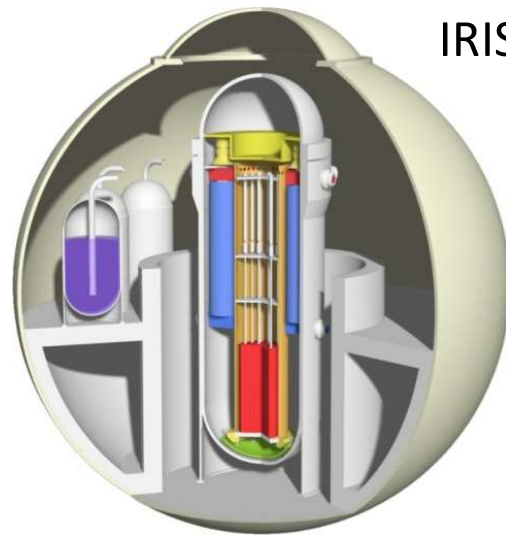
IRIS

IAEA TWG-SMR

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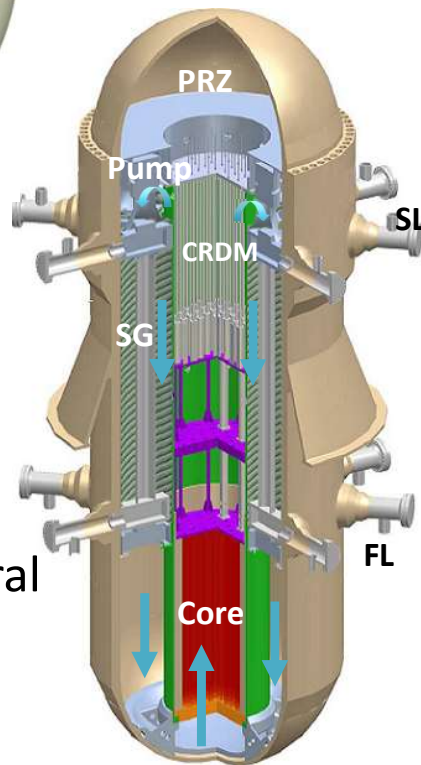
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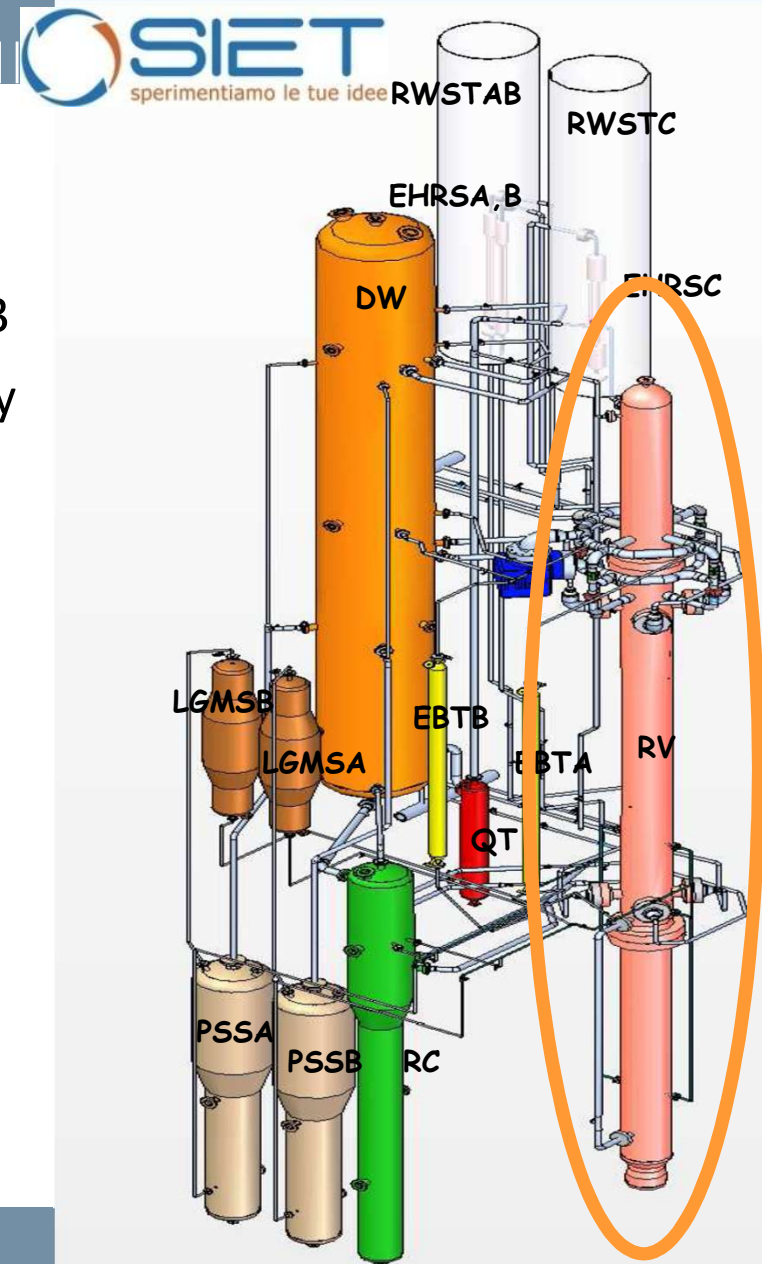
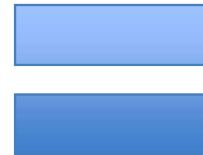
IRIS spherical
containment



IRIS integral
RPV



SPES3
facility



SMR – iPWRs: Integral Effect Test (IET) facilities

IRIS

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SPES3 side view



EHRP pools and Drywell



Pressure Suppression pools

> 700
measurement
points

innovative
instrumentation
developed

to be completed by
RPV simulator

SPES3 iPWR Integral Test Facility **(1:1 in height, 1:1 in P, T; 1:100 in power/volume)**

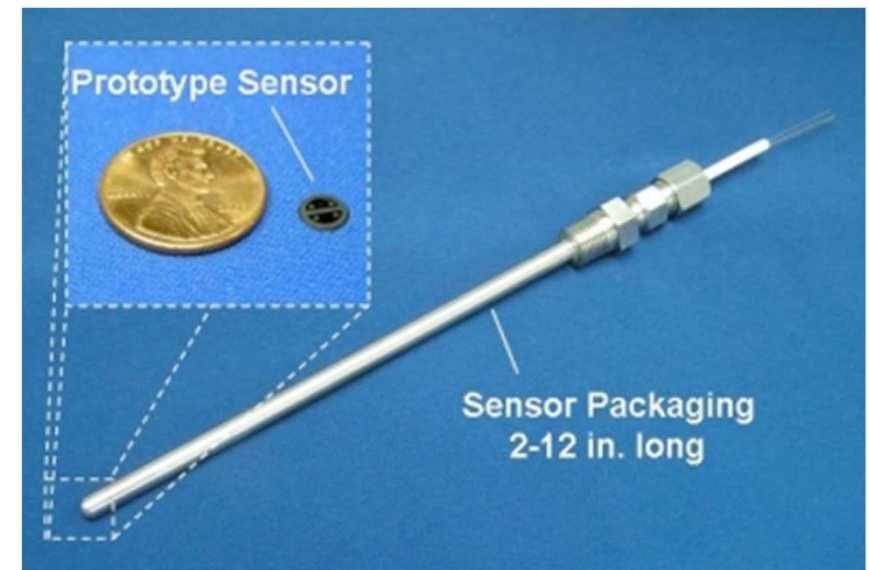
- Sensible level of **similarities** among SMR-iPWR concepts
- IET facilities usually adopted for licensing purposes (**proprietary / confidential**, hence not accessible)
- Usefulness of an “**open**” IET facility for iPWRs:
 - ✓ Regulators (independent V&V of safety codes)
 - ✓ Knowledge sharing / E&T

I&C devices & strategies

- **Flow**, Temperature, **Level**, **Pressure**, Flux/Power
- Some traditional options will not work in iPWRs: geometries involved & environment
- Re-engineered sensors: different mounting configurations, size constraints, radiation fields (n , γ)
- New technologies: MEMS, fiber optic, ultrasonic



FIBER OPTIC sensor (P)



MEMS sensor (P)

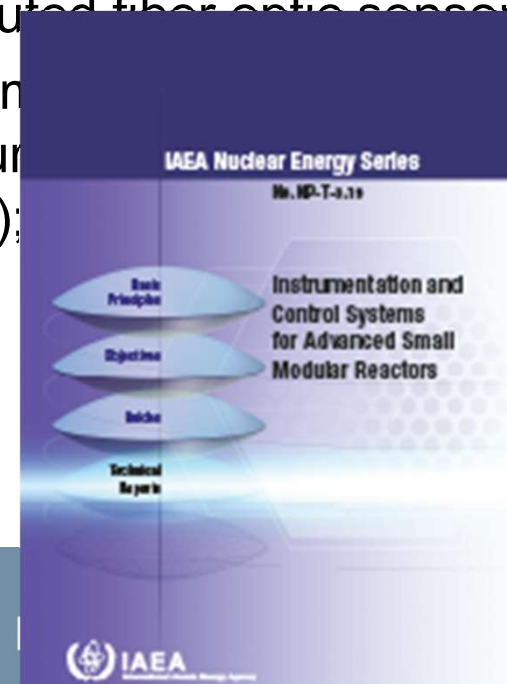


FIBER OPTIC
sensor (T)

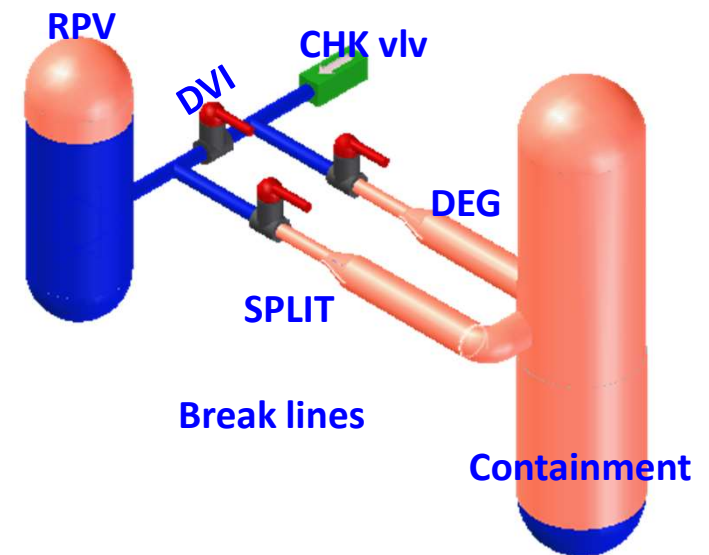
I&C devices & strategies

- **Pressure** transmitters (+ **Temp.** sensors): no DP → fiber optic/MEMS avoid long pressure sensing lines for classical transducers (+ drift compensation) → penetrations minimised, small size sensors, sensitivity to high freq pressure fluctuations, reliable in high rad fields, low maintenance
- **Level** sensors: no DP (no room & no mild environm. in iPWRs), acoustic/ultrasonic not viable → distributed fiber optic sensors
- **Flow** meters: no DP (no prim. piping, small size) → ultrasonic/fiber optic/MEMS → linear function (accuracy > $\sqrt{\text{DP}}$ especially at low-flow); no DP (no core)

*IAEA Nuclear Energy Series No. NP-T-3.19
“I&C Systems for Advanced SMRs”*



- **>700 measurement points** (120 wall TC at different levels on the rod bundle)
- Conventional and **two-phase flow** instrumentation for direct measures (T, P, velocity, etc.) and derived measures (level, density, mass flowrate, etc.).
- **Two-phase mass flow measures required at break lines**, during a LOCA simulation, for non-homogeneous mixture at high T and P.
- “Spool Piece”: 3-4 instruments in series providing velocity, momentum flux and void fraction:
 - Vortex for volumetric flow or velocity;
 - Drag Disk and/or Pitot tube for momentum flux;
 - Capacitance probe for void fraction by chord average fluid density.



I&C: iPWRs needs for innovation

SPES3 Spool piece testing results

Instruments installed in series: Pitot tube, Capacitance probe, Drag disk, Vortex. Tests performed according to a 3D matrix of conditions: mass flow, quality and pressure.

➤ Vortex

Very good agreement between tvortex measured velocity and steam theoretical speed.

Average error < 2.5%

➤ Capacitance probe

■: Void fraction by weighting

■: Void fraction by probe

Average error ~5%

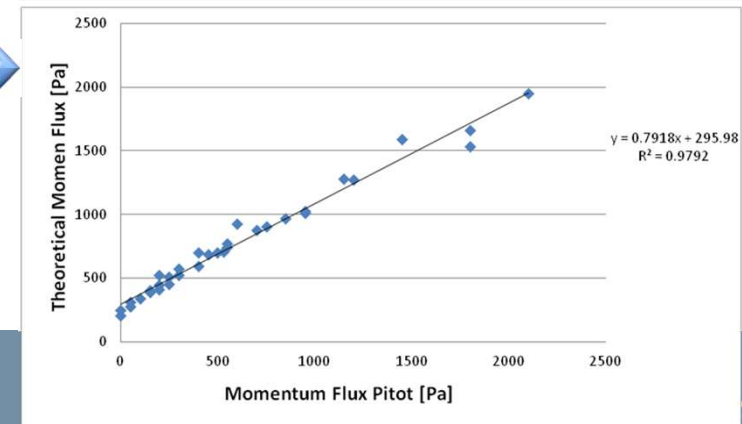
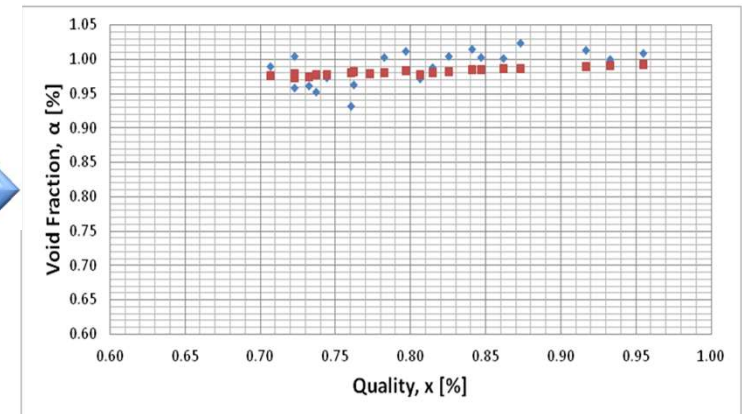
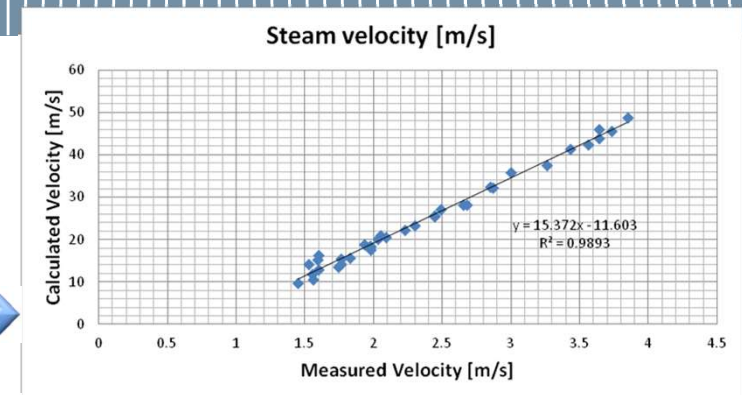
➤ Pitot tube

Good agreement between theoretical and measured momentum flux

Average error ~7%

➤ Drag disk

Testing conditions at the lower range value of the instrument.



Why international cooperation on R&D and E&T in SMR? (IAEA efforts: a key activity)

- nuclear R&D and innovation are complex and expensive: **share ideas** and share **costs**
- development of new solutions and **time-to-market** constraints: **share facilities** and **expertise** (e.g. to support licensing and training)
- nuclear sector in the wake of a generational change process: a **new generation** of nuclear experts
- nuclear sector in the development phase: new workforce (at industrial and institutional level, esp. in “**newcomer**” countries)
- nuclear is becoming a real **international** market: prepare experts on different nuclear technologies (international E&T)

- **Experimental data** are key for:
 - ✓ Knowledge improvement
 - ✓ Licensing process
 - ✓ Technology development
- **Modelling** development and **Instrumentation** innovation are needed
- SET and IET are typically **proprietary / confidential** (IET mandatory for licensing purposes)
- Potential interest for “**open**” experimental efforts

EU: Horizon2020-Euratom call on LWR-SMRs NFRP-2018-3: Research on the safety of Light Water Small Modular Reactors

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Latest News on EU side

- **SMRs: “interesting safety features”**
- **“residual heat removal and size of containment structure”**
- **“compliance with the EU Safety Directive may significantly vary depending on safety options of proposed design”, hence “need to be further investigated”**

“The challenge”

- **“investigate improved safety features of Light Water SMRs”**
- **“provide fundamental technical specifications” (to be tested by safety regulators)**
- **“propose a methodology for the performance of these tests” (including experimental validation of essential items + effects on SMR licensing process, considering potential fields of application)**
- **other items: “safety of refuelling”, “of spent fuel management”, “decommissioning”**
- **5% Edu&Training**

“The scope”

- **establish a “baseline for testing LW-SMRs compliance with EU Safety Directive and for SMR’s licensing process”**
- **preparation for a “robust science-based recommendations to decision makers regarding nuclear safety of Light Water SMRs at EU level”**

“The impact”

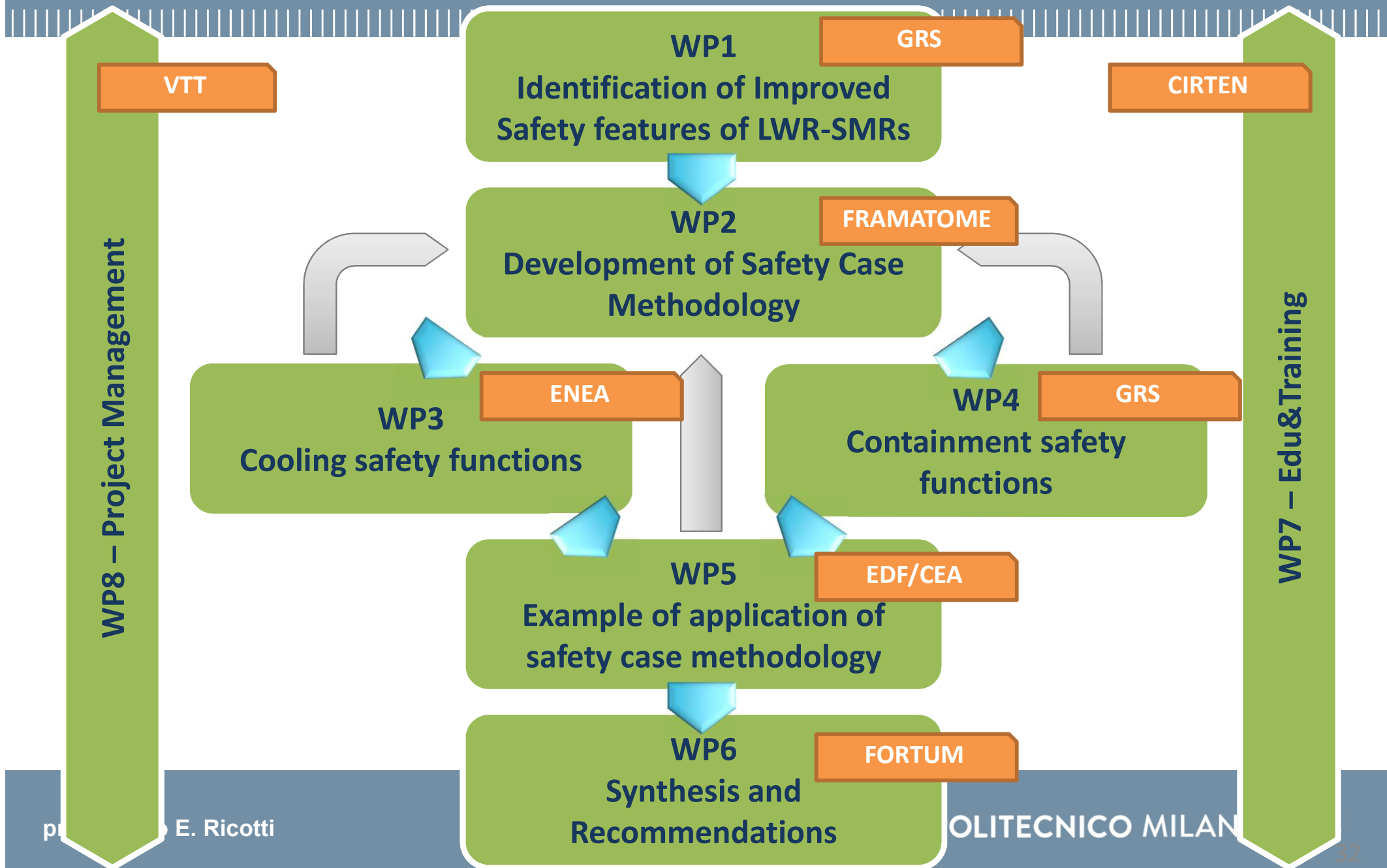
ELSMOR proposal

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towards European Licensing of Small MOdular Reactors



Core Team of the proposal

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	Partners	Country	Industry	Utility	R&D Center	University	TSO	SME
1	VTT	FIN			⊙		⊙	
2	CEA	FRA			⊙			
3	CIRTEN	ITA				⊙		
4	EDF	FRA		⊙				
5	ENEA	ITA			⊙		⊙	
6	FORTUM	FIN		⊙				
7	FRAMATOME	FRA	⊙					
8	GRS	GER			⊙		⊙	
9	IRSN	FRA					⊙	
10	JRC	EU			⊙			
11	SIET	ITA	⊙					
12	TECHNICATOME	FRA	⊙					

