3rd IAEA – ICTP Workshop, Physics and Technology of Innovative Nuclear Energy Systems, 12-16 December 2022, ICTP, Trieste, Italy

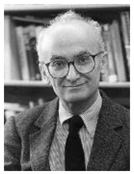
OntarioTech UNIVERSITY

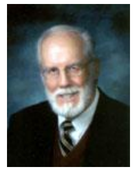
Technical and associated challenges in establishing a viable SMR

Akira.Tokuhiro
(@ontariotechu.ca)
***former students,**
C. Zeliang*, Y. Mi*

Scott Cosgrove, graphic designer

Career summary, Akira Tokuhiro





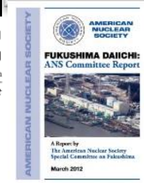

University of Idaho College of Engineering

Ontario Tech University

World Nuclear University

INL Idaho National Laboratory

U.S.NRC United States Nuclear Regulatory Commission *Protecting People and the Environment*



Battelle Putting Technology To Work

Argonne National Laboratory

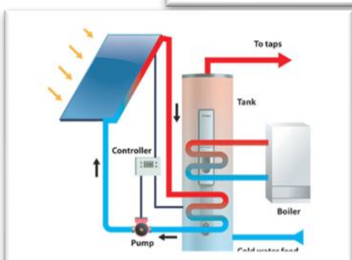
Missouri S&T

Paul Scherrer Institut PSI

JAEA

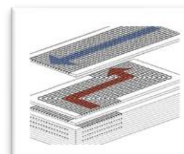
NuScale

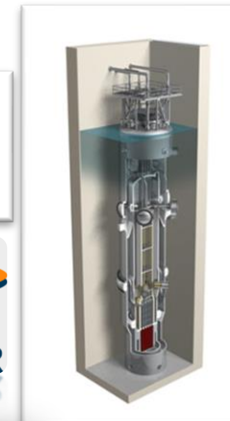
PBMR



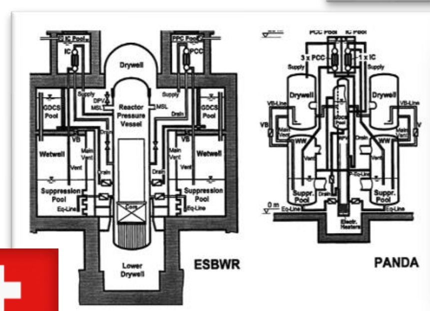
1980 1985 1990 1995 2000 2005 2010 2020 2022

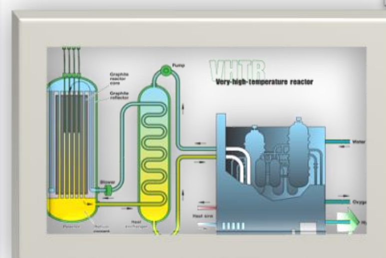
Renewables/Solar thermal, LWRs, LMFR, EFR, GE-SBWR, SCO2_HX, SFR, VHTR, SMR, CANDU





LWRs; BWR, PWR





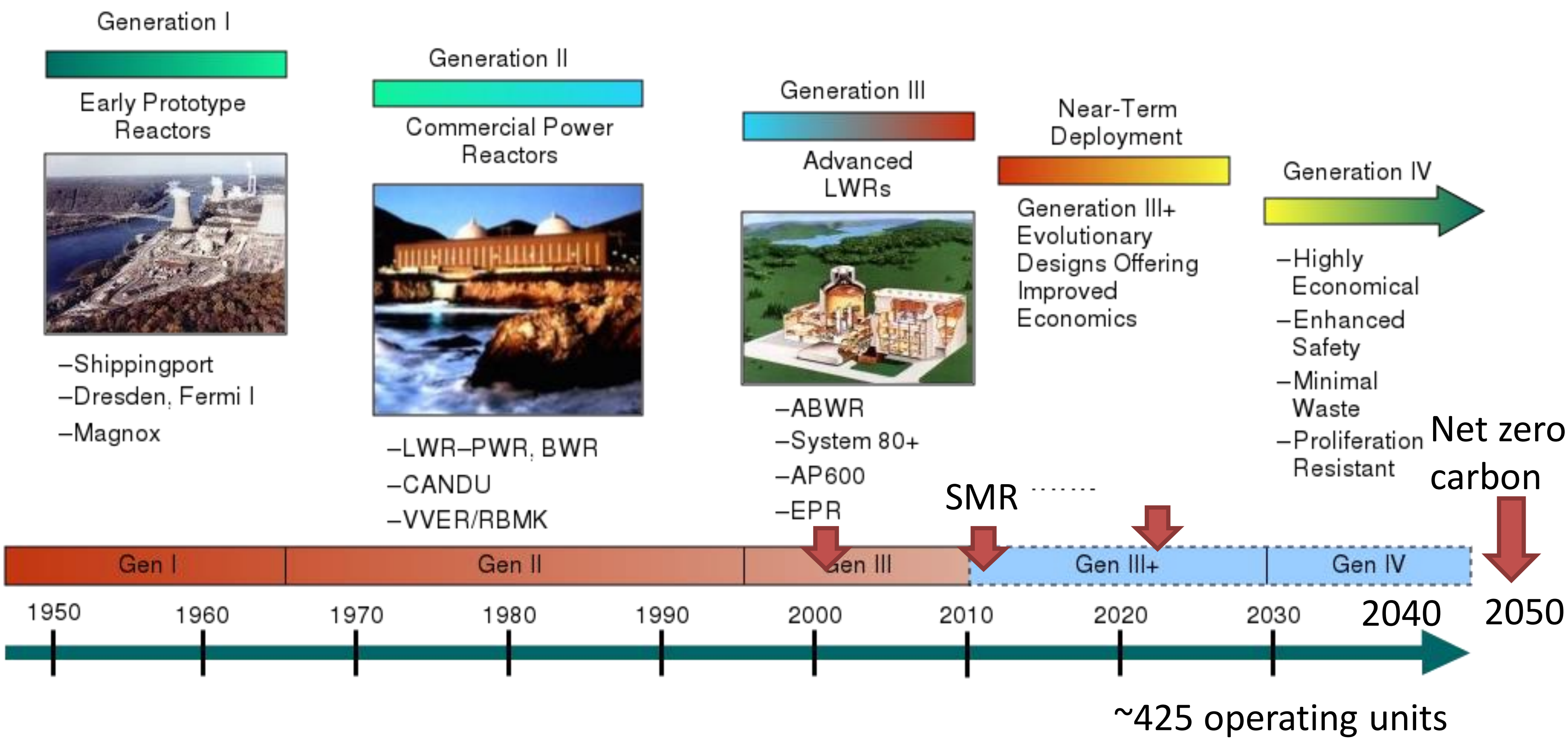
Linked-In profile; https://www.linkedin.com/in/akira-tokuhiro-b0612a6/

confidential

To start…

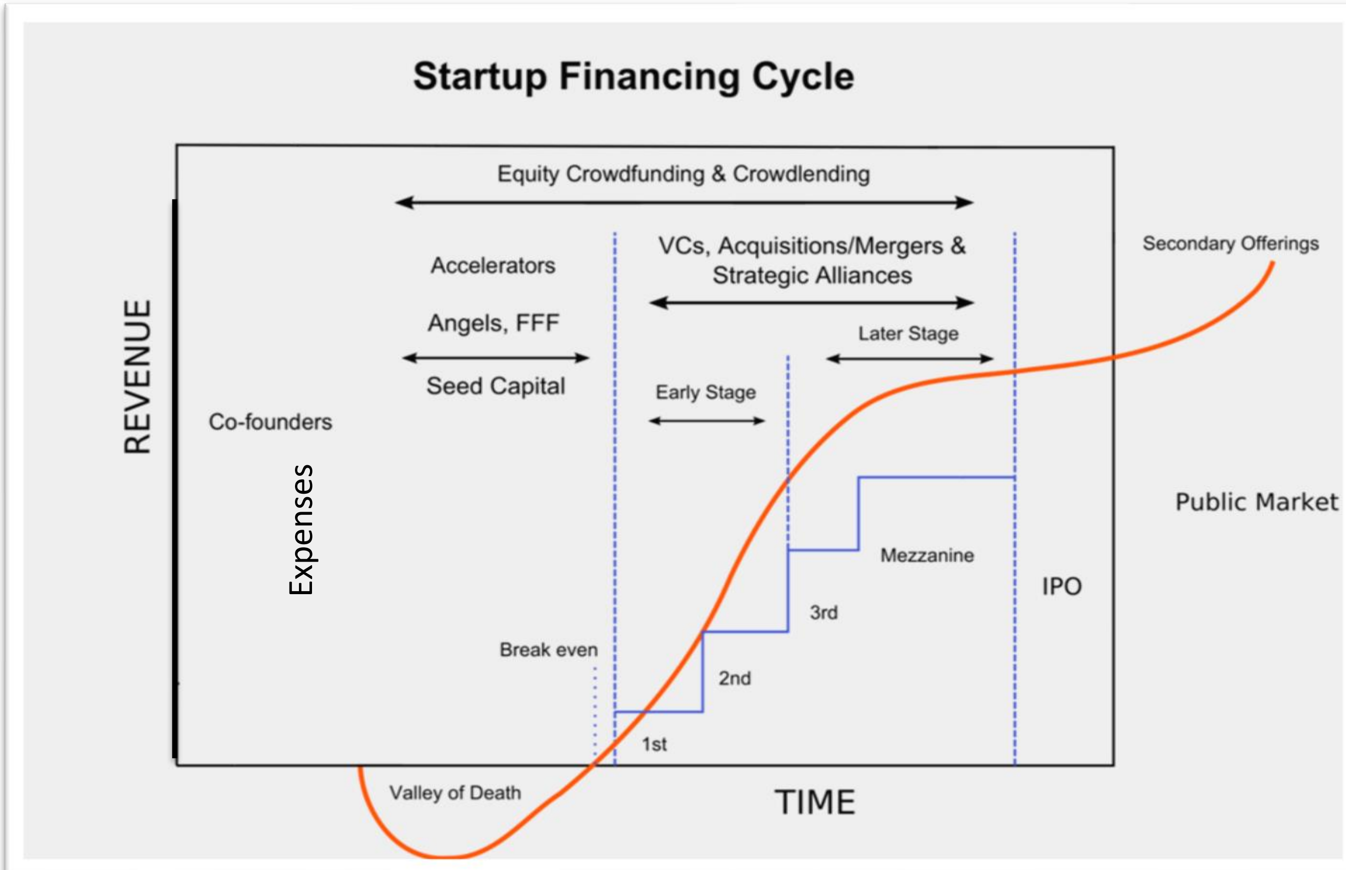
Evolution of commercial nuclear reactor concepts and plants

Generation IV: Nuclear Energy Systems Deployable no later than 2030 and offering significant advances in sustainability, safety and reliability, and economics



SMR/MMR – small/micro modular reactors

Startup financing cycle; commercial sector

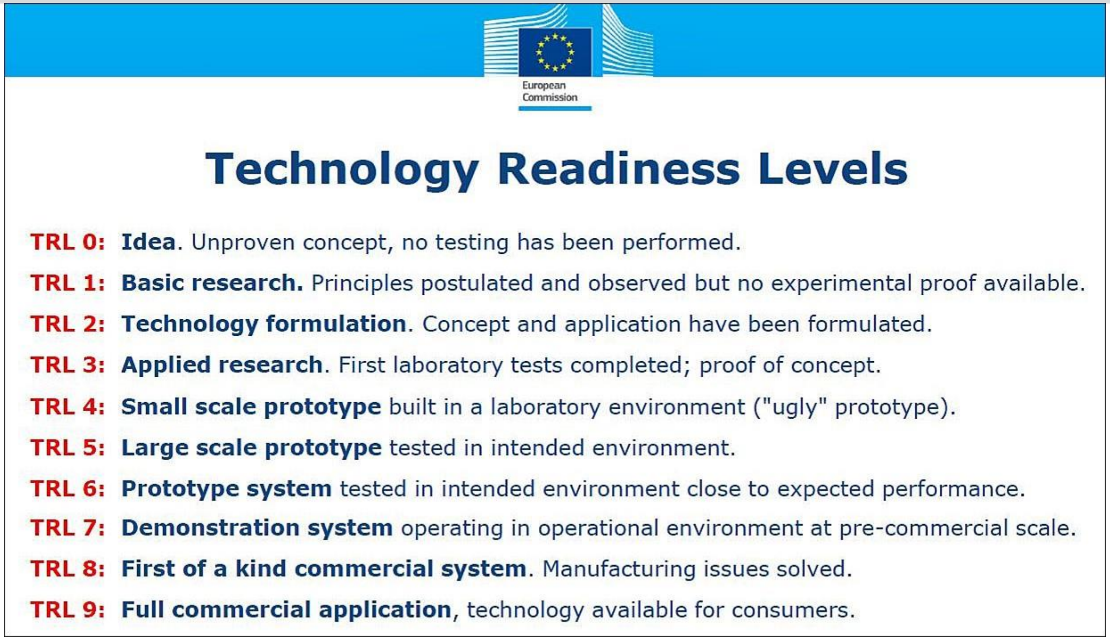


1) **Solyndra**
2) **Flywheel energy storage**
3) **Cellulosics biofuels**
4) **Solar power tower**
5) **Small wind turbines**
6) **Marine energy**
7) https://www.worldoil.com/news/2019/8/15/green-energy-has-a-pletho

Startups

- Do you start a startup full-time or do it part-time, after your full-time job?
- Do you want a startup to eventually sell and retire young?
- Do you want a startup to do good for humanity and undergo $ hardship?
- Do you want a startup to do both good and make it financially sustainable?

Technology Readiness Level (scale)



Technology Readiness Levels

TRL 0: **Idea**. Unproven concept, no testing has been performed.

TRL 1: **Basic research.** Principles postulated and observed but no experimental proof available.

TRL 2: **Technology formulation**. Concept and application have been formulated.

TRL 3: **Applied research**. First laboratory tests completed; proof of concept.

TRL 4: **Small scale prototype** built in a laboratory environment ("ugly" prototype).

TRL 5: **Large scale prototype** tested in intended environment.

TRL 6: **Prototype system** tested in intended environment close to expected performance.

TRL 7: **Demonstration system** operating in operational environment at pre-commercial scale.

TRL 8: **First of a kind commercial system**. Manufacturing issues solved.

TRL 9: **Full commercial application**, technology available for consumers.

Wikipedia. “TRL”
1) English. https://en.wikipedia.org/wiki/Technology_readiness_level

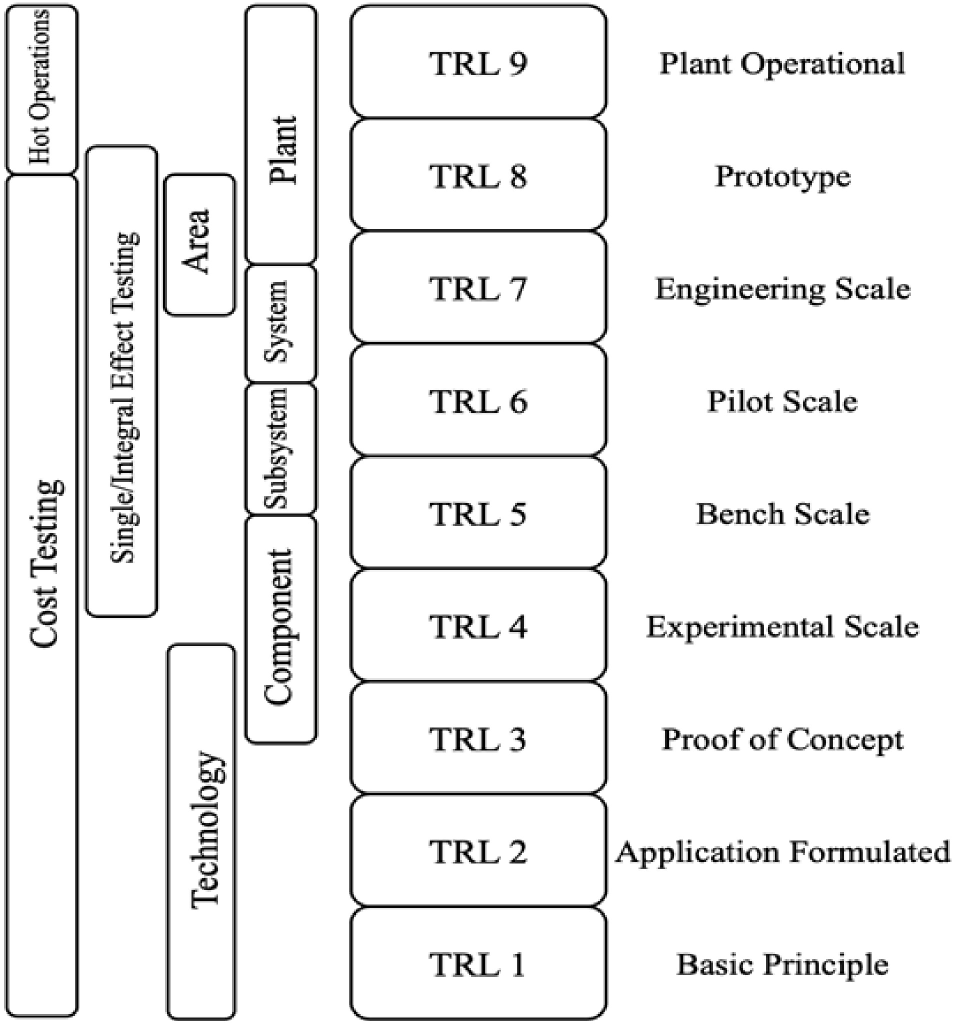
TRL Definitions

- TRL 1 **basic principles observed**
- TRL 2 **technology concept formulated**
- TRL 3 **experimental proof of concept**
- TRL 4 **technology validated in lab**
- TRL 5 **technology validated in relevant environment** (industrially relevant environment in the case of key enabling technologies)
- TRL 6 **technology demonstrated in relevant environment** (industrially relevant environment in the case of key enabling technologies)
- TRL 7 **system prototype demonstration in operational environment**
- TRL 8 **system complete and qualified**
- TRL 9 **actual system proven in operational environment** (competitive manufacturing in the case of key enabling technologies; or in space)
- Cf. https://serkanbolat.com/2014/11/03/technology-readiness-level-trl-math-for-innovative-smes/

TRL - technology readiness level

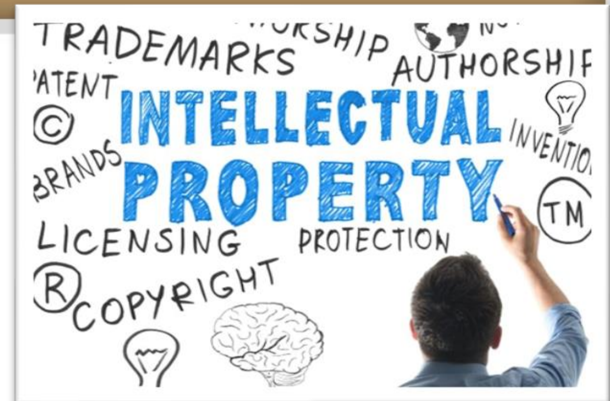
- Cf. Wikipedia; https://en.wikipedia.org/wiki/Technology_readiness_level
- Twitter. @nuclear4climate

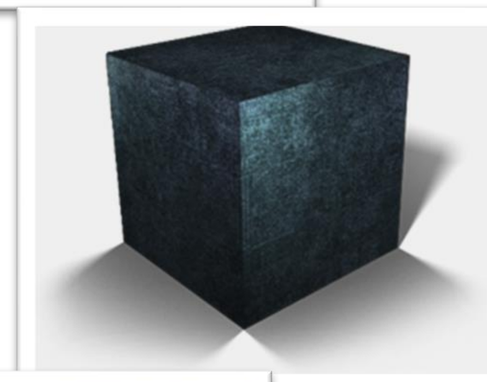
Nuclear for CLIMATE



SMR designs and proprietary information. (Q: what's inside the black box?)

- SMR/reactor vendor designs are proprietary
- The design process/practice within a SMR/vendor may also be proprietary
- It can be a "black box".
- One is curious. Q1: what is inside the box?
- One is curious. Q2: how was it designed?
- One is curious. Q3: can I reverse engineer it if I look at the parts and disassemble it?
- Q4: what is protected as intellectual property?
- Q5: are there patents associated with the design and design processes?





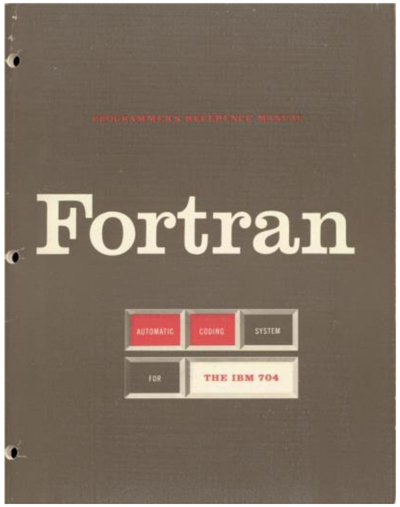
SMR/MMR, beyond TRL and investments, technical issues

Nuclear engineering and scales

- Length.
  - Area. From cross-section, barns 1E-28 m^2, to ~100 sq. km^2 (1E9 m^2)
  - Volume. For example, reactor size to volume of spent fuel.
- Energy. From 1E-3 MeV to 1E+7 MeVs
- Number. Cost ($), number of NPPs, systems/sub-systems.
- Distribution. For example, neutron density, radio-toxicity vs. years.
- Information. Usually models, methods, experiments, simulations.
- Time. From femtosecond, 1E-15 to thousands of years, 8E12 sec
- Derived metrics. L/T, N/T, number density, flux, many others.
- Methods, models, simulations, computations involve LENDIT scales.
- Please note that there are can be more than one, per metric.

Traditional nuclear reactor engineering; “codes”

- Probabilistic safety/risk analysis (PSA/PRA) codes.
- System codes (LWR). RELAP, GOTHIC etc.
- Accident codes (LWR). MELCOR (SNL), MAAP, ASTEC etc.
- Dispersion codes. AEROMOD, PAVAN etc.
- Monte Carlo transport codes. MCNP, MCNPX
- US code archive/repository. RSICC – Radiation Safety Information Computational Center, at ORNL.

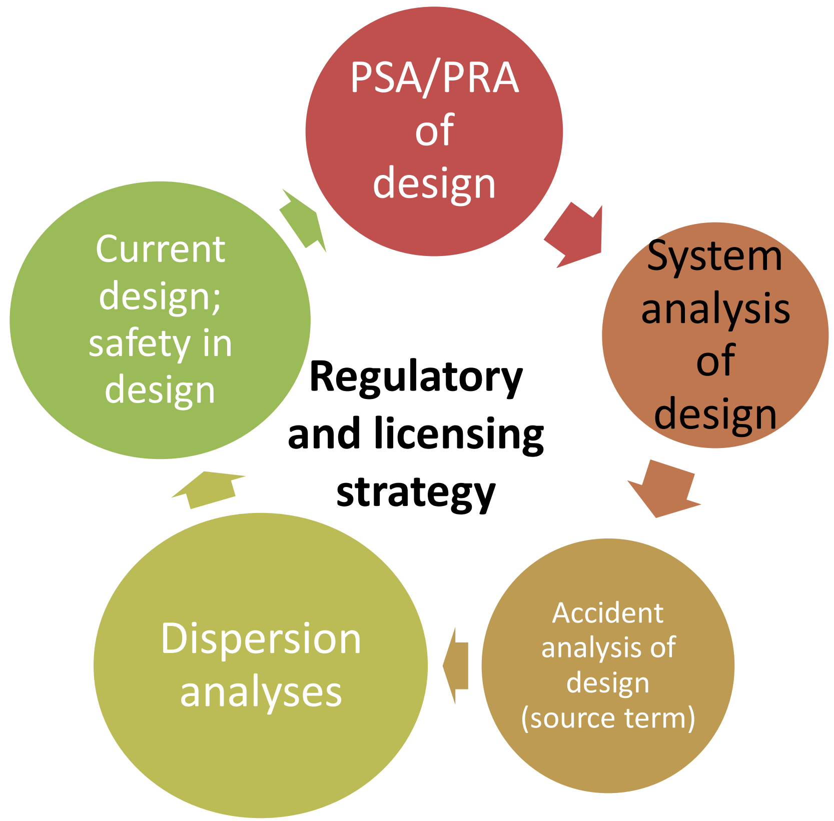


- Access to software by younger generation. Many times, codes, results and details are in shared platforms. Paradigm shift in access, sharing.
  - Slack, Github etc.

Because of its (smaller) scale, simplicity in design, it's possible to integrate, model and simulate much more (than LWRs)

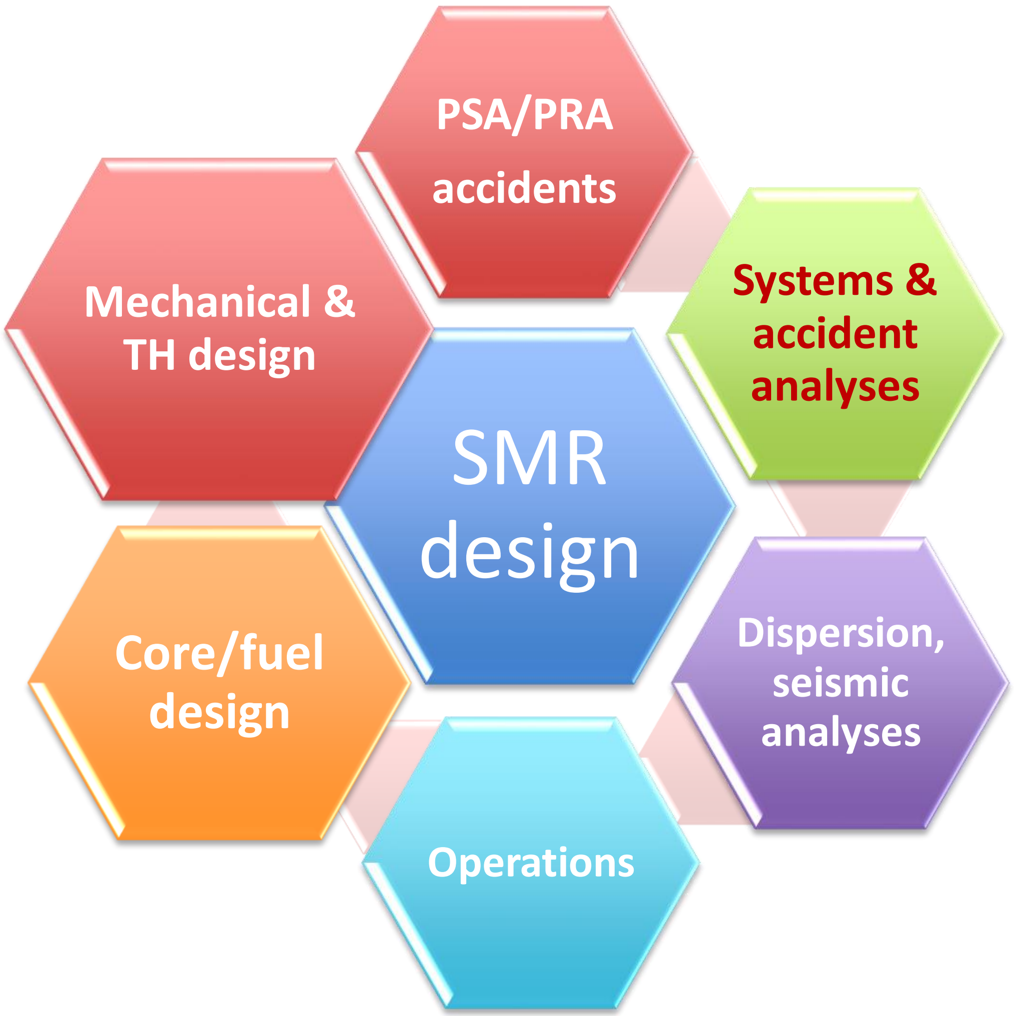
Technical needs in SMR safety-in-design

- Regardless whether national or start-up effort, regulatory approval, investments and commitment to construct (FOAK – first-of-a-kind) are key and "smart approach".
- Planned integration of "5" elements, with licensing, investments and commitment is critical!
- On scale, 0%-100% project completion, "freezing" design should be late OR use several designs
- Integral test facility and testing are key, V&V engineering & design



Investments and business development must also be sustained

Aspects and specialisation



Key design philosophies & metrics

- Reduced to "zero" design basis accidents (DBAs) from "greatness" of the design
- No beyond DBAs
- Very low CDF –core damage frequency; perhaps 1E-8 or smaller; from PSA/PRA
- Very low large early or early release frequency (LERF/ERF)
- Meets/exceed INSAG-10; given a level, design makes it difficult to progress to next level
- Reduced or no leakage accidents; SBLOCA, LBLOCA
- No human intervention during decay heat cooling/removal
- Economic; low/lower $/kwh
- Proliferation resistant; small EPZ

High level design objectives/functional design requirements; the "triple crown" for nuclear

- No operator or computer action
- No AC or DC power
- No additional water
- Q1: Why no operator or computer action?
- Q2: Why no AC or DC power?
- Q3: Why no additional water?
- Q4: What are key design concepts?

PSA/PRA basic questions.
Q5: what can happen/how often can it happen?
Q6: how can it happen?
Q7: what are the consequences?

PSS and INSAG-10 (Defense in depth in nuclear safety, 1996)

INSAG-10 Levels of defense-in-depth (DiD)

Level of DiD	Objective	Essentially means...
1	Prevention of abnormal operation and failures	Conservative design and high quality in construction and operations
2	Control of abnormal operation and detection of failures	Control, limiting and protection systems and other surveillance features
3	Control of accidents within the design basis	Engineered safety features and accident procedures
4	Control of severe plant conditions, including prevention of accident progression and mitigation of the consequences of severe accidents	Complementary measures and accident management
5	Mitigation of significant releases of radioactive materials	Off-site emergency response

Cf. https://www-pub.iaea.org/MTCD/publications/PDF/Pub1013e_web.pdf

Q1: do you design so that all 5 levels are considered?
OR
Q2: do you design so that from a level 1, the design makes it difficult to reach level 2 and so on?
OR
Q3: do you eliminate levels 4 and 5?

Relationship among DiD, PRA, existing requirements and expectations

DiD Level	SMR target frequency (/yr)* *small values can be argued, conservatively	Attributes	PRA Levels	Current regulatory requirements (/yr)
Level 1	$< 10^{-2}$	Initiating event frequency	Level 1	$< 1 \times 10^{-5}$ and $< 1 \times 10^{-4}$ (depending on regulator)
Level 2	$< 10^{-5}$	Failure detection capability and control action (automatic or manual)		
Level 3	$< 10^{-8}$	Core damage frequency (CDF)		
Level 4	$< 10^{-10}$	Conditional containment failure probability	Level 2	< 0.1 (depending on regulator)
Level 5	$< 10^{-12}$	Large early release frequency (LERF)	Level 3	$< 1 \times 10^{-6}$ (depending on regulator)

Cf. Zeliang, C., Mi, Y., Tokuhiro, A., Lu, L., & Rezvoi, A. (2020). Integral PWR-Type Small Modular Reactor Developmental Status, Design Characteristics and Passive Features: A Review. *Energies (Basel)*, *13*(11), 2898-. https://doi.org/10.3390/en13112898

Design and System Selection

SMR Technology

- Concept of modularity
- Concept of integrated reactor coolant system
- Multi-module concept

SMR Technology Development

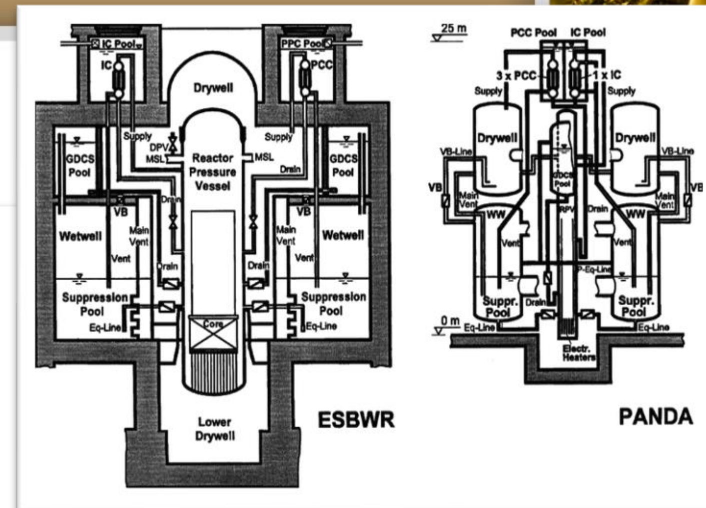
- Integrated PWR design
- BWR reactor design
- Heavy water reactor design
- Integrated molten salt reactor

Safety Systems in NPPs

- Active safety systems
- Passive safety systems
- Hybrid safety systems

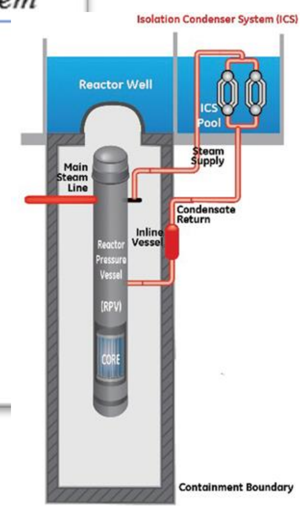
Passive Safety Systems in NPPs

- Review of passive safety systems
- Categorization of PSSs by class and safety functions
- PSSs in SMR Technology



Selected Technology and System

- Integrated PWR design
- Passive Isolation Condenser System



https://magazine.appro.org/news/national-news/6267-1587317600-ge-submits-its-smr-design-to-cnsc.html

Integrated approach from lessons learned

Linking three elements in modern design of SMRs

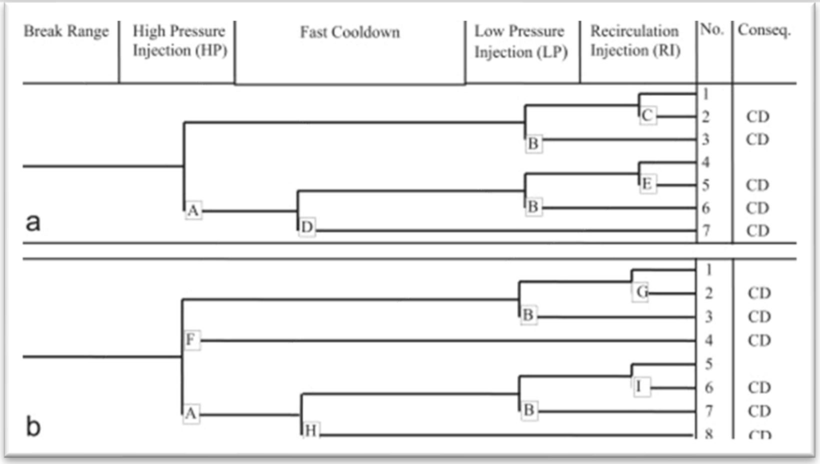
- **PRA-probabilistic risk analysis**
  - Level 1. What can happen? (How often can it happen? What is the frequency?)
  - Level 2. How can it happen?
  - Level 3. What are the consequences?
  - Scenario A. High probability, low consequence
  - Scenario B. Small probability, high consequence

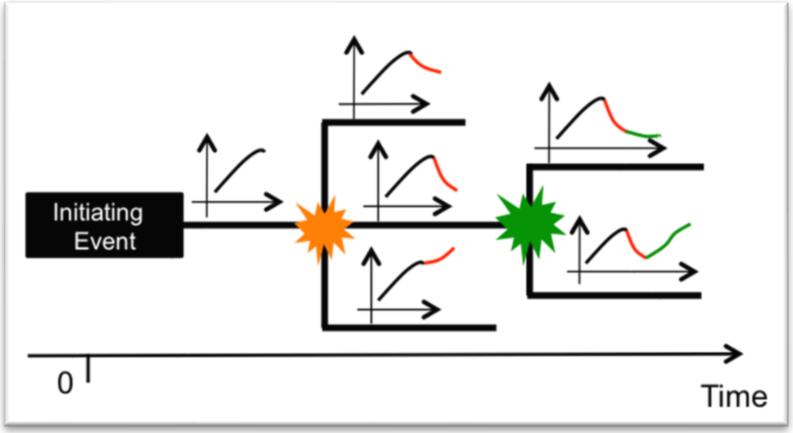
- **System (SA) & Accident Analyses (AA)**
  - (Time) evolution of the severe accidents
  - SA provides sequence of engineered safety systems/components
  - SA provides information on "(P, T, G, V, L)" [more later]
  - AA ultimately provides source term
  - AA provides engineered barriers

- **Reactor designs, lessons learned**
  - History of reactor designs; Generation I to III+
  - Lessons learned from accidents & operations
  - Advances in "tools"; modeling, simulations & engineering (CAD)
  - Integration of tools
  - 30+ years of licensing & regulations

Time evolution of events, including accidents and PSS

- Accidents evolve in time
- Classic PRA is a discrete model; for large reactors, models are complex
- Dynamic PRA (DPRA) includes time as variable
- For SMR, classic PRA models are simpler; an opportunity to use classic PRA (for licensing) & DPRA
- PRA is linked to safety-in-design





https://www.sciencedirect.com/science/article/abs/pii/S0951832015001234 ; https://www.researchgate.net/figure/Dynamic-Event-Tree-Conceptual-Scheme_fig1_267271239

(US) 10CFR50, App. A, GDC- General Design Criteria (GDC 25, 26, 27 -Protection and Reactivity Control Systems)

- https://www.nrc.gov/reading-rm/doc-collections/cfr/part050/part050-appa.html
- *Criterion* ***25****—Protection system requirements for reactivity control malfunctions*. The protection system shall be designed to assure that specified acceptable fuel design limits are not exceeded for any single malfunction of the reactivity control systems, such as accidental withdrawal (not ejection or dropout) of control rods.
- *Criterion 26—Reactivity control system redundancy and capability*. Two independent reactivity control systems of different design principles shall be provided. One of the systems shall use control rods, preferably including a positive means for inserting the rods, and shall be capable of reliably controlling reactivity changes to assure that under conditions of normal operation, including anticipated operational occurrences, and with appropriate margin for malfunctions such as stuck rods, specified acceptable fuel design limits are not exceeded. The second reactivity control system shall be capable of reliably controlling the rate of reactivity changes resulting from planned, normal power changes (including xenon burnout) to assure acceptable fuel design limits are not exceeded. One of the systems shall be capable of holding the reactor core subcritical under cold conditions.
- *Criterion* ***27****—Combined reactivity control systems capability*. The reactivity control systems shall be designed to have a combined capability, in conjunction with poison addition by the emergency core cooling system, of reliably controlling reactivity changes to assure that under postulated accident conditions and with appropriate margin for stuck rods the capability to cool the core is maintained.

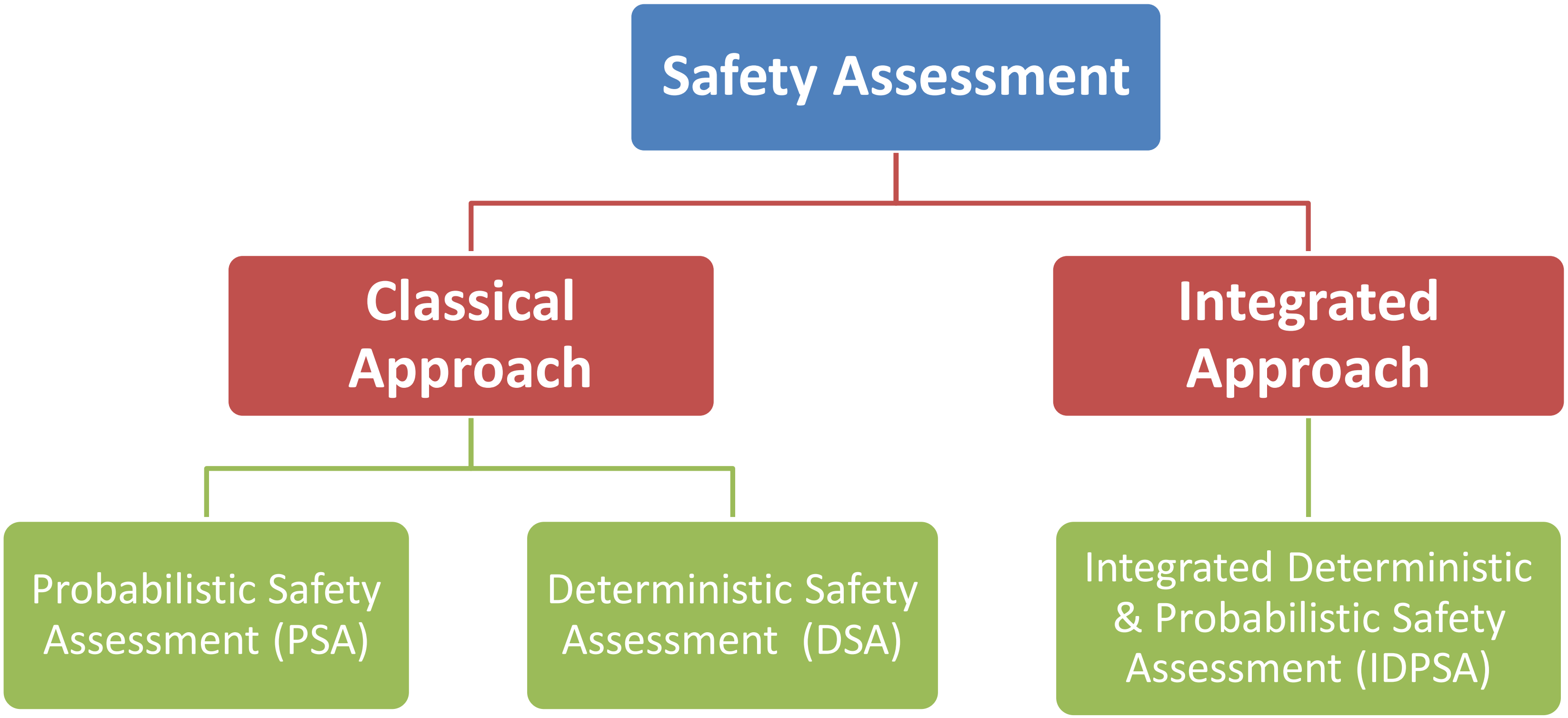
CFR – Code of Federal Regulations

SMR design features that challenge conventional safety analysis

No.	Generic eliminated scenarios	Contributing innovative features
1	LB-LOCAs	Integrated Reactor Cooling System
2	Elimination of control rod ejection/injection accidents	Integrated CRDMs
3	Exclusion of inadvertent reactivity insertion as a result of boron dilution	Eliminated liquid boron reactivity control system
4	Elimination of loss of flow accidents and failures/scenarios related to reactor coolant pumps	Naturally circulated primary system
5	Elimination of the need for external power under accident conditions	Fail-safe passive safety features on loss of power

Cf. Zeliang, C., Mi, Y., Tokuhiro, A., Lu, L., & Rezvoi, A. (2020). Integral PWR-Type Small Modular Reactor Developmental Status, Design Characteristics and Passive Features: A Review. *Energies (Basel)*, *13*(11), 2898-. https://doi.org/10.3390/en13112898

Safety Systems Assessment



Classification of PSS – Passive Safety Systems

Classification based on function:

1. PRHRS Passive Residual Heat Removal System

- Removes the core decay and sensible heat by natural circulation

2. PSIS Passive Safety Injection System

- Accommodates loss of coolant due to leaks or loss of coolant accident (LOCA)

3. PRDS Passive Reactor Depressurization System

- Rapidly reduces the reactor coolant system pressure to enable safety injection systems operation

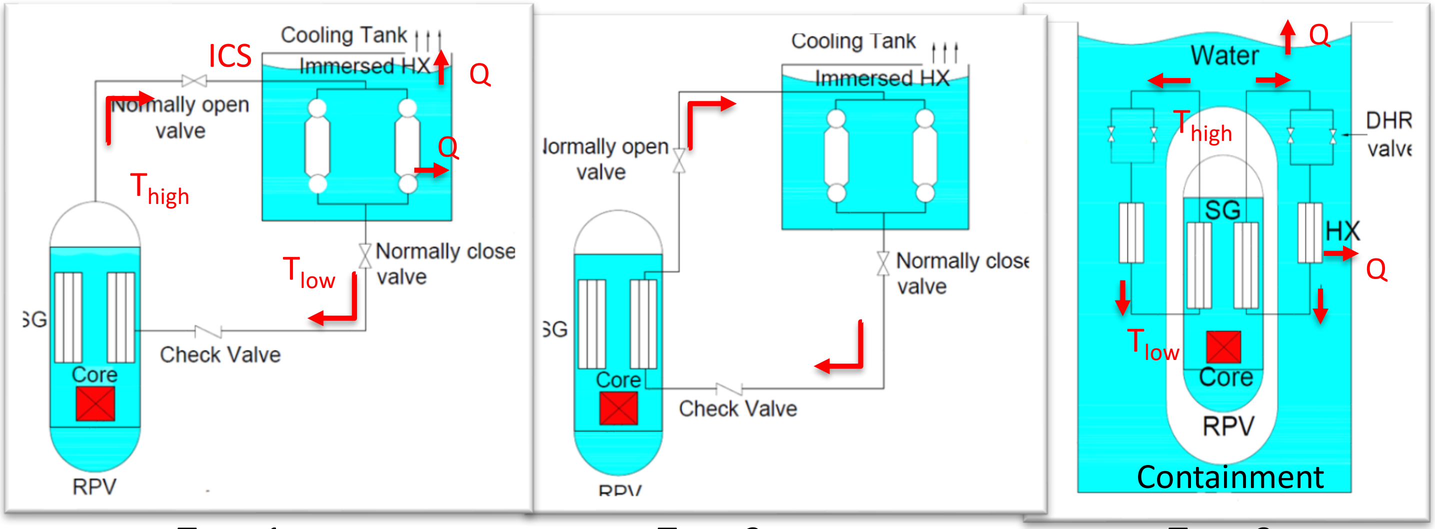
4. PCCS Passive Containment Cooling System

- Maintains the integrity, pressure and temperature inside the containment within the design limit

Example.

PRHRS: Passive Residual Heat Removal System

Type 1: RPV side natural circulation (NC) with immersed heat exchangers (HXs) (e.g. ICS)
Type 2: Steam generator (SG) side NC with immersed HXs
Type 3: SG side NC with immersed reactor pressure vessel (RPV)



Type 1 Type 2 Type 3

Potential advantages of implementing PSSs in iPWR-type SMRs

Design characteristics	***Facilitating factors in (SMR) PSSs start-up/operation***
Integral RCS design- reduced accident initiators	Minimizes accident initiators, thus consider use of PSS. Results in a simplified design
Lower core power capacity	Less (magnitude) decay heat to be removed
Larger surface to volume ratio	Facilitates decay heat removal due to large surface area, particularly for single phase flow
Larger primary coolant inventory per MW(th)	Larger heat sink for natural circulation; larger buoyancy-driven flows/regioins; reduces requirements for heat removal systems
Smaller reactor core power density	Larger thermal-hydraulics margins; favourable in long term decay heat removal, in particular via PSSs
Large secondary coolant inventory, e.g., common reactor pool	Facilitates passive decay heat removal and containment cooling
Taller and broader reactor pressure vessel or vessel containing core	Facilitates decay heat removal via natural circulation, i.e., higher elevation difference between heat source and sink

Cf. Zeliang, C., Mi, Y., Tokuhiro, A., Lu, L., & Rezvoi, A. (2020). Integral PWR-Type Small Modular Reactor Developmental Status, Design Characteristics and Passive Features: A Review. *Energies (Basel)*, *13*(11), 2898–. https://doi.org/10.3390/en13112898

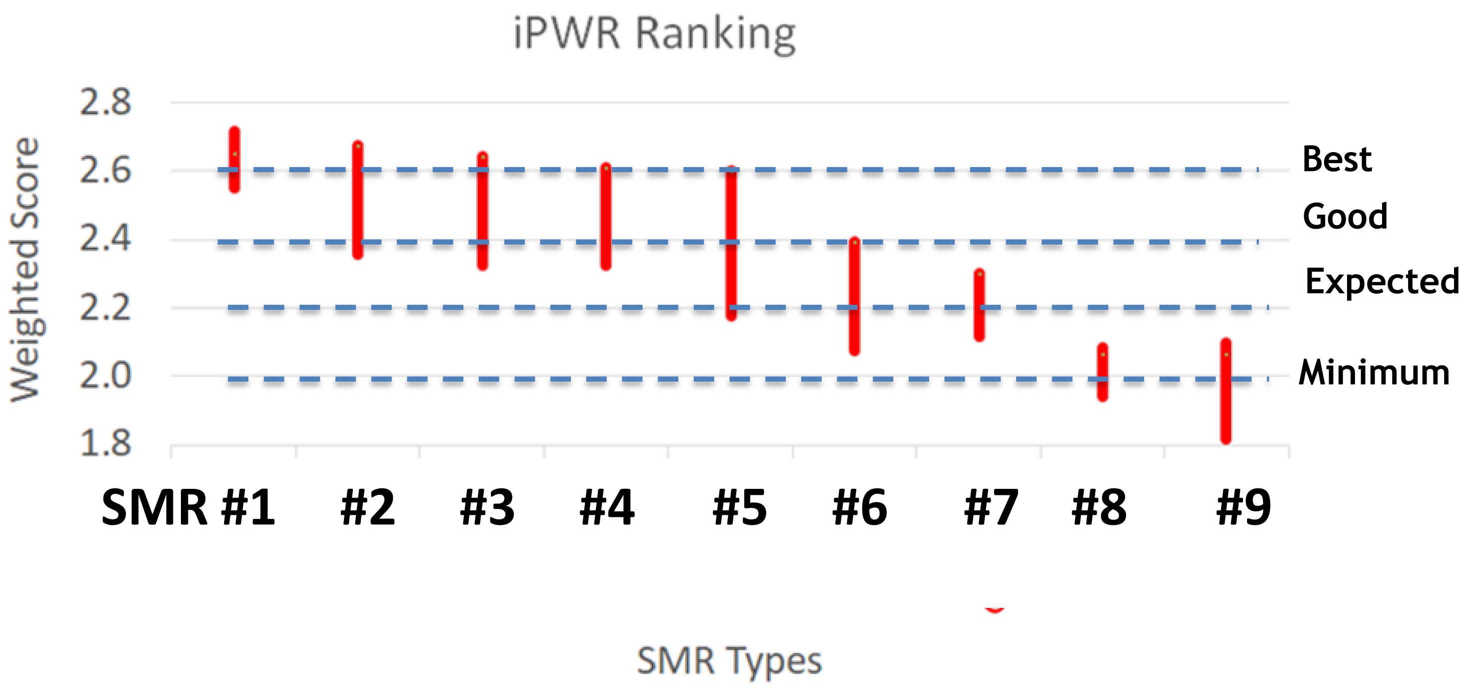
Representative ranking of types of PSS

Evaluation metrics of PSS among iPWR designs

PSS	Attributes	Evaluation Metrics			
		4	3	2	1
RHRS	Type	SG side HXs in pool	SG side HXs in tank		RPV side
	CT		>72 hour	>24 h and ≤72 h	≤24 hour
	R&D	Both R and D	4 R	2 R	No R nor D
SIS	Type	Both	NC based		One-time
	CT		>72 hour	>24 h and ≤72 h	≤24 hour
	R&D	Both R and D	4 R	2 R	No R nor D
RDS	Type	Both	NC based		ADS
	R&D	Both R and D	4 R	2 R	No R nor D
CCS	Type	Pool type	Suppression pool		air-cooled
	CT		>72 hour	>24 h and ≤72 h	≤24 hour
	R&D	Both R and D	4 R	2 R	No R nor D

CT: cooling time, R&D: redundancy and diversity, R: redundancy, D: diversity

Representative ranking of iPWR type SMRs



Part of today’s presentation

- ATW’s International Journal of Nuclear Power.
- A. Tokuhiro, C. Zeliang, Y. Mi, *Small Modular Reactor Safety-in-Design and Perspective*, ATW – International Journal for Nuclear Power, v. 66, March (3) 2021.
- https://www.kernd.de/kernd-wAssets/docs/presse/Article-atw-2021-3-Small-Modular-Reactor-Safety-in-Design-and-Perspectives-Tokuhiro-et-al.pdf
- Key reference: C. Williams, W.J. Galyean, and K.B. Welter. “*Integrating Quantitative Defense-in-Depth Metrics into New Reactor Designs*.” *Nuclear engineering and design* 330 (C) (2018): 157–165.
- https://www-sciencedirect-com.uproxy.library.dc-uoit.ca/science/article/pii/S0029549318300098

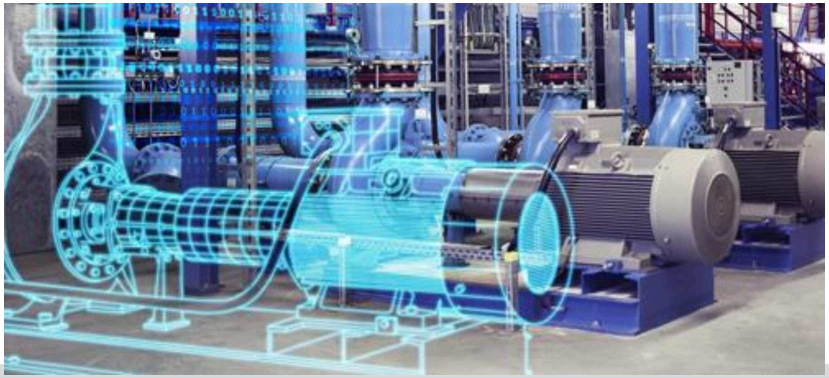
Mr. Zeliang, Mi (left, right)

A word about digital twins

Challenges, “low, medium and high”

Not in any order

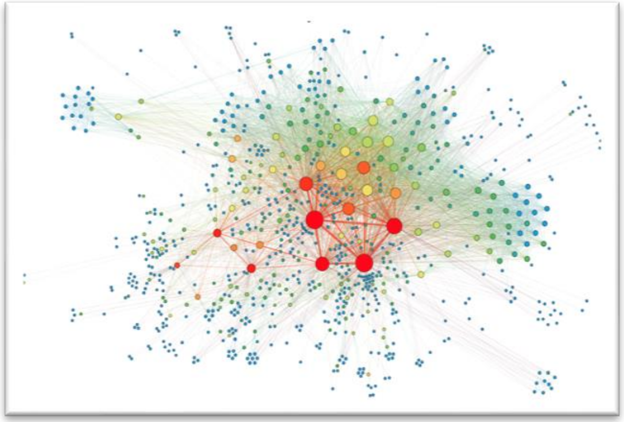
- Initiatives such as “digital twin”, though useful in some defined respects, often requires high-performance, computing resources (methods, simulations and $$$) and therefore is unlikely to be substantial use in ongoing engineering and design practices.
- As some nuclear reactor concepts (engineering, design) and related thermohydraulic concepts are dated, there is greater global need to maintain knowledge in some of these areas (examples): fast reactors theory, sodium and liquid metal thermohydraulics, fusion reactor concepts, turbulence theory and applications, fundamentals of CFD, analytical methods and simulations, high-performance computational methods, experimental methods, validation and verification.
- There is urgent need to maintain classic books in the above disciplines.
- Increasing focus (scrutiny) on “cost and price” of technology solutions, ROI –Return on Investment, in investments, coupling of global supply-chain markets, disinformation/misinformation in shared communications. Polarizing “G7/G20” geopolitics.

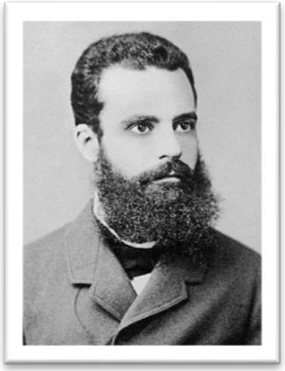


Applied Complexity, Hueristics and Optimisation

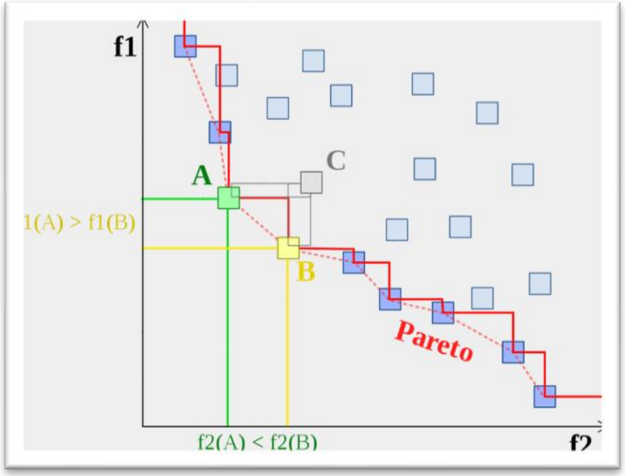
Complex systems, design; complexity & optimization

- Complex system, dynamic behavior
- Heuristic or heuristic technique is an approach to problem solving ; employs a practical method that does not guarantee an optimal or “near perfect” approach but nevertheless reaches a short-term goal or approximation. Use of heuristics can speed up the process of finding a satisfactory solution. (Cf. Wikipedia, Heuristic)
- On optimization, using Pareto “efficiency” or optimality is a engineering design situation where no objective or preference criterion can be “improved” without making at least one individual or preference criterion “worse “. (Cf. Wikipedia, Pareto efficiency)
- Keywords. Complexity, complex systems dynamics, multi-objective, multi-parameter,





Vilfredo Pareto 1848-1923, Cf. https://en.wikipedia.org/wiki/Vilfredo_Pareto



Complex Issues; 'Metrics' LENDIT

Length Scales

L

Energy Scales

E

Number Scales

N

Distribution Scales

D

Information Scales

I

Time Scales

T

Purpose:
common communication basis; potentially risky communication effective; applicable across soft and hard domains; linked to analytical approaches

PTGVL - Pressure, Temperature, Mass flowrate, Valve position, Liquid level

Pressure

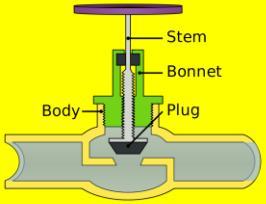
P

Temperature

T

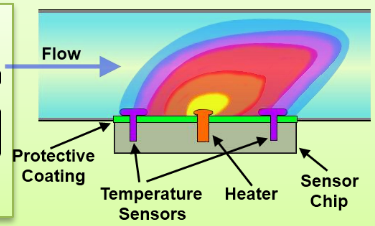
Valve position

V



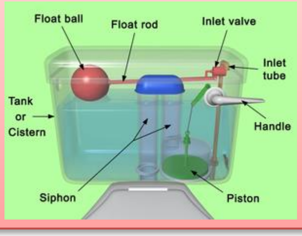
Mass flowrate

G



Liquid level

P



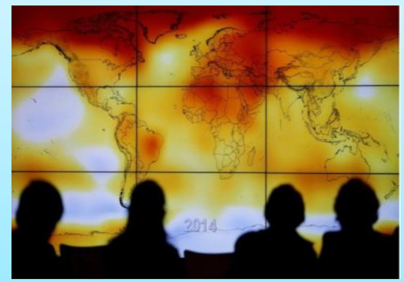
S2R2 - System, State, Resource, Response

System

S

State

S



Resource

R

Response

R

In summary..

Technical, non-technical SMR challenges

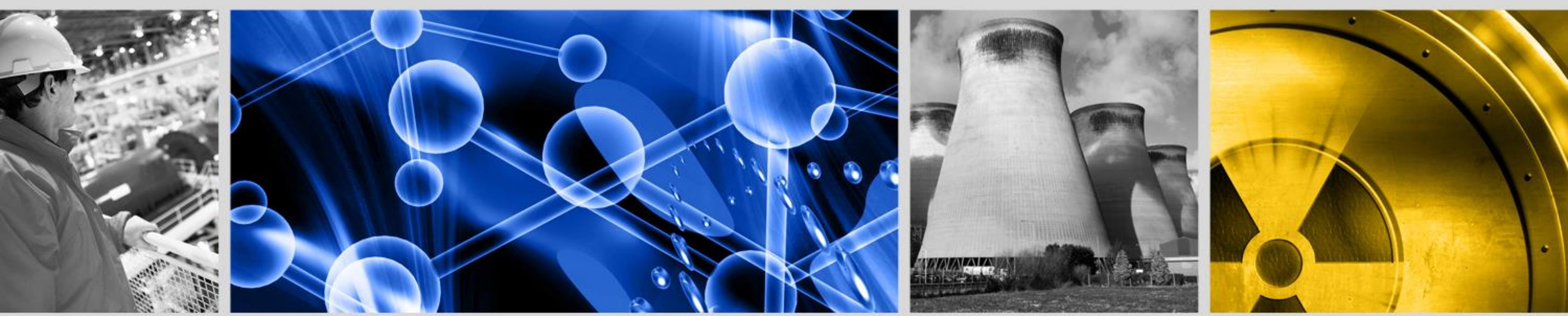
Not in any priority/order.

- Non-technical. Financial, sustained investments – relative to progress to completion of the SMR design and engineering.
- Non-technical/partially technical. Lack of completed regulatory review and approval. NuScale SMR has USNRC approval; Russia, China, Argentina, otherss are operating or constructing SMR(type) plants of their own design. Export of said design unclear.
- Non-technical. 80 current SMR concepts. Is there sufficient workforce? At maximum, how many SMR/new nuclear could be under construction simultaneously?
- Recognize differences in funded approach – national initiatives/programs, federal/cmmercially funded under investors.
- Technical/partially non-technical. No reference design that is publically accessible. IAEA SMR simulator does exist but PSA/PRA of this design does not. Proprietary nature of commercial SMRs.

QUESTIONS?

akira.tokuhiro@ontariotechu.ca

Twitter. @TokuhiroAkira (my own)
Instagram. @wehaveenergy



References

References

- A. Tokuhiro, C. Zeliang, Y. Mi, Small Modular Reactor Safety-in-Design and Perspective, ATW – International Journal for Nuclear Power, v. 66, March (3) 2021. https://www.kernd.de/kernd-wAssets/docs/presse/Article-atw-2021-3-Small-Modular-Reactor-Safety-in-Design-and-Perspectives-Tokuhiro-et-al.pdf
- C. Williams, W. J. Galyean, and K.B. Welter. "Integrating Quantitative Defense-in-Depth Metrics into New Reactor Designs." Nuclear engineering and design 330 (C) (2018): 157–165. https://www-sciencedirect-com.uproxy.library.dc-uoit.ca/science/article/pii/S0029549318300098
- Many others, depending on area. However, many details are proprietary for commercial SMRs.

Land acknowledgement, to Ontario Canada’s Indigeous peoples

Land acknowledgement

(Ontario indigenous below)

Ontario Tech University is proud to acknowledge the lands and people of the Mississaugas of Scugog Island First Nation. We are situated on the Traditional Territory of the Mississaugas, a branch of the greater Anishinaabeg Nation which includes Ojibway, Odawa and Pottawatomi.

Cf. Truth and reconciliation

Ontario Tech University

Oshawa, Ontario Canada

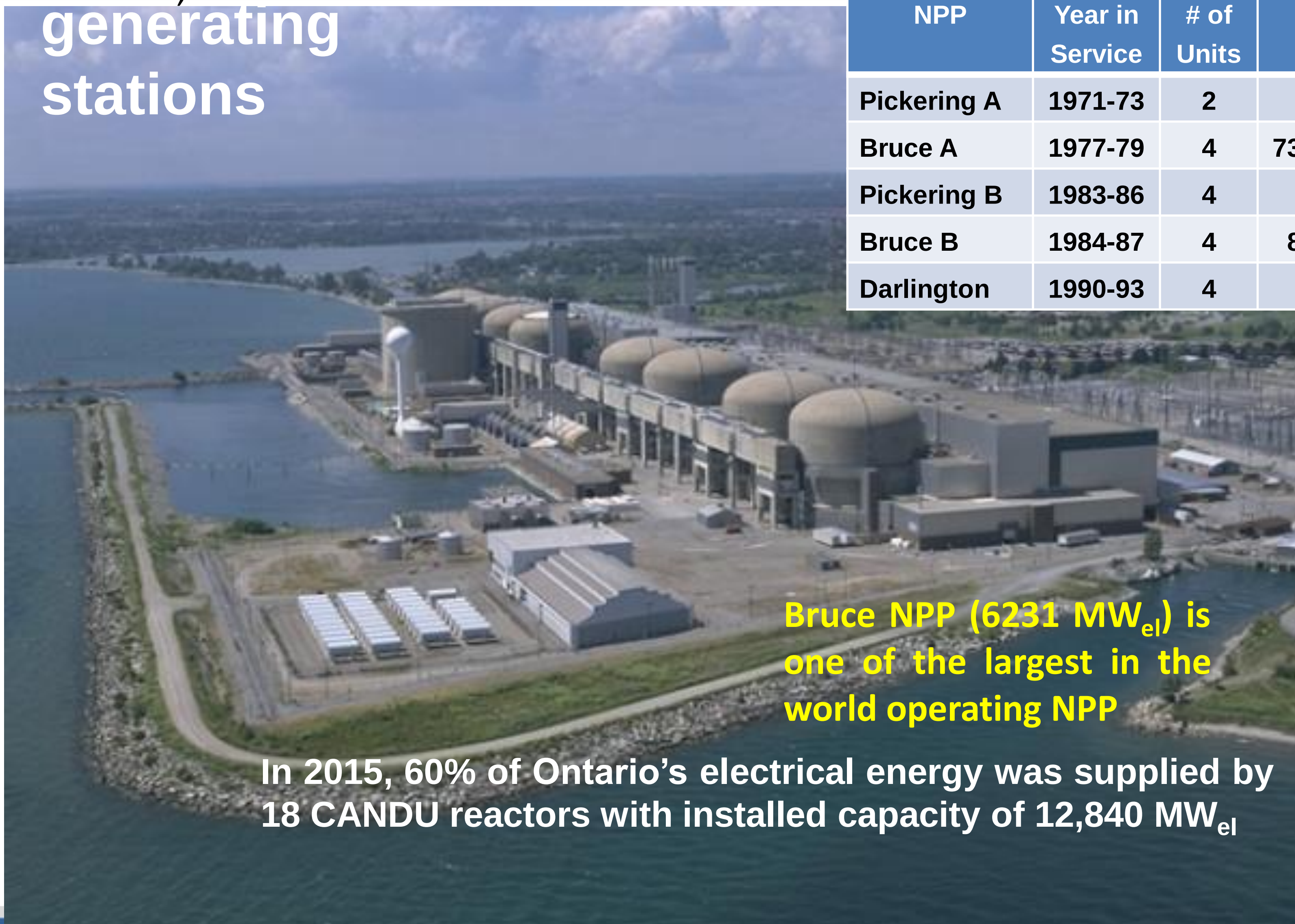
Ontario Tech University

- *Faculty of Engineering and Applied Science; 6 Faculties*
- *Ontario Tech U. (UOIT); started 2002, 1st students in 2003; 1st graduates in 2007; ~10,000 students ("millenials")*
- *BEng, MS, PhD, MEng, GDip in NE, HP&RS*
- *1000+ Fac.of Energy Sys. & Nucl. Sci. graduates since 2007*
- *#3 (average) in North America, BEng graduates*
- *15 faculty members*
- *Brilliant Energy Institute, IAEA Collaborating Centre; CfSMRs, CERL*

Ontario's nuclear generating stations

NPP	Year in Service	# of Units	Units' Installed Capacity, MW_{el}
Pickering A	1971-73	2	515×2=1030
Bruce A	1977-79	4	730×2+770×2=3000
Pickering B	1983-86	4	515×4=2060
Bruce B	1984-87	4	817×3+782=3233
Darlington	1990-93	4	878×4=3512

Cf. G. Harvel



Bruce NPP (6231 MW_{el}) is one of the largest in the world operating NPP

In 2015, 60% of Ontario's electrical energy was supplied by 18 CANDU reactors with installed capacity of 12,840 MW_{el}